Characterizing Damage Accumulation in CMCs

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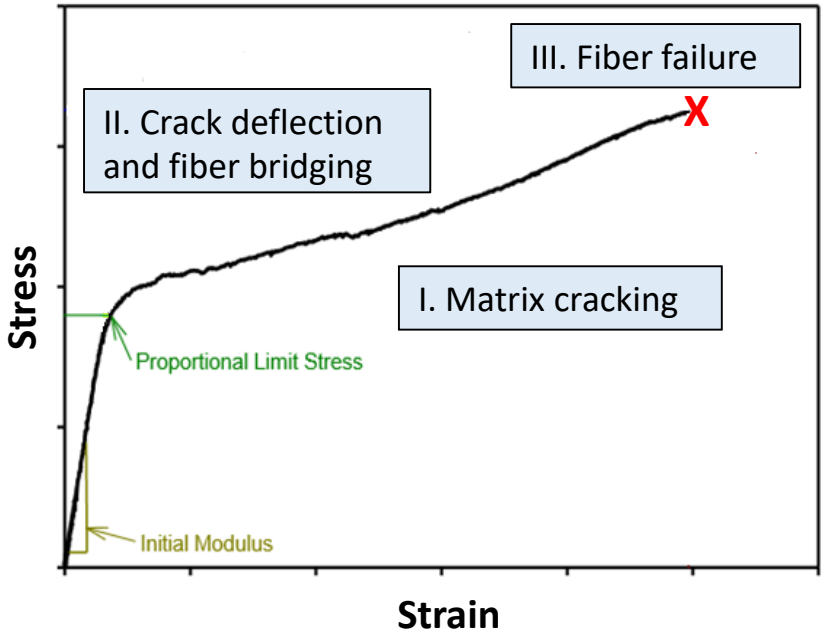
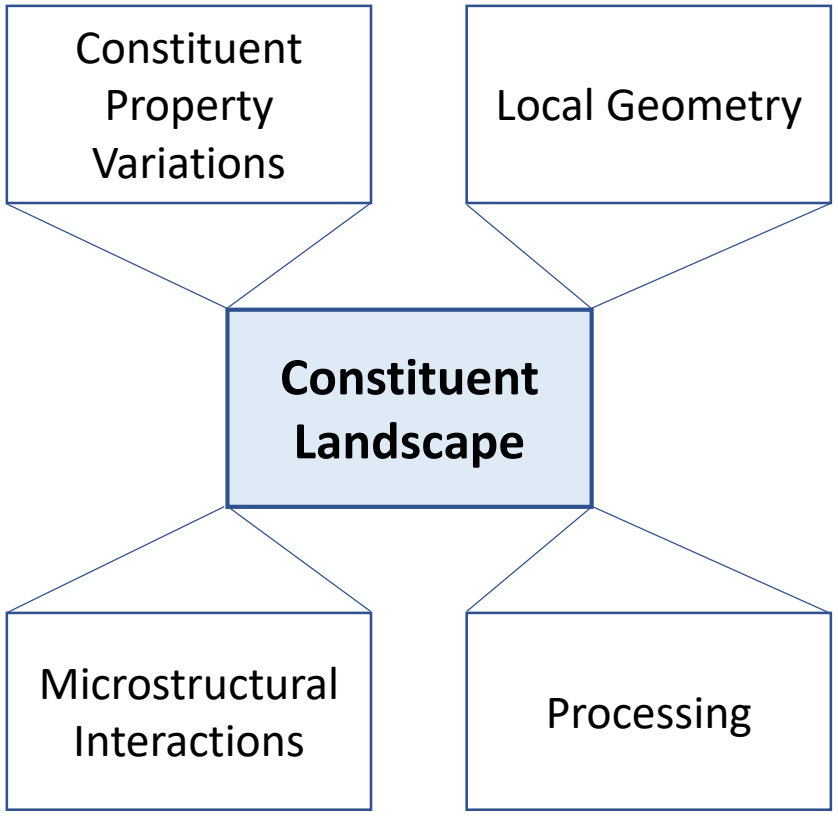
CMC Damage Behavior is Influenced by Constituent Landscape Effects

Hypothesis: Locally averaged structural features are significant drivers in the manner in which damage accumulates, moves, and interacts

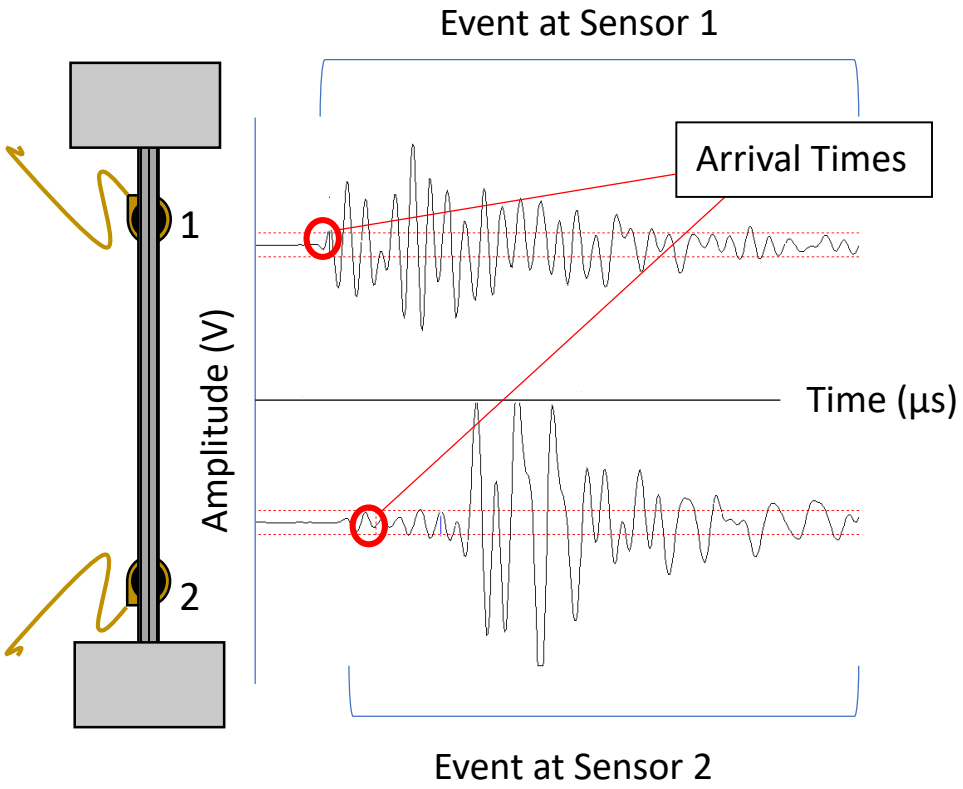


Corman and Luthra, Handbook of Ceramic Composites (2005).



Acoustic Emission (AE) Enables Real-Time Damage Assessment

AE can be used to locate event sources and characterize damage in the bulk



$$Location = \frac{x}{2} \cdot \left[\frac{\Delta t}{\Delta t_x}\right]$$

x = sensor separation
Δt = arrival time difference
Δt_x = difference in arrival times across AE window

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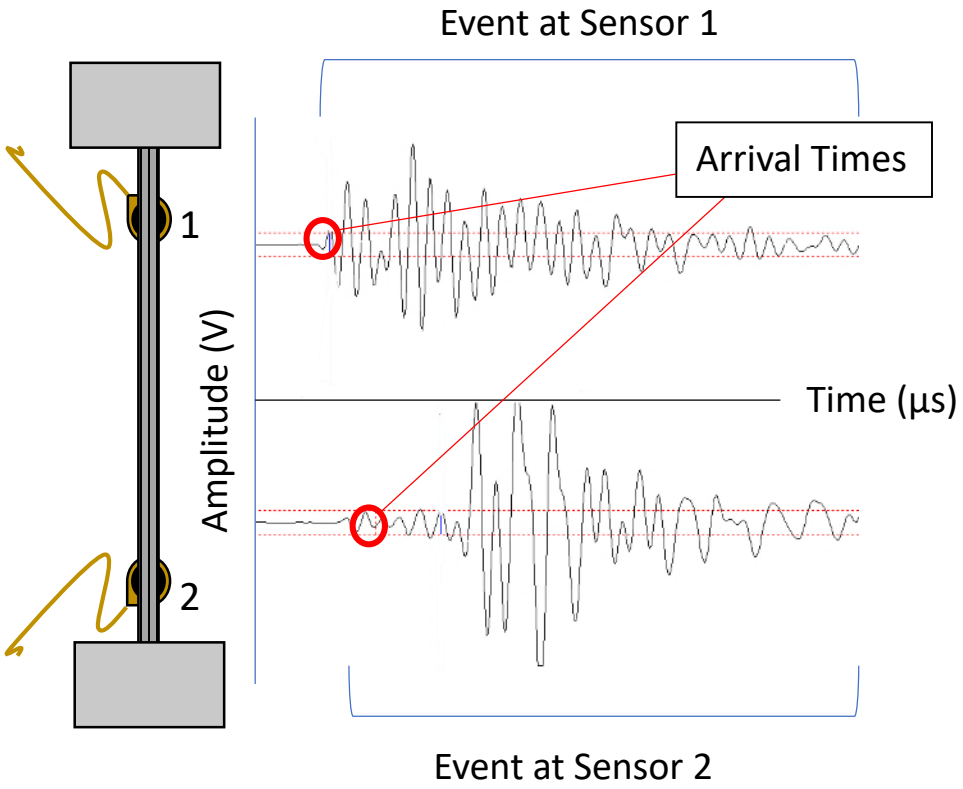
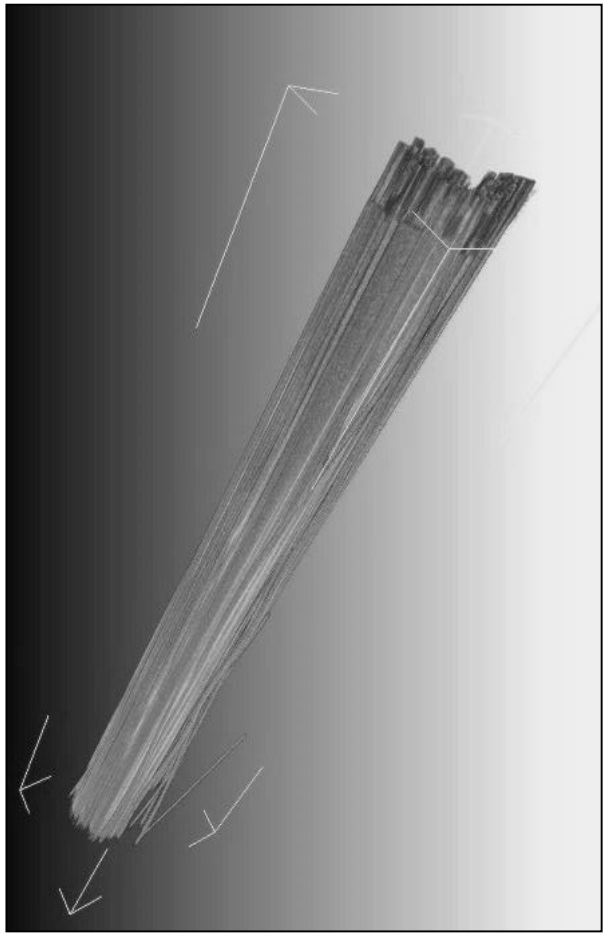


Advantages

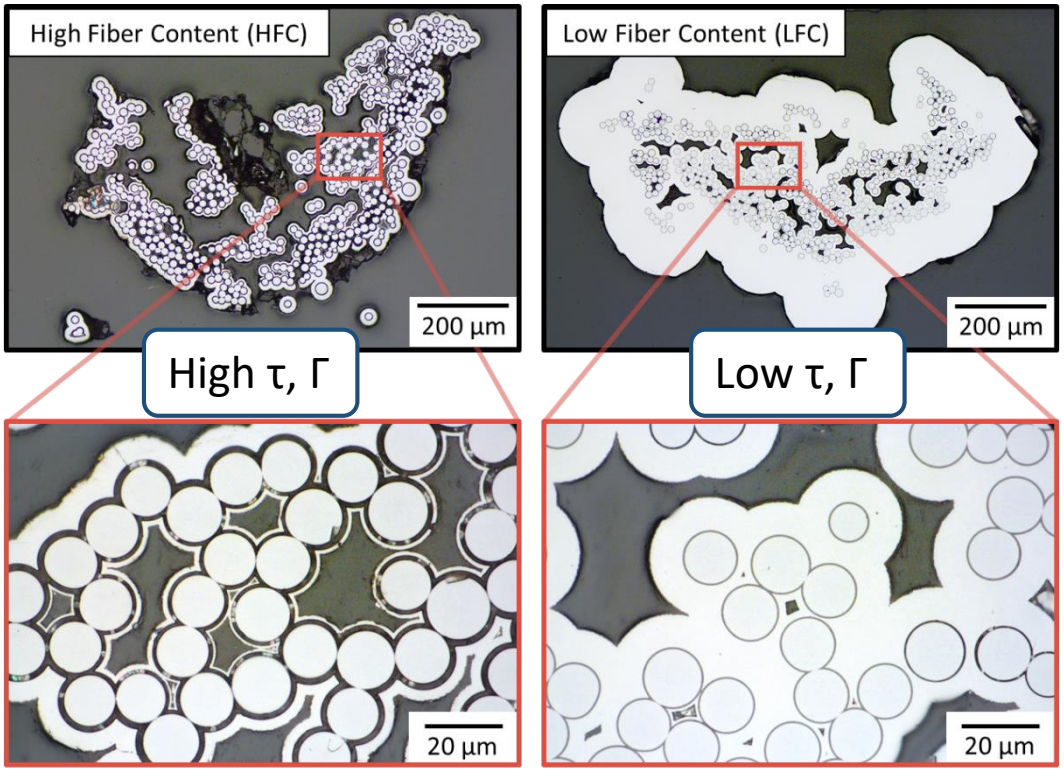
- In-operation monitoring
- Damage localization
- Volumetric inspection
- Early detection of damage

Minicomposites Provide Simplified Architecture Suited to Study Microscale Damage



Courtesy of Richard Rauser (GRC)

Specimen ID	BN Thickness (µm)	V_f (%)	V_{BN} (%)	V_m (%)	Area (mm^2)
HFC	1.9 ± 0.6	33.5	24.6	41.8	0.167
LFC	0.3 ± 0.08	21.3	2.2	76.5	0.266



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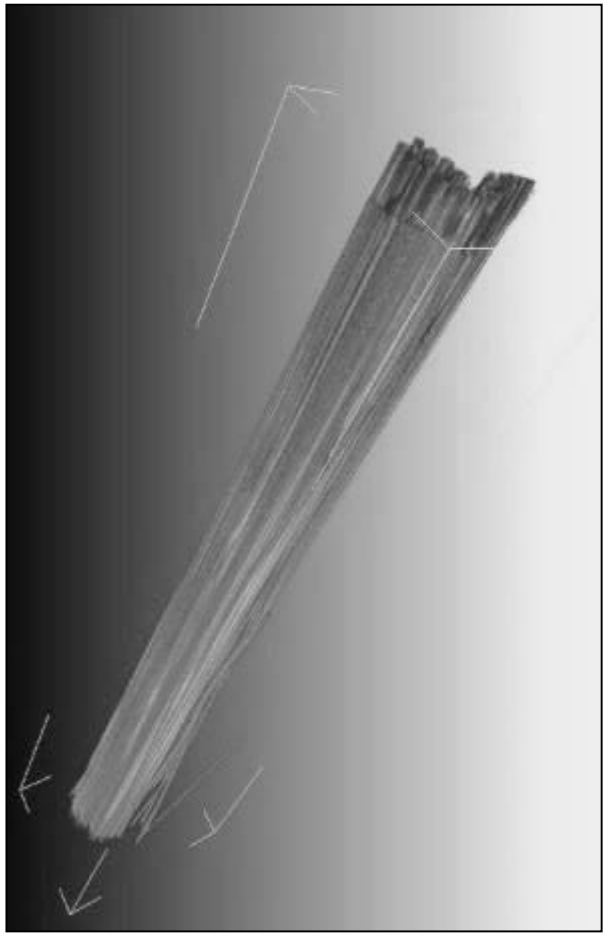
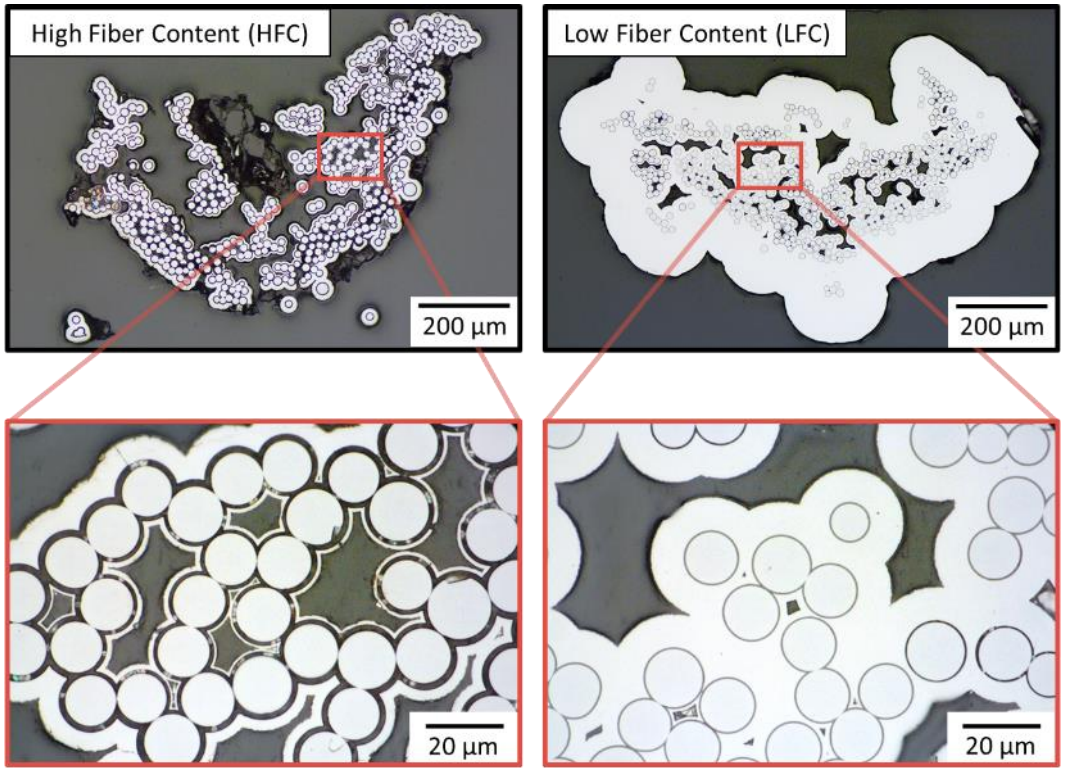


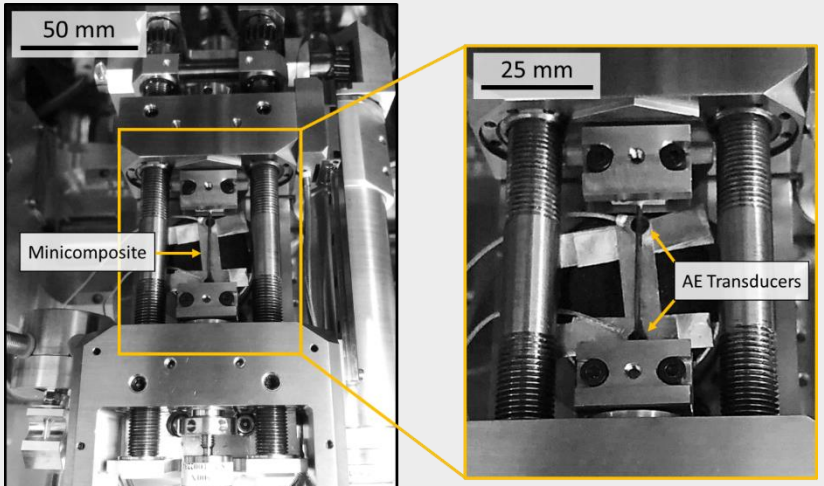
Courtesy of Richard Rauser (GRC)

Specimen ID	Sliding Stress (τ)	Debond Toughness (τ)
HFC	34.5 ± 13.0 MPa	5.5 ± 3.9 J/m^2
LFC	18.1 ± 4.8 MPa	1.2 ± 0.5 J/m^2



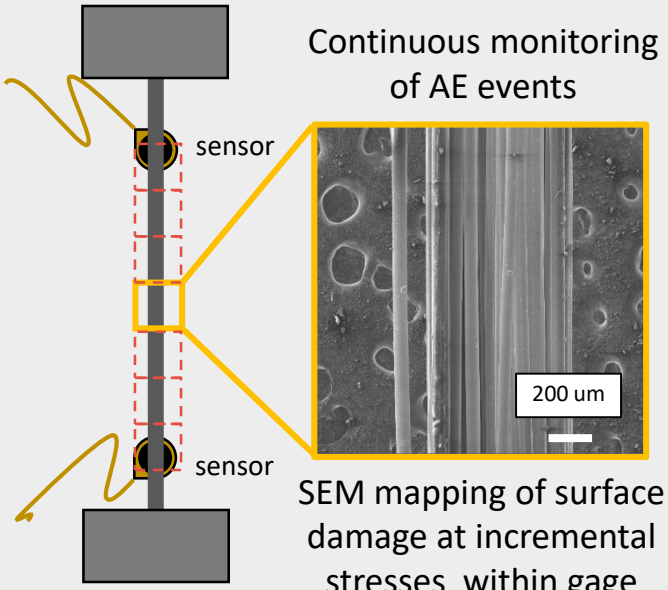
A Multi-Modal Approach for Damage Characterization

In-SEM Mechanical Testing



Test minicomposite to failure

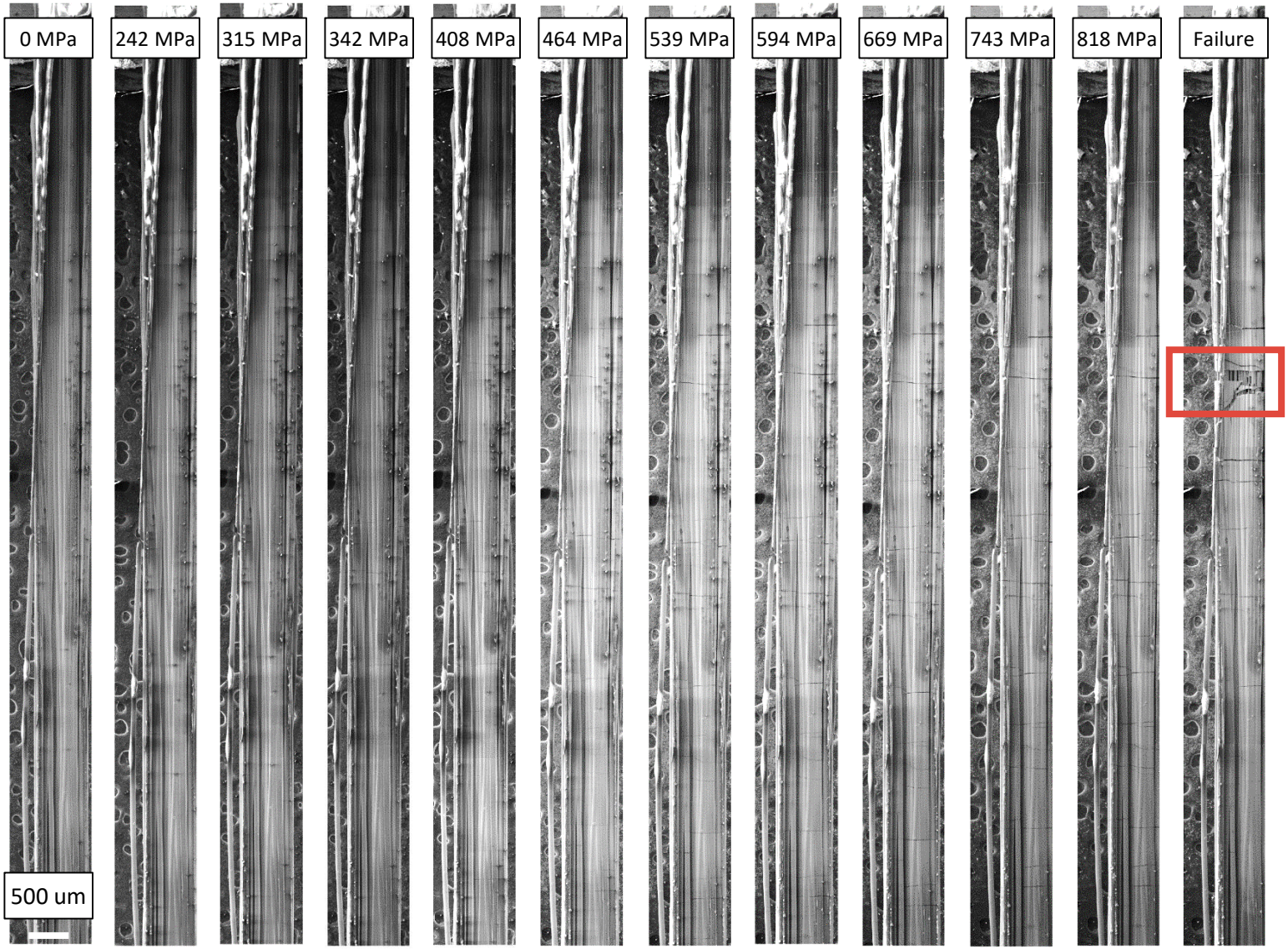
Acoustic Emission (AE)



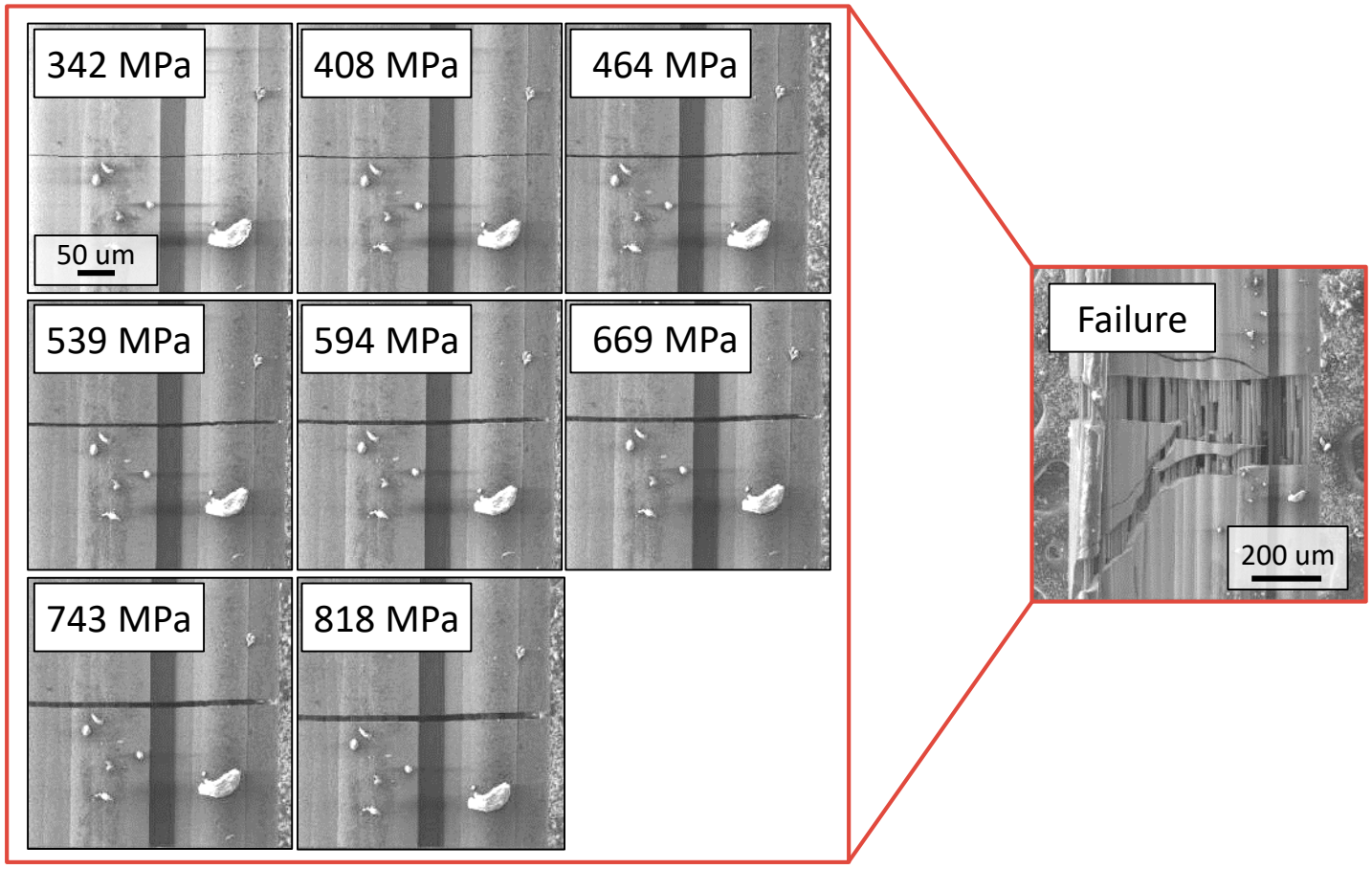
Continuous monitoring of AE events

SEM mapping of surface damage at incremental stresses within gage

Incremental Loading to Capture Damage Progression



Incremental Loading to Capture Damage Progression



Two Domains: Matrix-Dominated and Fiber-Dominated Damage

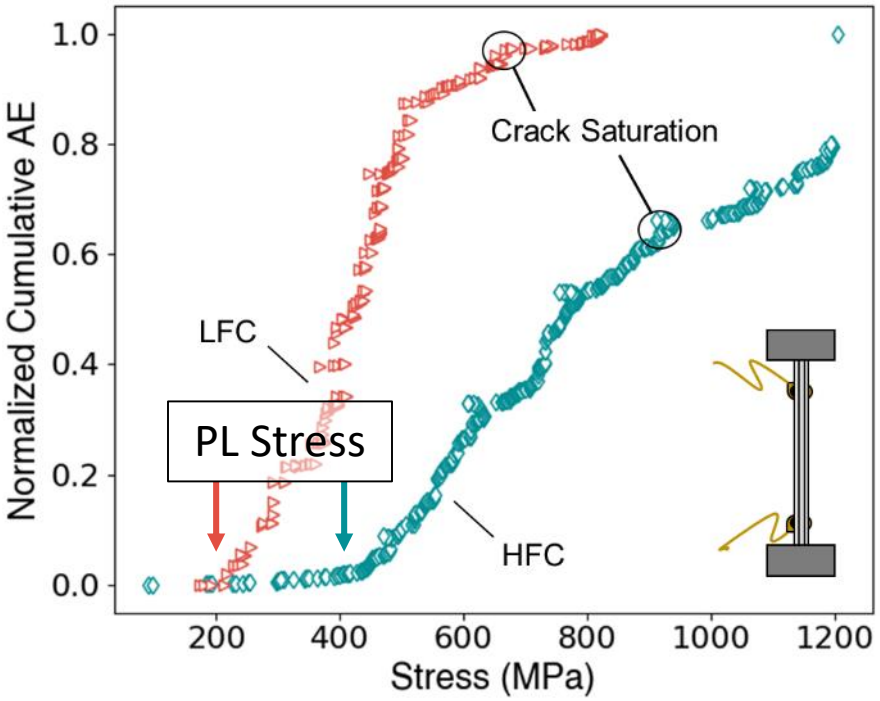
Matrix-Dominated Damage

- Matrix crack initiation
- Matrix crack propagation
- Interfacial debonding
- Fiber sliding
- Early fiber failures

Crack Saturation

Fiber-Dominated Damage

- Fiber loading
- Fiber sliding
- Fiber breakage
- Fiber pullout



Two Domains: Matrix-Dominated and Fiber-Dominated Damage

Dominant Mechanisms

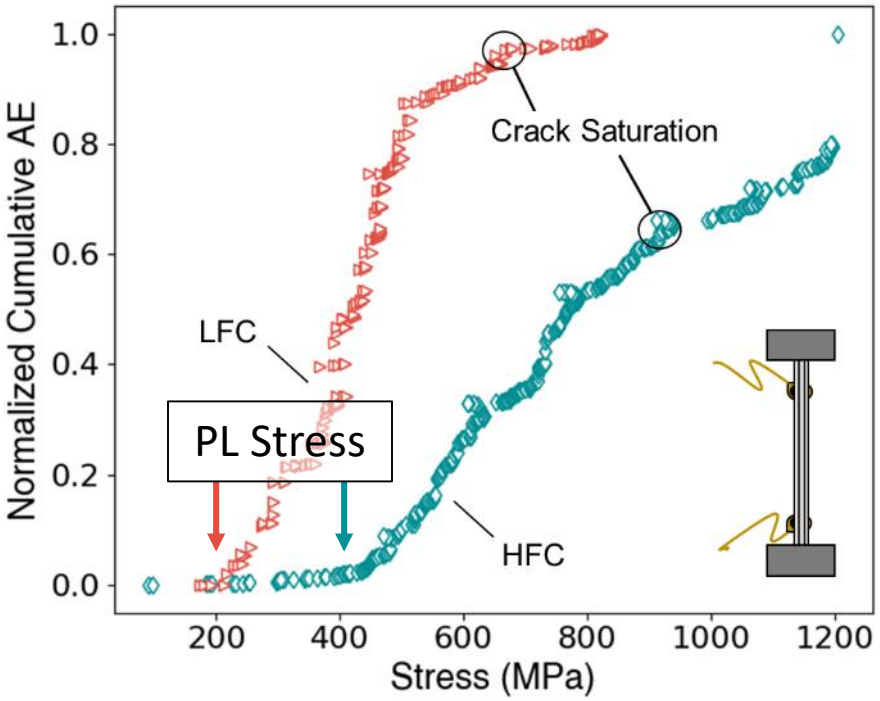
- Matrix crack initiation
- Fiber breakage

High Energy AE

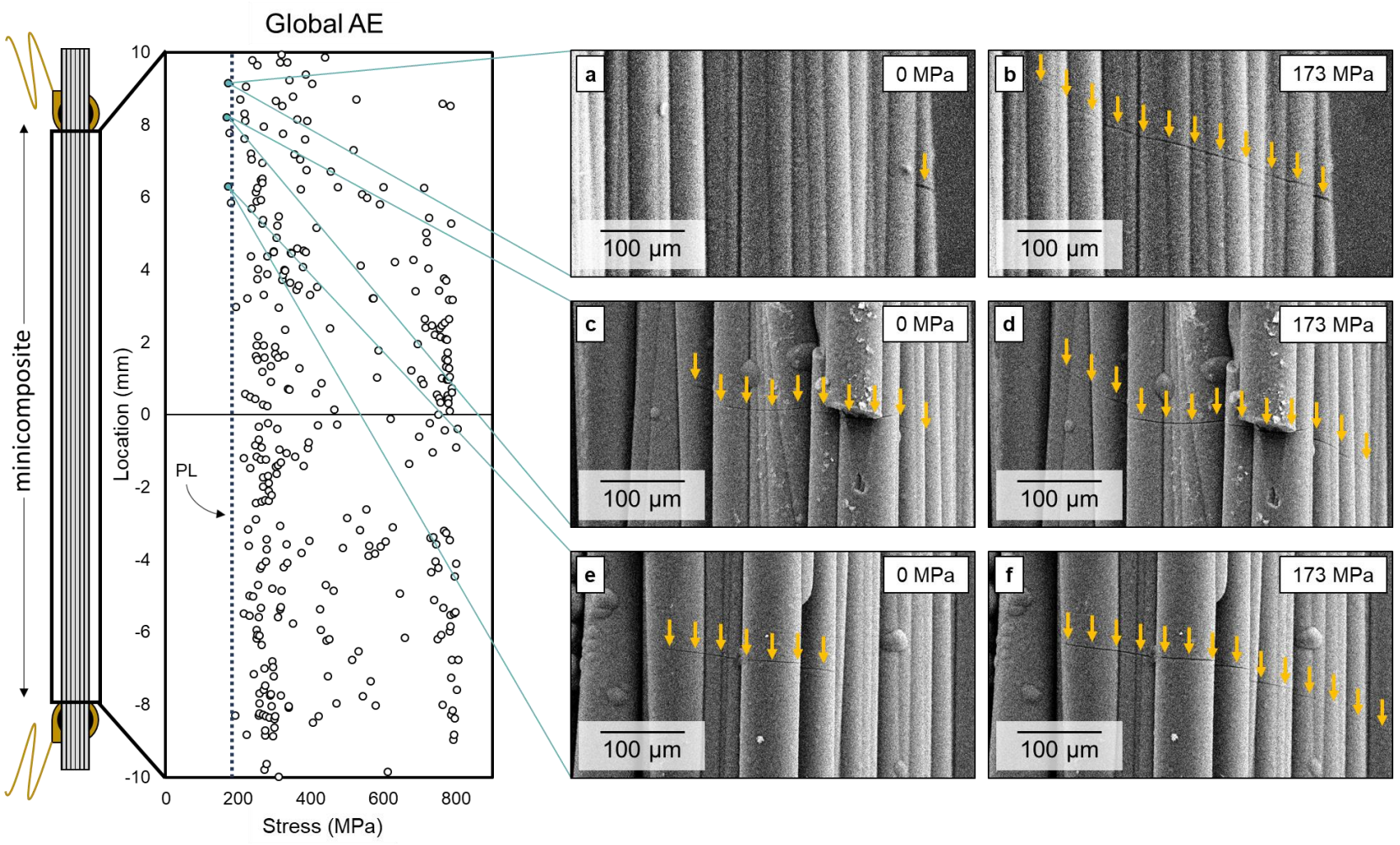
Low Energy AE

Nondominant Mechanisms

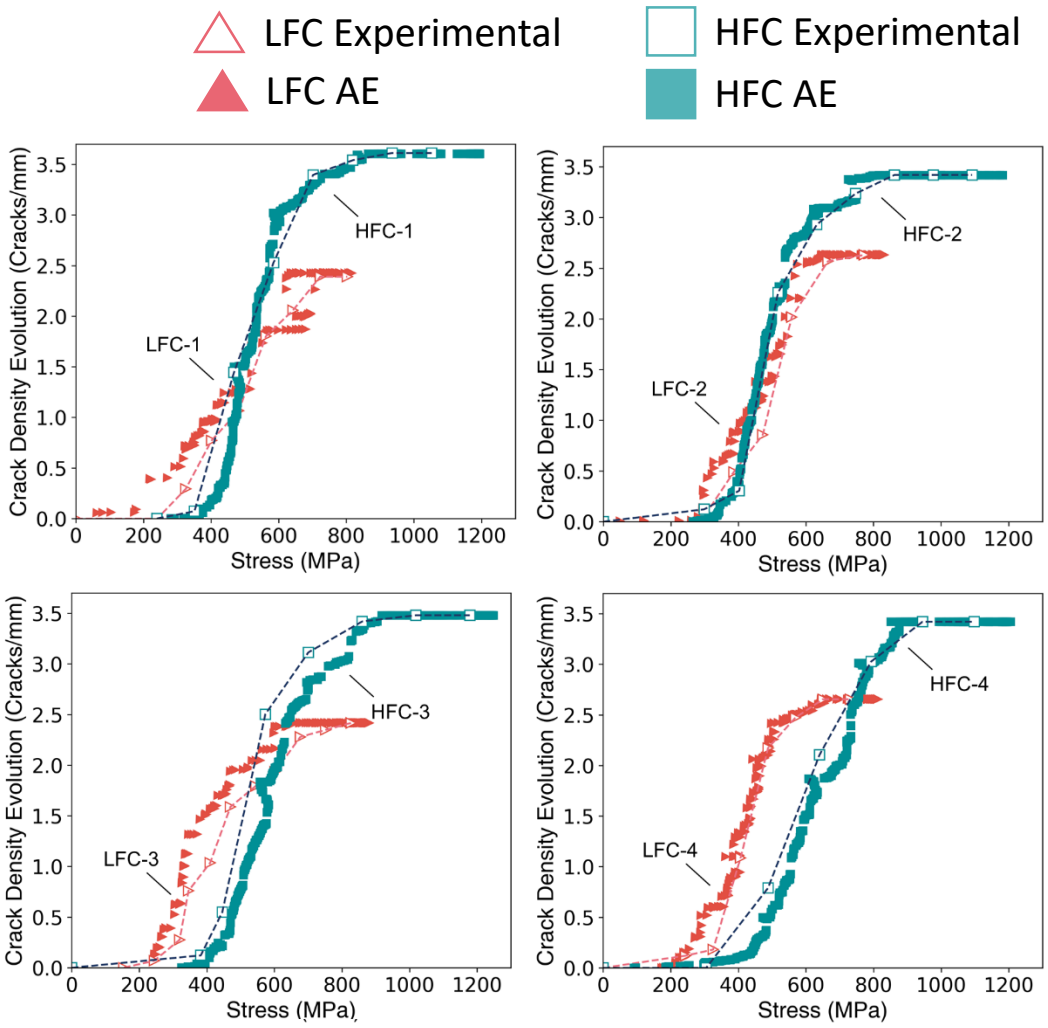
- Matrix crack propagation
- Interfacial debonding
- Fiber sliding
- Fiber pullout



Damage Accumulation below PL due to Propagation of Flaws

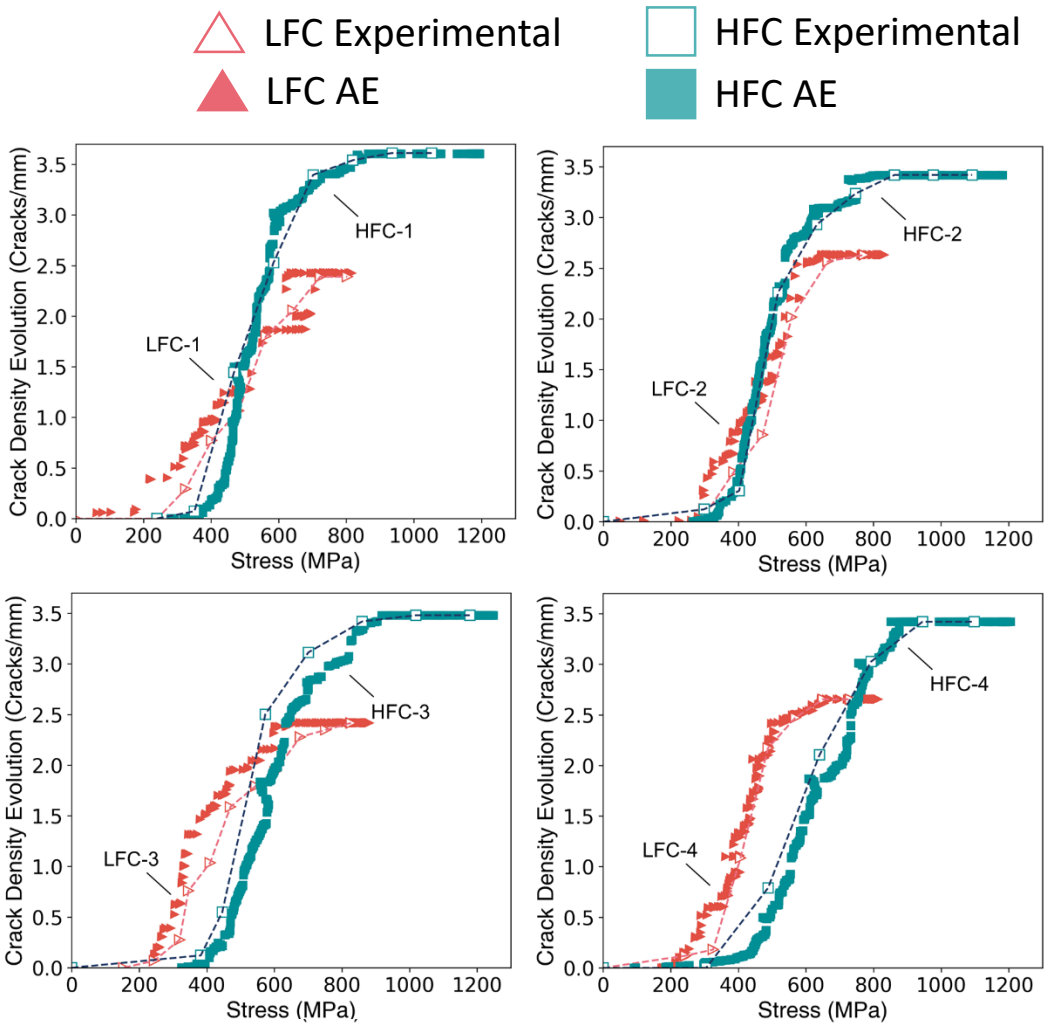


Agreement between In-SEM Measured and AE-Predicted Crack Density Evolution



$$CDE(N) = \mathrm{CD}_{\mathrm{rup.}} \cdot \frac{\text{Cumulative AE (N)}}{\text{Cumulative AE at saturation}}$$

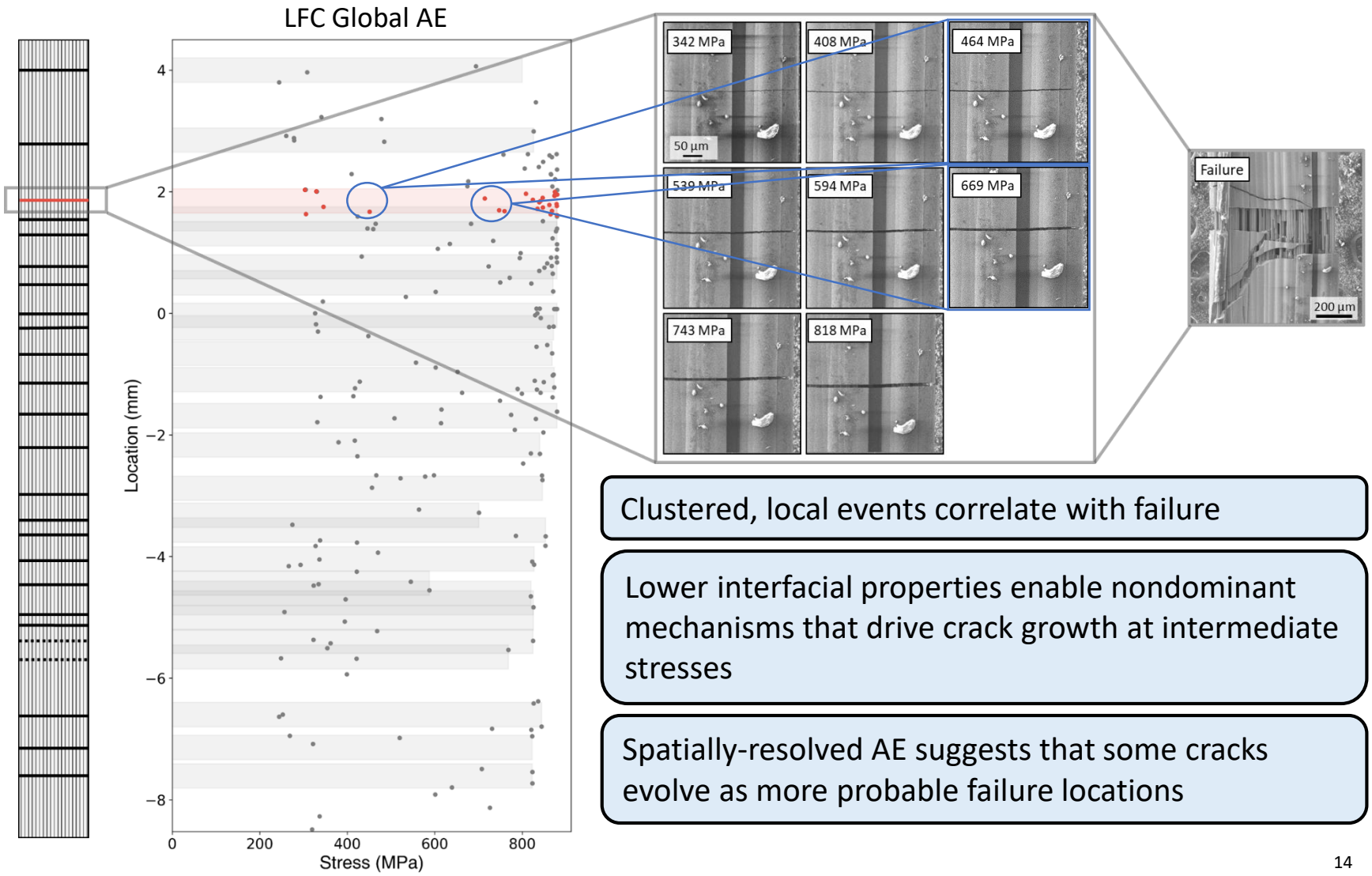
Agreement between In-SEM Measured and AE-Predicted Crack Density Evolution



- Agreement at early and intermediate stresses shows transverse matrix cracking dominance

- Agreement at early stresses shows transverse cracking
- Variations in real and predicted response[s] due to other phenomena detected by AE

Correlation of Spatially-Resolved AE and In-SEM Observed Damage

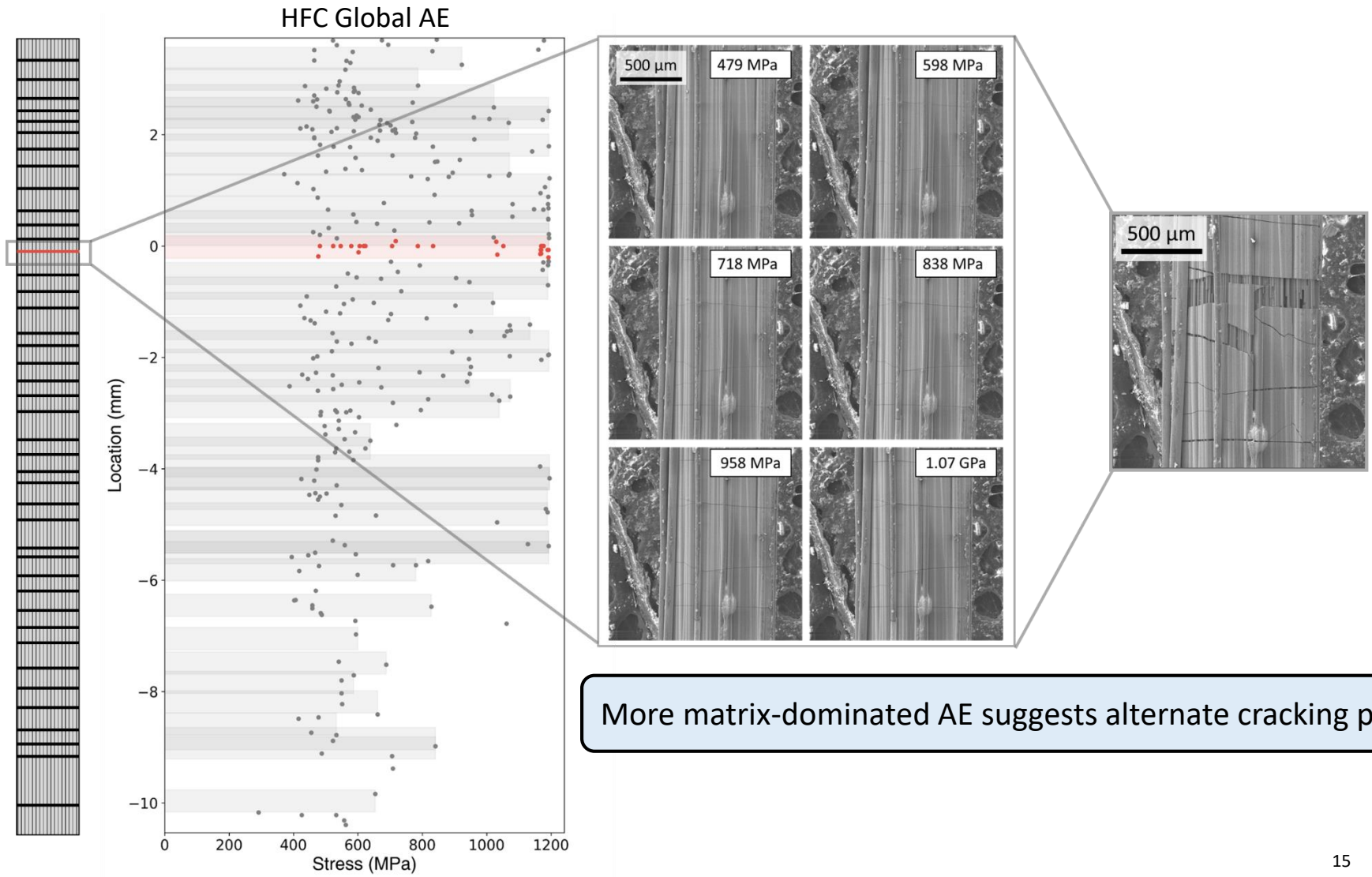


Clustered, local events correlate with failure

Lower interfacial properties enable nondominant mechanisms that drive crack growth at intermediate stresses

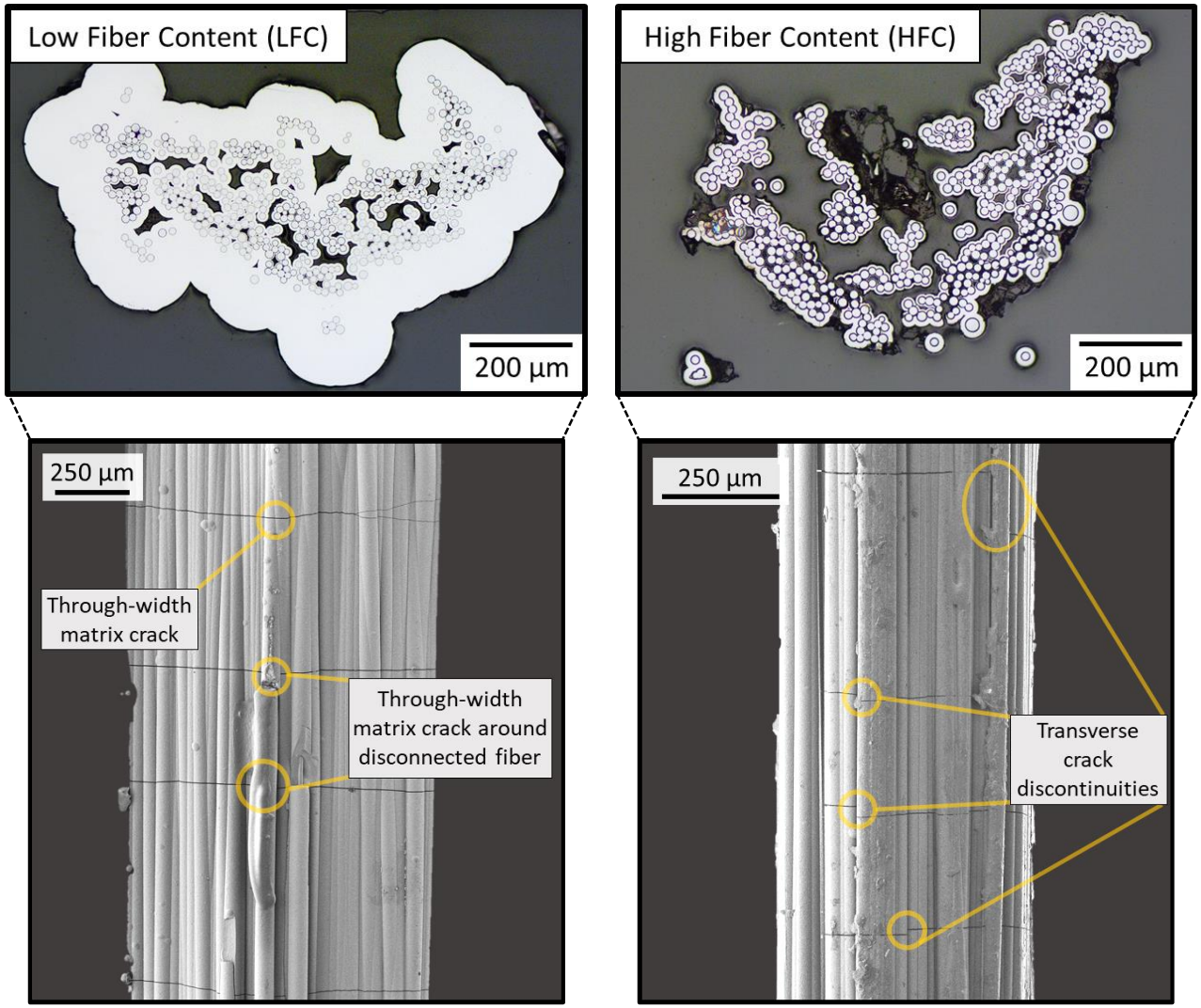
Spatially-resolved AE suggests that some cracks evolve as more probable failure locations

Correlation of Spatially-Resolved AE and In-SEM Observed Damage



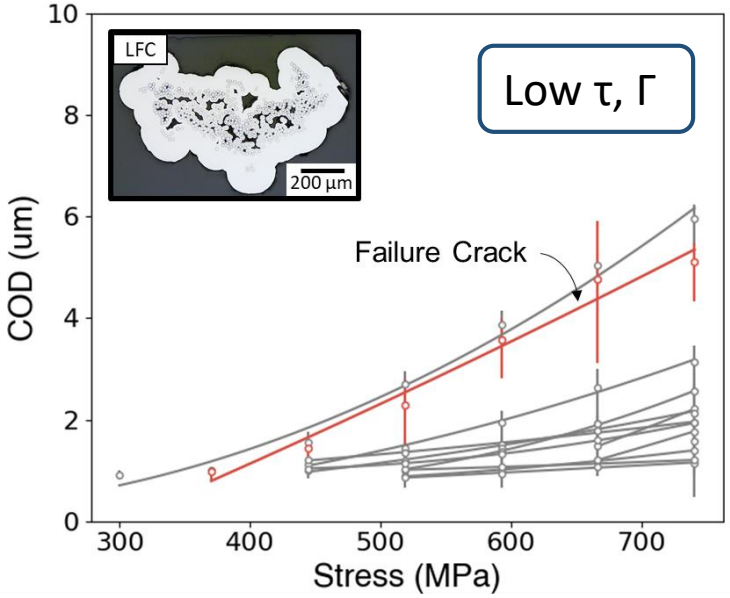
More matrix-dominated AE suggests alternate cracking path

Incremental vs. Through-Thickness Crack Propagation

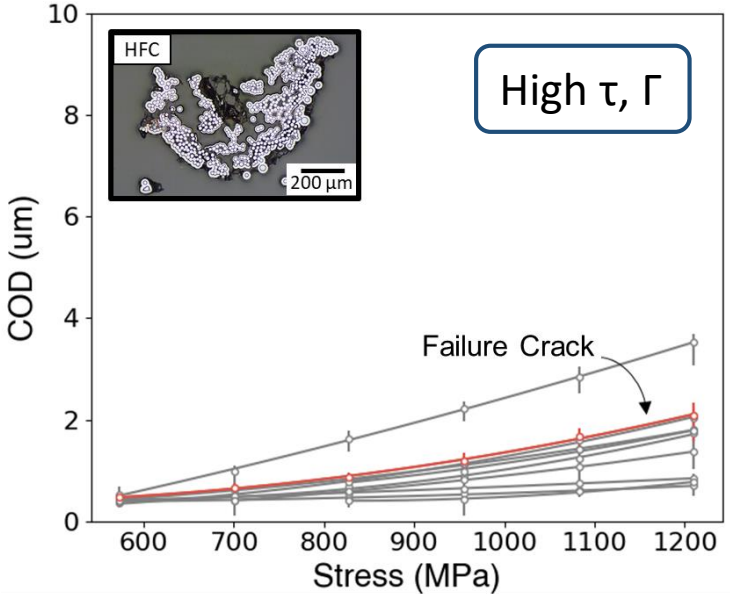


Local Microstructural Effects Influence Crack Opening Displacement (COD)

- Earliest crack openings: 600 nm
- Fiber sliding w/ larger debond lengths to accommodate opening
- Saturation of non-dominant phenomena prior to fiber breaks
- Fiber breaks redistribute load to tow

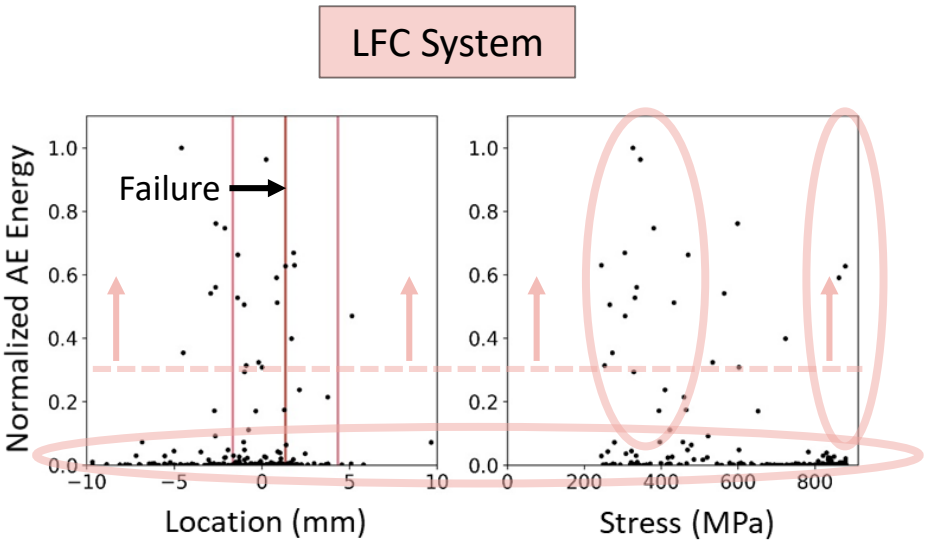


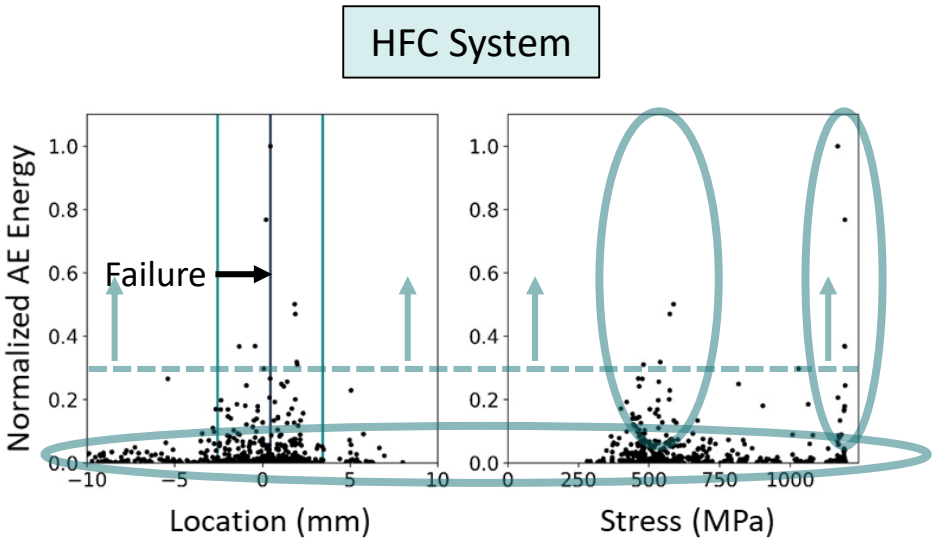
- Earliest crack openings: 300 nm
- High fiber content for initial crack bridging
- Fiber breaks redistribute load to pillar
- Fiber reloading through sliding



AE Event Energy May Correlate with Source Damage Mechanism

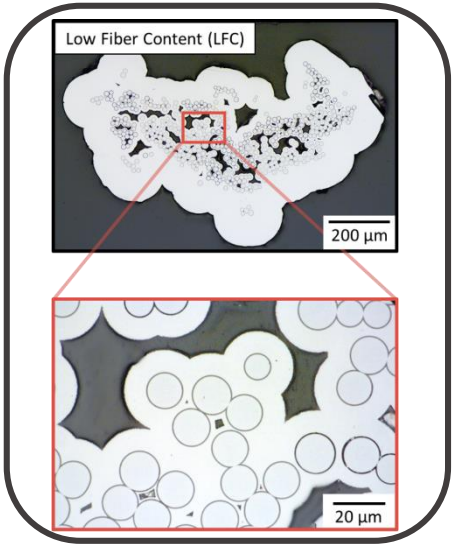
Correlation between high-energy AE and proximity to failure location

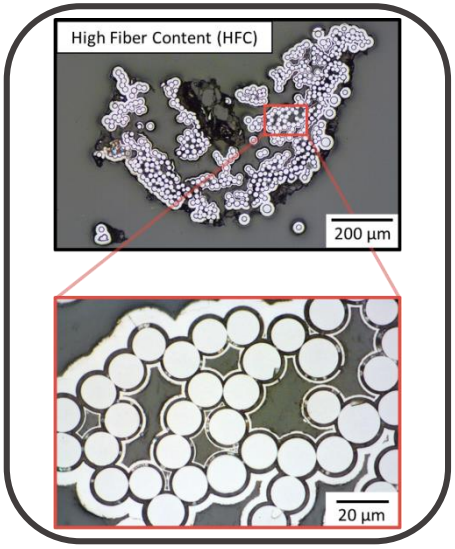




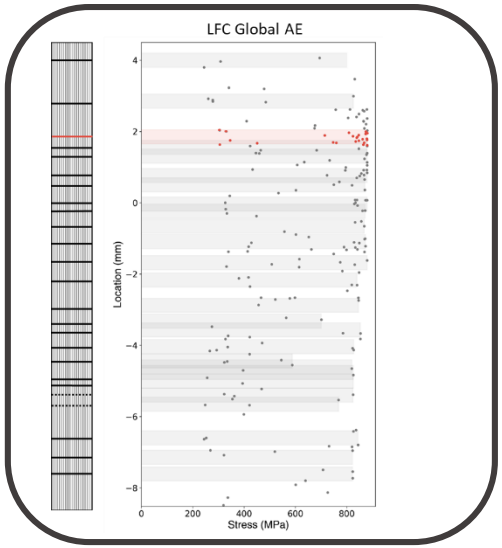
- High-energy AE activity from dominant damage mechanisms (matrix cracking / fiber breakage)
- Ultra-high-energy AE activity from large crack formation
- Low-energy AE activity from nondominant damage mechanisms

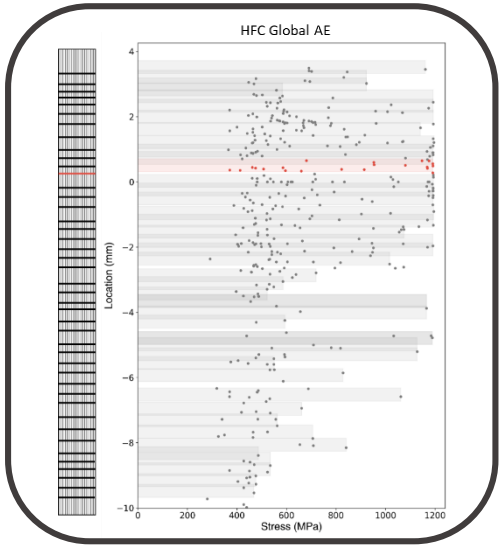
Damage characterization in two minicomposite systems



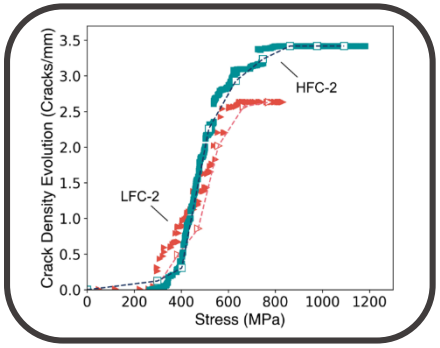


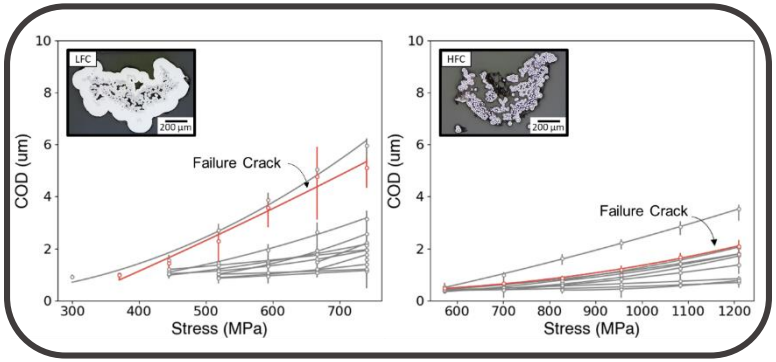
Correlation of spatially-resolved AE to microscale surface damage

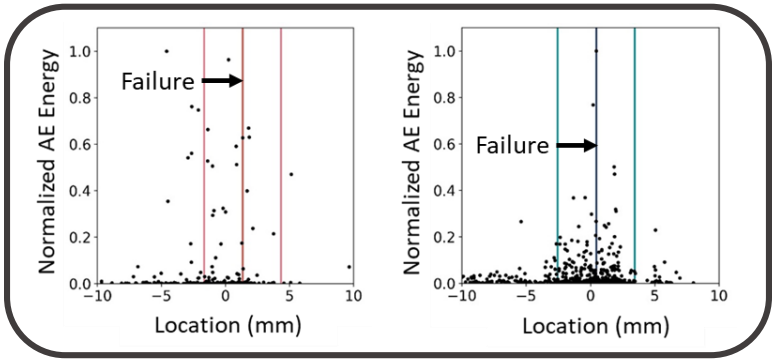




Structural features and local phenomena drive damage response







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