U.S. ARMY RDECOM — ARL

Micromechanical FE modeling of tensile failure of unidirectional composites

Enterprise for Multi-scale Research of Materials

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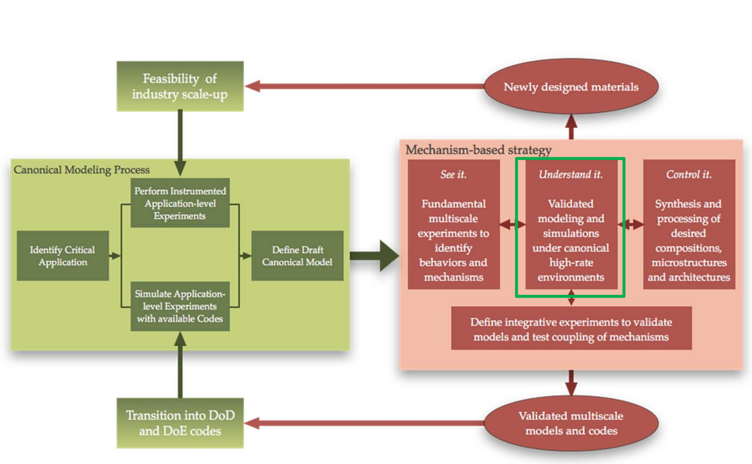
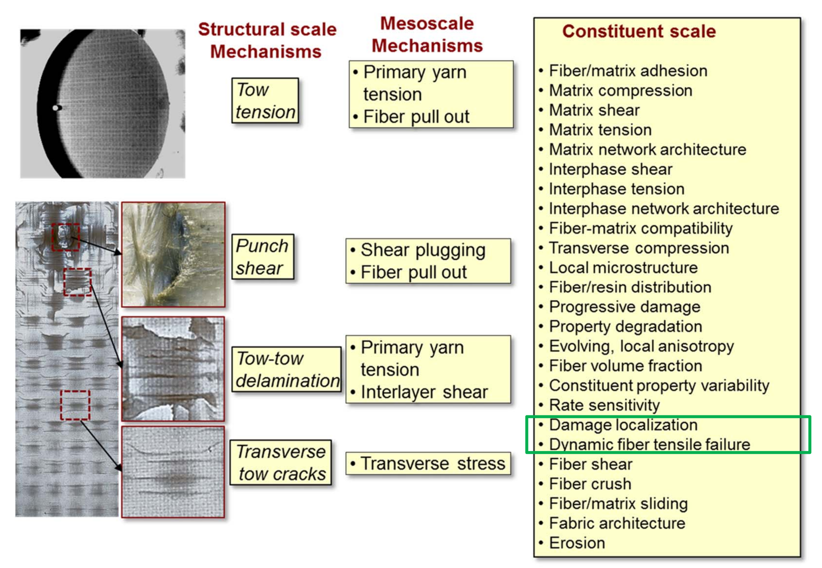
How We Fit

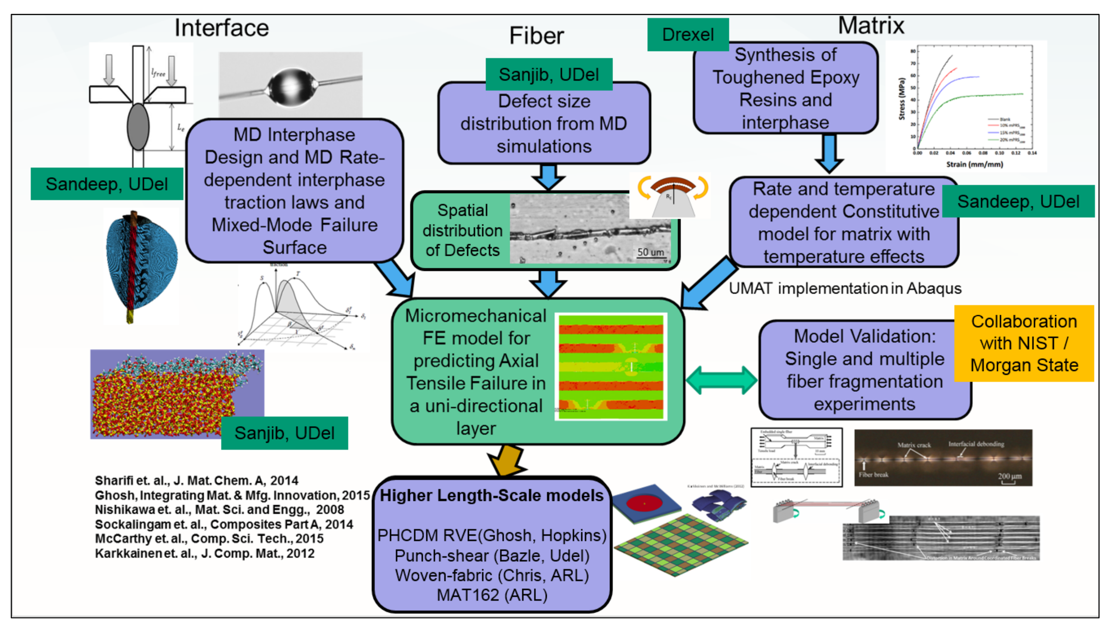
Materials-by-Design Process



Mechanism-based Approach



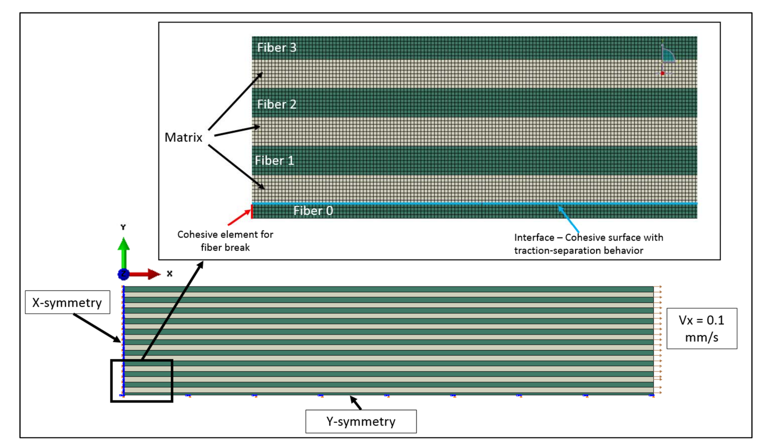
Interaction with composites CMRG tasks

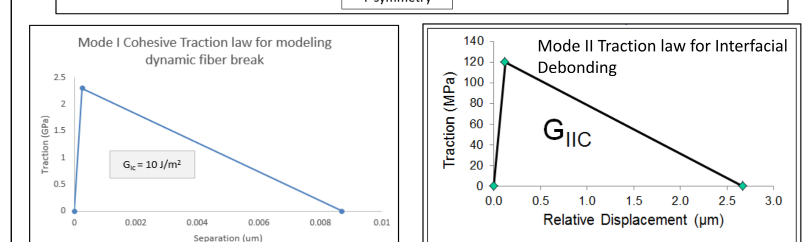


Technical Approach

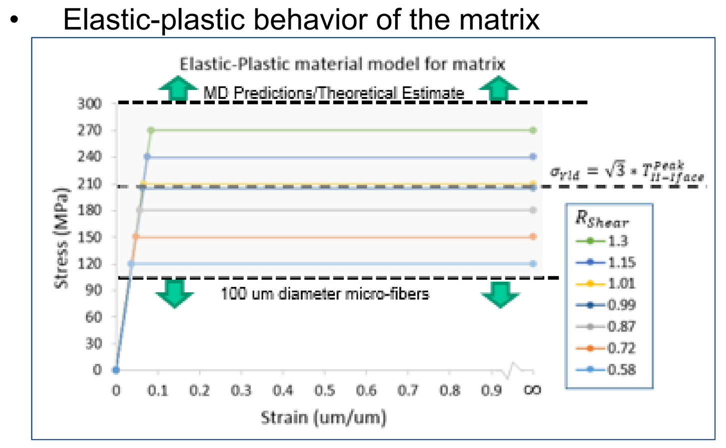
Micromechanical FE model

- Dynamic brittle fiber fracture using cohesive elements
- Interface modeled as 'zero-thickness' cohesive surface

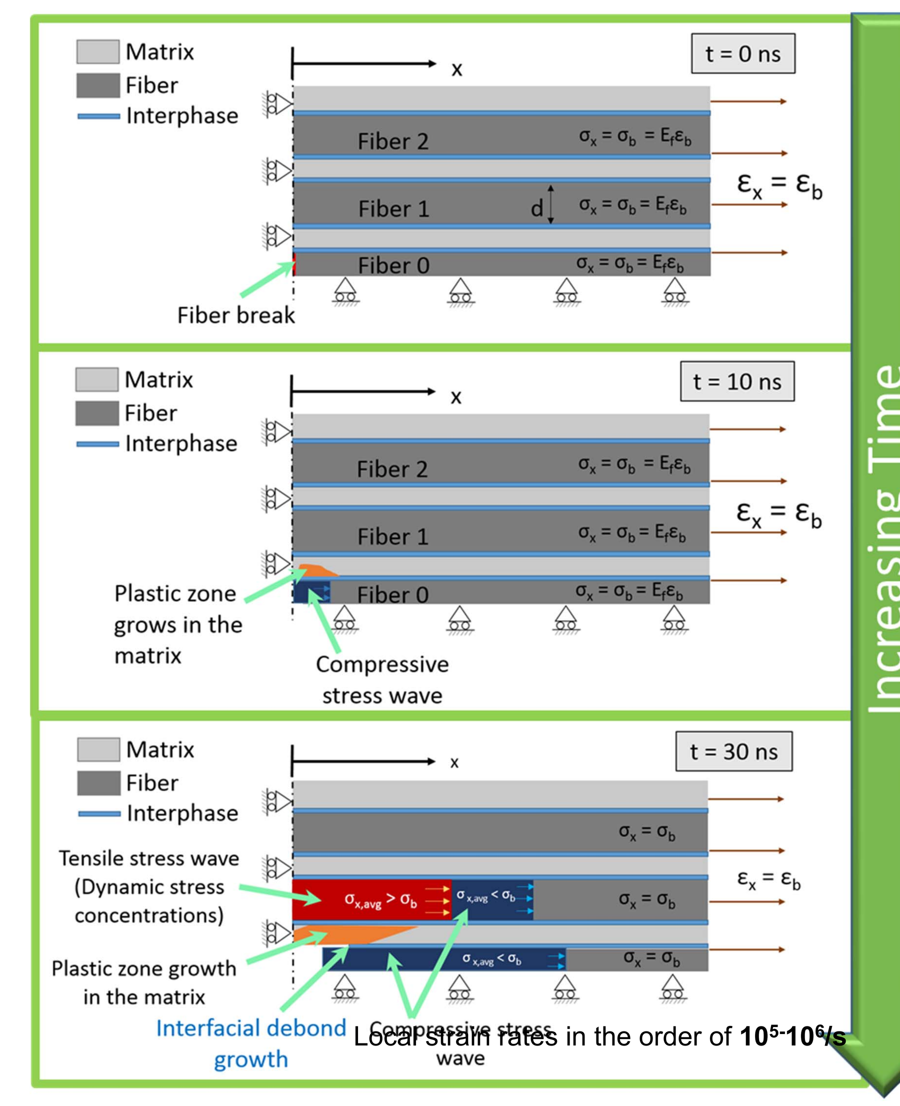




- Elastic-plastic behavior of the matrix



Range of Epoxy yeld strengths considered



Local strain rates in the order of 10^5-10^6/s

Axial wave-speed in the fiber :

$$c_f = \sqrt{\frac{E_f}{\rho_f}} = 6.1\ km/s$$

Peak tensile strain rate in Fiber 1 $\sim 10^6\ /s$

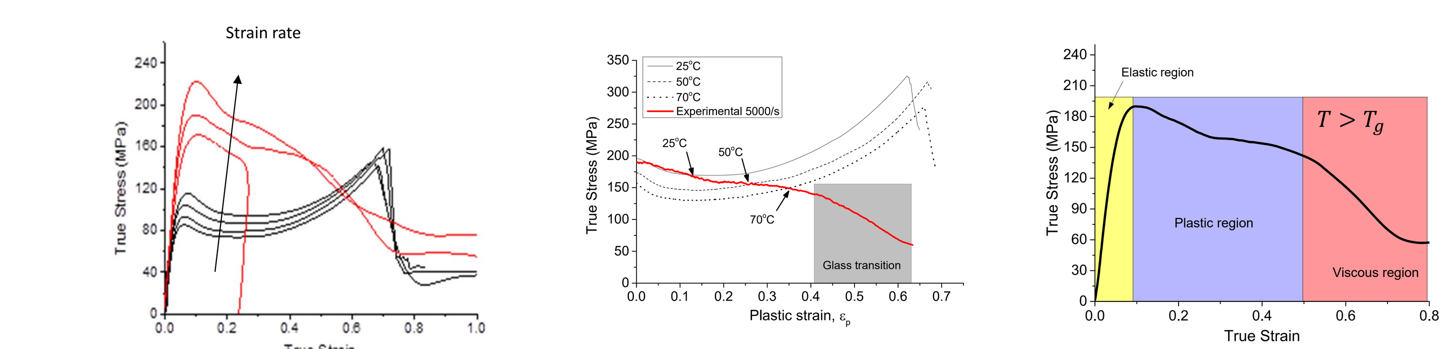
Key Accomplishments

- 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
- Dynamic stress concentrations are shown to be significantly higher and are shown to envelop a much larger volume of the microstructure than the corresponding predictions based on quasi-static models
- Dynamic interfacial failure is predicted where debonding initiates, propagates and arrests at longer distances than predicted by models that assume quasi-static fiber breakage.
- At larger break strengths, unstable debonding is predicted by the dynamic model.
- Consistent with experimental observation of Axial splitting in high-rate tensile test specimens

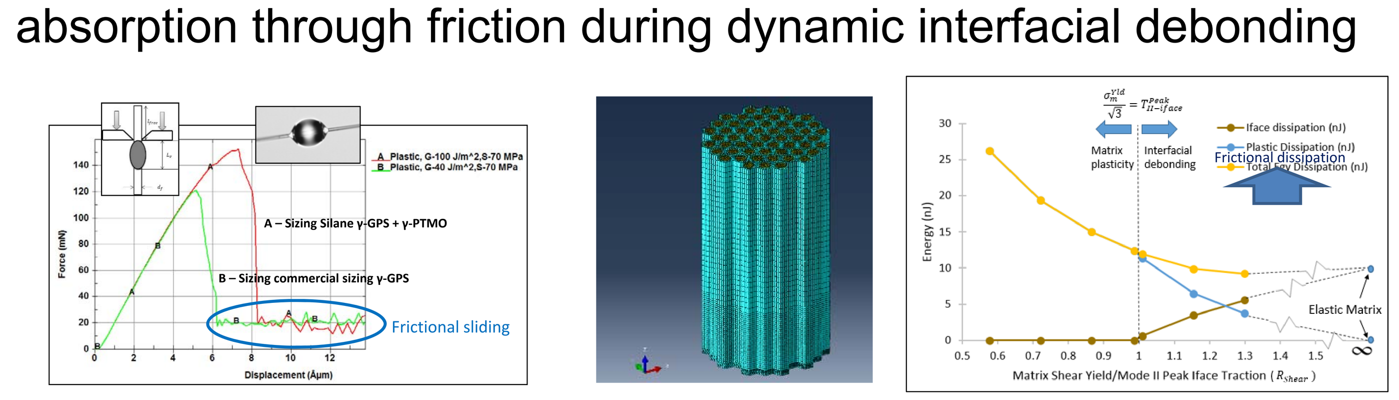
Shokrieh et. al., Comp. Struct., 2009

Future Directions in 2018

- UMAT implementation of rate-dependent matrix properties accounting for adiabatic heatic and thermal softening at high strain rates
- Based on experimental data from high-rate compression tests
- Model predicts local shear strain rates in matrix in the range of $10^6 - 10^7$/s



- Extension to 3D models that include effects of thermal residual stress in the matrix and interface and frictional sliding of the debonded interface
- Fiber surface texture can be controlled to achieve additional energy absorption through friction during dynamic interfacial debonding



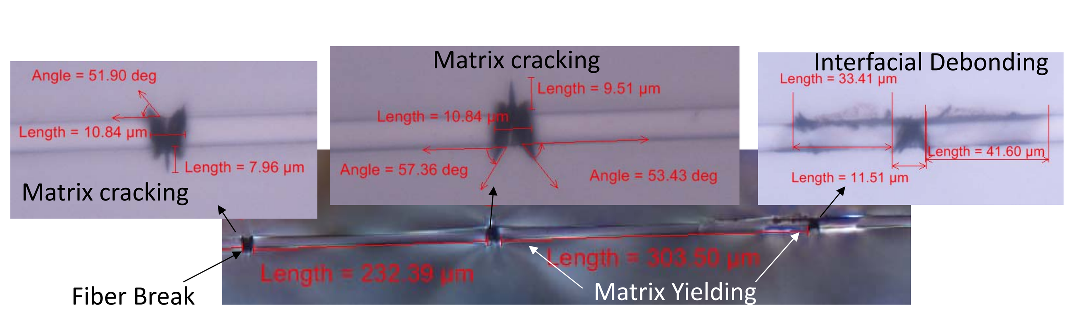
Key Goals

Develop a detailed FE modeling framework to predict the high strain rate tensile failure of unidirectional composites while accounting for micro-mechanical damage mechanisms

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 unidirectional composites

Develop a systematic method to translate the results from these models into inputs for dynamic Punch-shear models and homogenized models at higher length scales (eg. MAT162 in LS-DYNA)



Micromechanical damage mechanisms

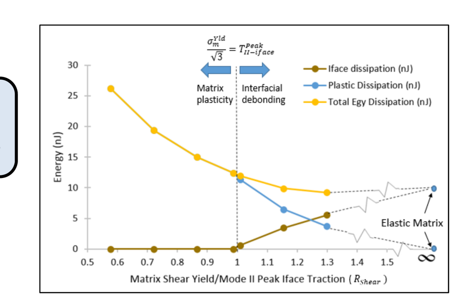
- Fiber break
- Matrix plasticity
- Interfacial debonding
- Matrix micro-cracking

Major Results

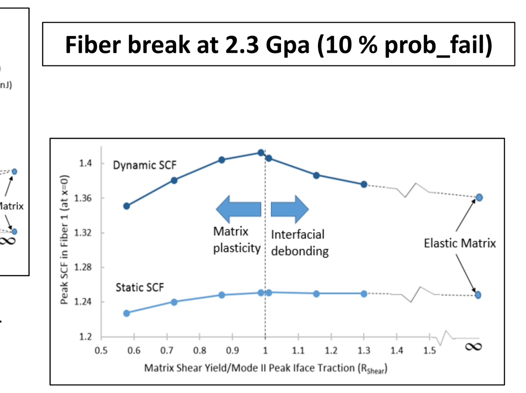
- **Shear Yld. Ratio,** $R_{Shear} = (\frac{\sigma_{Y-mises}}{\sqrt{3}})/T_{II-Peak}^{iface}$

$$R_{Shear} < 1, Matrix - yielding$$
$$R_{Shear} > 1, Interface\ debonding\ \&\ Matrix\ yielding$$

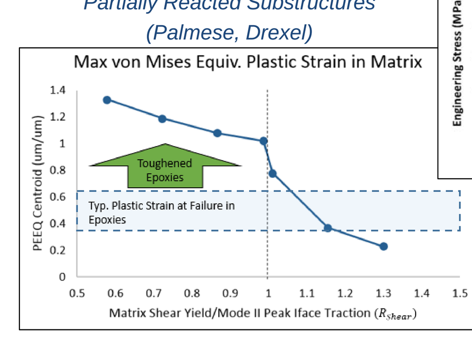
- Non-dimensional parameter, R_{Shear}, gives insights into energy dissipation mechanisms
- Useful for materials design

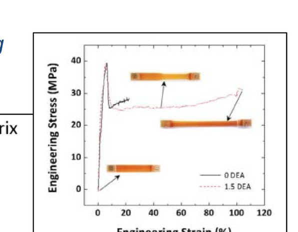


Fiber break at 2.3 Gpa (10 % prob_fail)

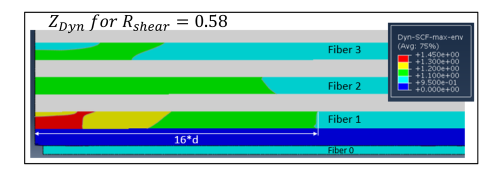


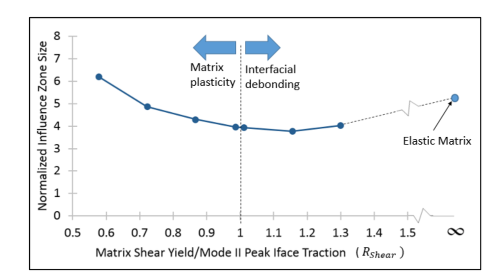
Toughened Epoxy resin systems using Partially Reacted Substructures (Palmese, Drexel)





- Dynamic zone-of-influence size, Z_{Dyn} = Area over which Peak Dynamic SCF > 1.1
- Normalized influence zone size = $Z_{Dyn}/Z_{Sta-Elastic}$
- Dynamic enhancement of the influence zone is significant for all yield ratios (4-6 times the size of the static zone)



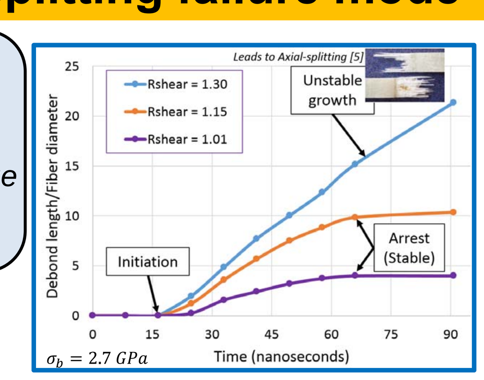


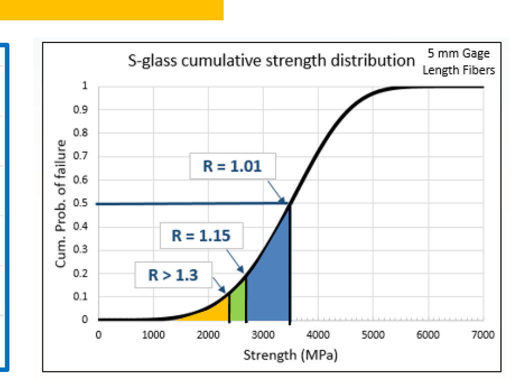
Axial-splitting failure mode

Occurs when:

Rate of elastic energy released by unloading of broken fiber > *Rate of energy dissipated due to interfacial debonding* + *Rate of energy dissipated due to matrix plasticity*

- Leads to unstable dynamic debond growth





- Plastic matrix absorbs additional energy from the fiber break
- **Higher break strengths achievable for matrices with lower yield strengths**

R_{Shear}	Highest σ_b that can be achieved without initiating unstable interfacial debonding	Max. von Mises Equiv. Plastic strain in the Matrix
1.01	3.5	49 %
1.15	2.7	28 %
1.30	2.4	23 %

Ganesh et. al., J. Composite Materials, 2016
Ganesh et. al., J. Composite Materials, 2017

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

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