Multiscale Modeling of Composite Materials with the Generalized Finite Element Method

Student: Bryce Mazurowski

Student Email: brycepm2@Illinois.edu

Faculty: Prof. C. Armando Duarte

Faculty Email: caduarte@Illinois.edu

AFRL Sponsor: Dr. Patrick O'Hara

AFRL Directorate: AFRL/RQHF

PA #: AFRL-2023-5125

Motivation

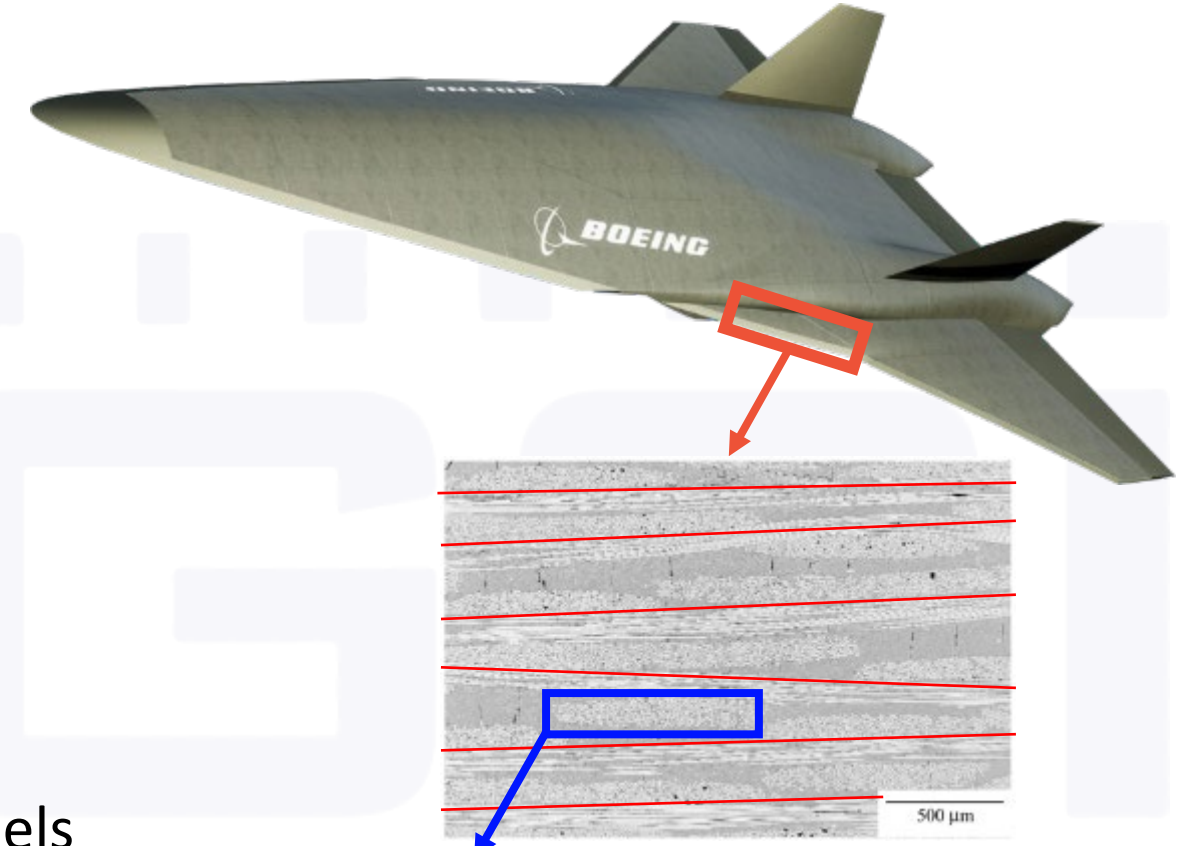
Solve problems where separation of length scales does not hold

- Extreme environment structures
- Local structural features
- Sharp-gradient loading
- Material damage
- Ceramic Matrix Composite (CMC) body

Goal: Incorporate heterogeneity into global structure behavior efficiently

Strategy: Adopt homogenized material models everywhere except at localized hot-spots

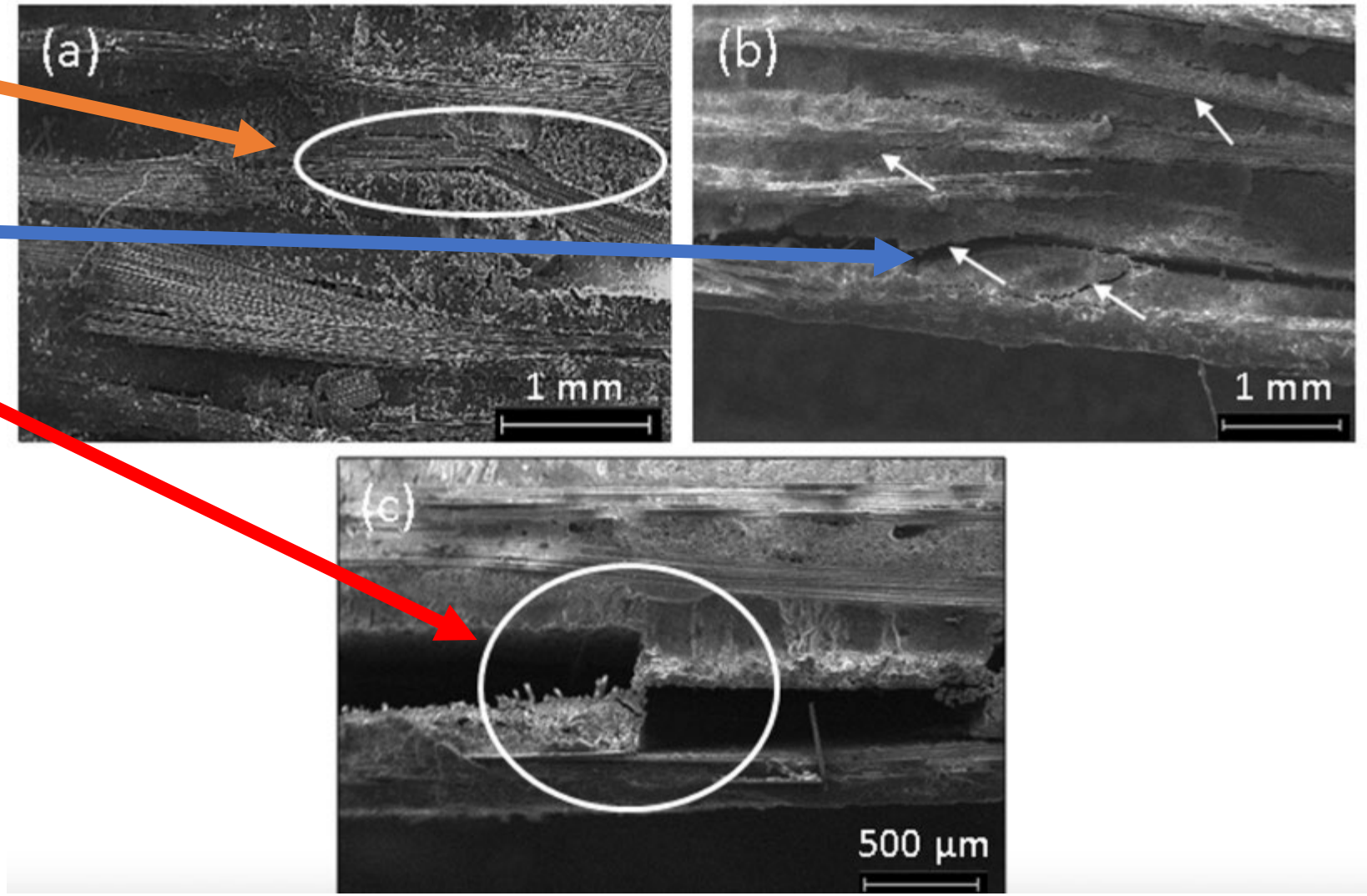
Valkyrie – Boeing hypersonic concept vehicle



Keller et al. Handbook of Ceramic Composites. 10.1007/0-387-23986-3_16

Oxide-Oxide CMC Failure

- Fiber buckling
- Fiber pullout
- Matrix cracking
- Delamination

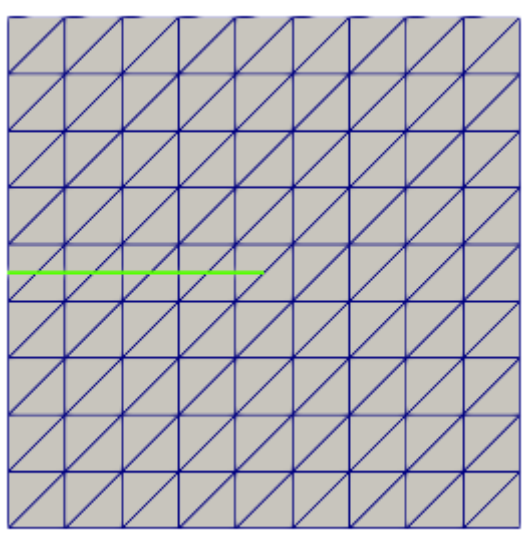


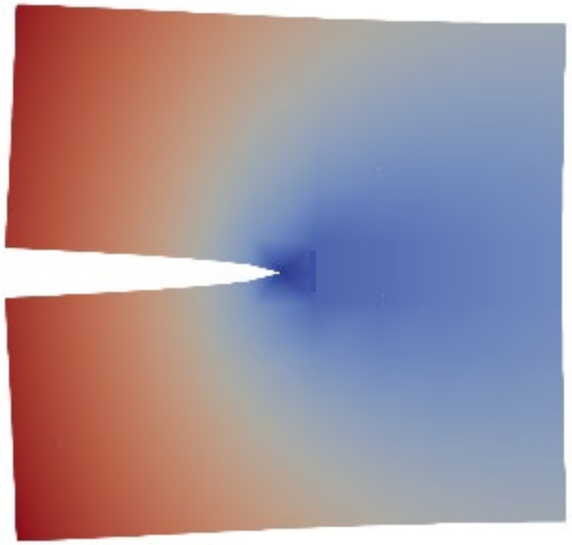
Broutelle et al. Composite Structures, 10.1016/j.compstruct.2020.111902

Generalized FEM

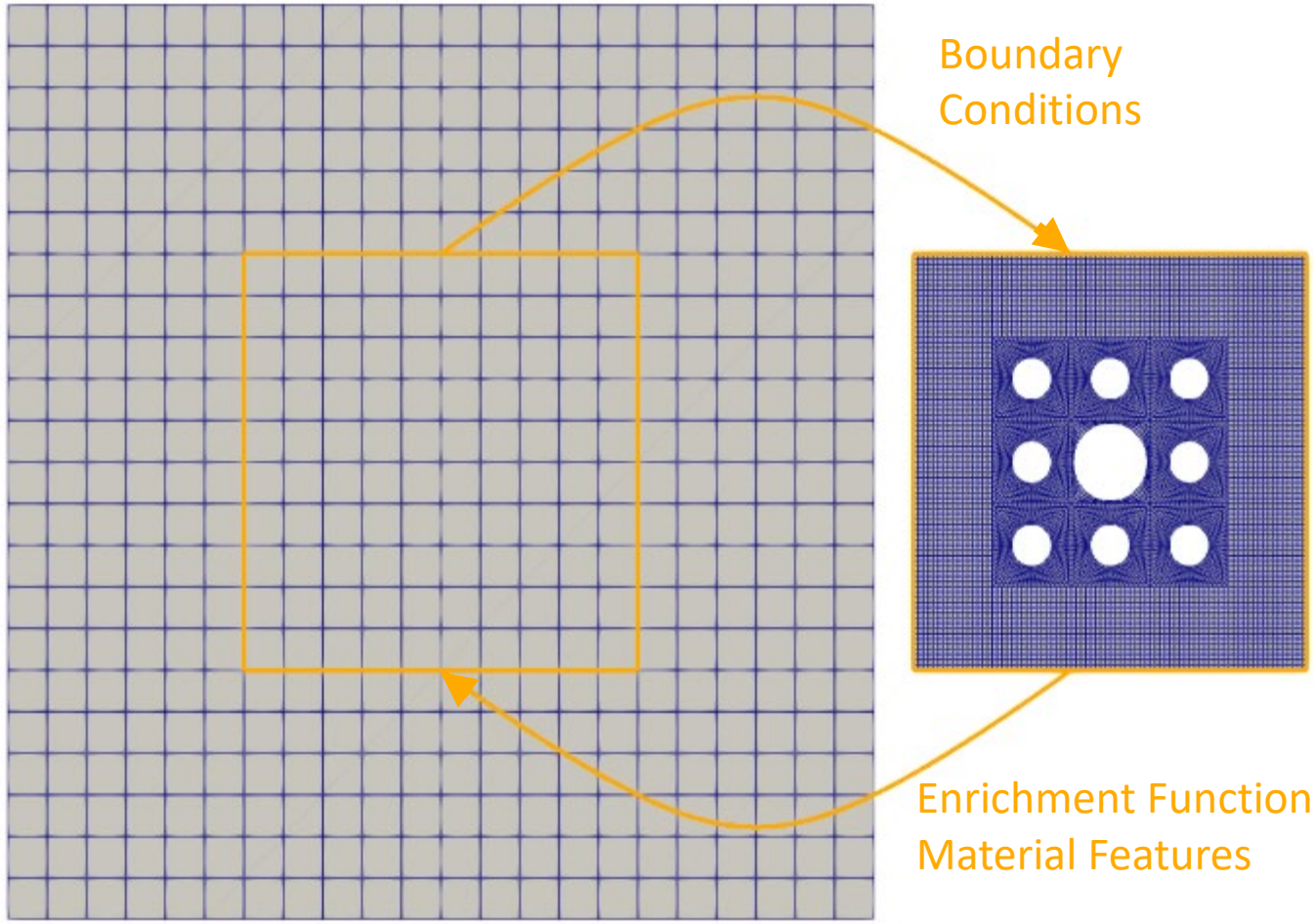
$$u(x) = \underbrace{N_\alpha(x)a_\alpha}_{\text{FEM}} + N_\alpha E_{\alpha i}(x)\hat{a}_{\alpha i}$$

- Augment standard FEM space with *enrichment functions*
- Introduce solution features directly to approximation space
- Remove meshing restrictions
- GFEM Applications
  - Fracture Mechanics
  - Material discontinuities
  - Contact
  - Porous media





Proposed GFEM^{gl}



Global:

- Coarse solid mesh
- Homogenized material

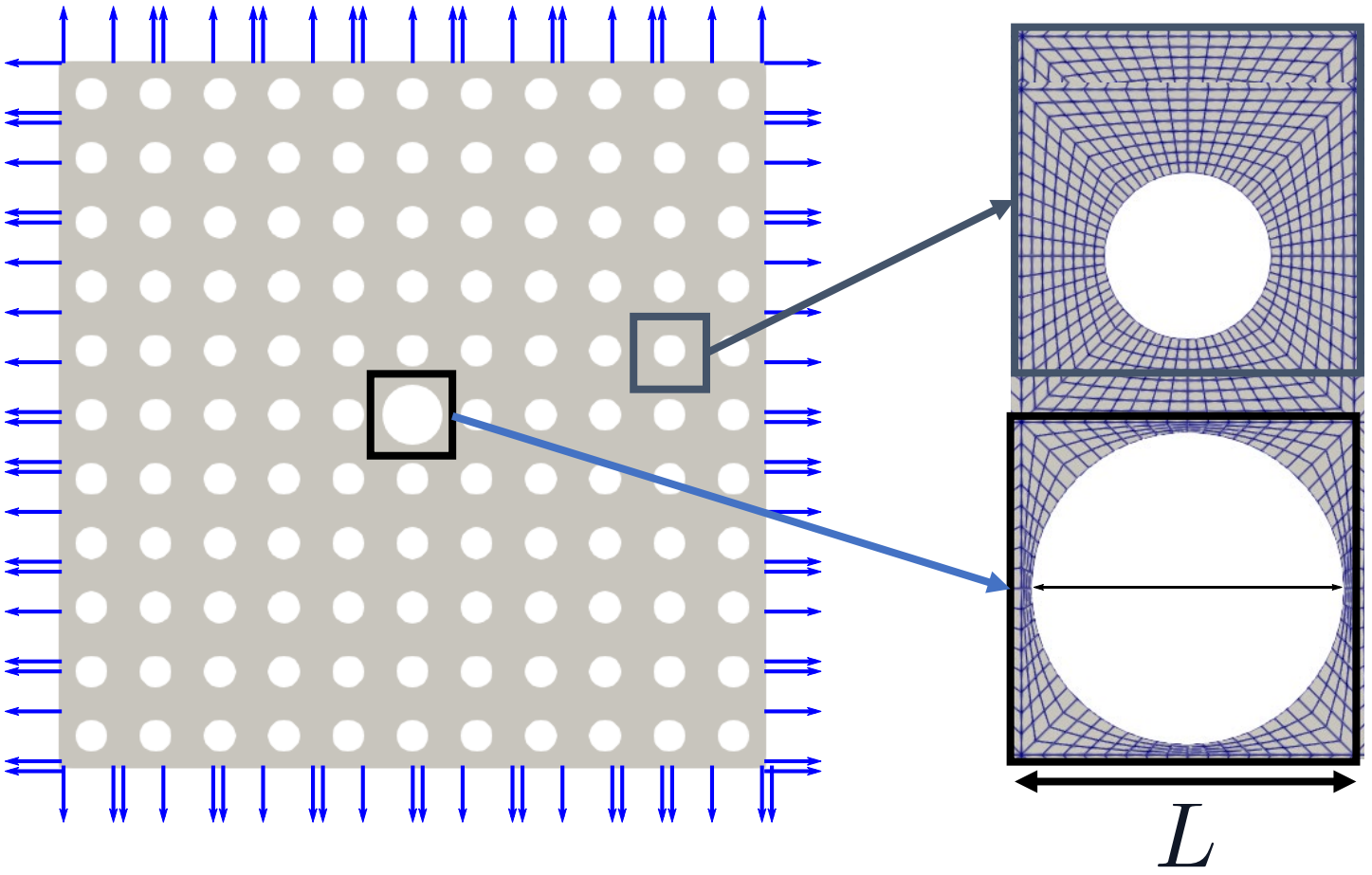
Local:

- Fine solid mesh
- Heterogeneous material
- Microstructure-informed damage models

GFEM^{gl} establishes two-way communication between the global and local scale

Material heterogeneity and nonlinearity incorporated only at localized hot spots

Perforated plate with Localized Plasticity

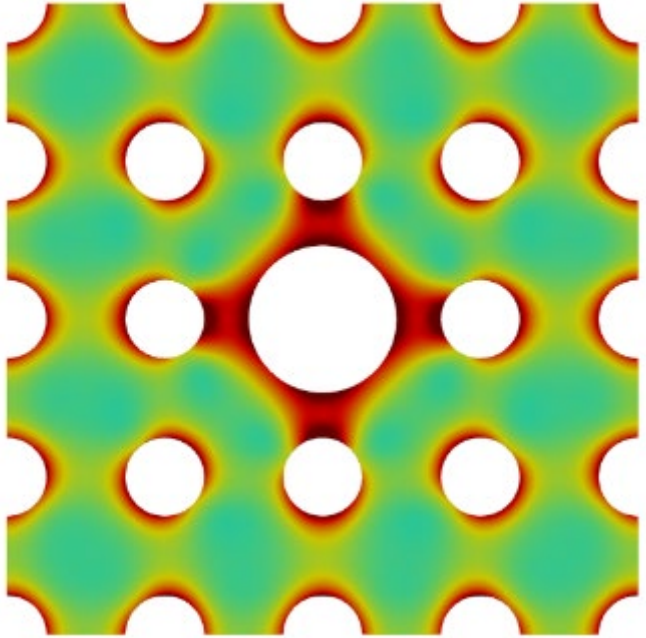


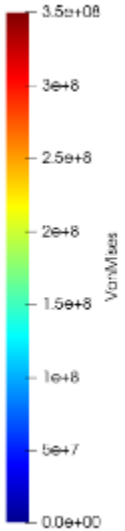
$$\sigma_y = 350 \text{ MPa}$$
$$K = 210 \text{ MPa}$$

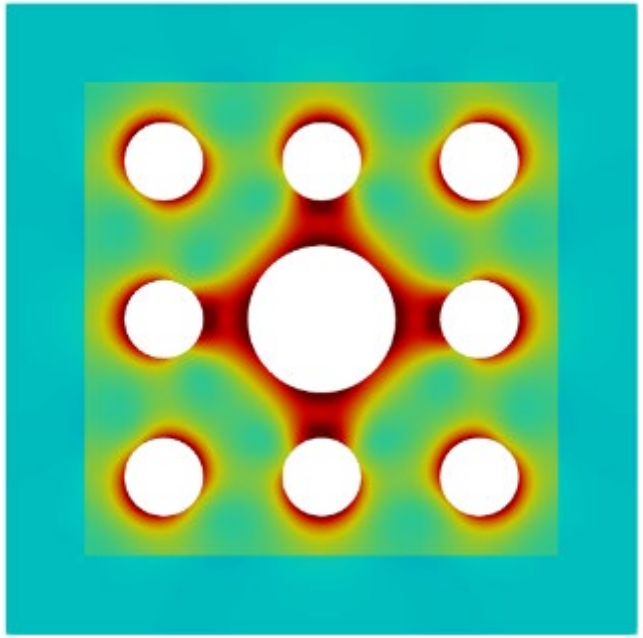
Plasticity with linear isotropic hardening

	E_1 (GPa)	E_2 (GPa)	ν_1	ν_2	G_1 (GPa)	G_2 (GPa)
Steel	210	-	0.3	-	80.8	-
Homogenized	132.3	168.8	0.251	0.235	40.9	54.2

Von Mises Stress



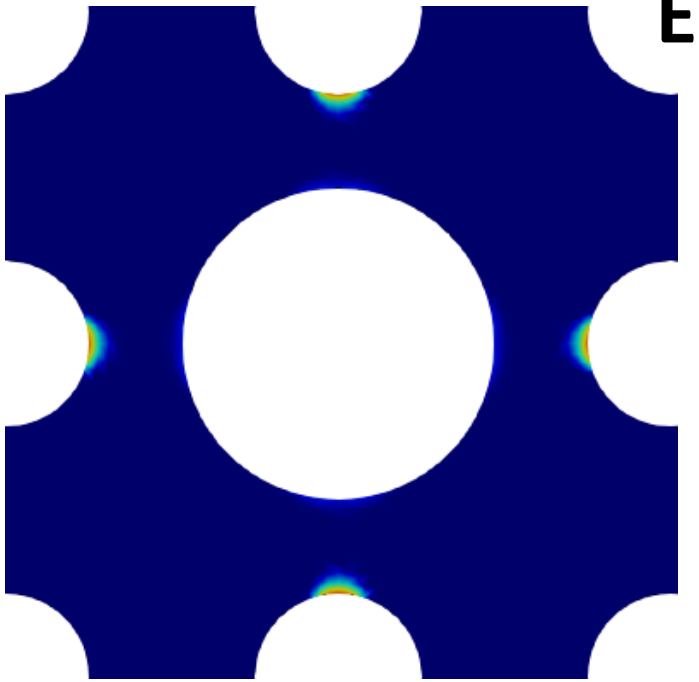


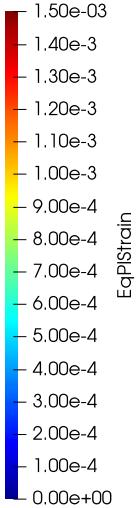


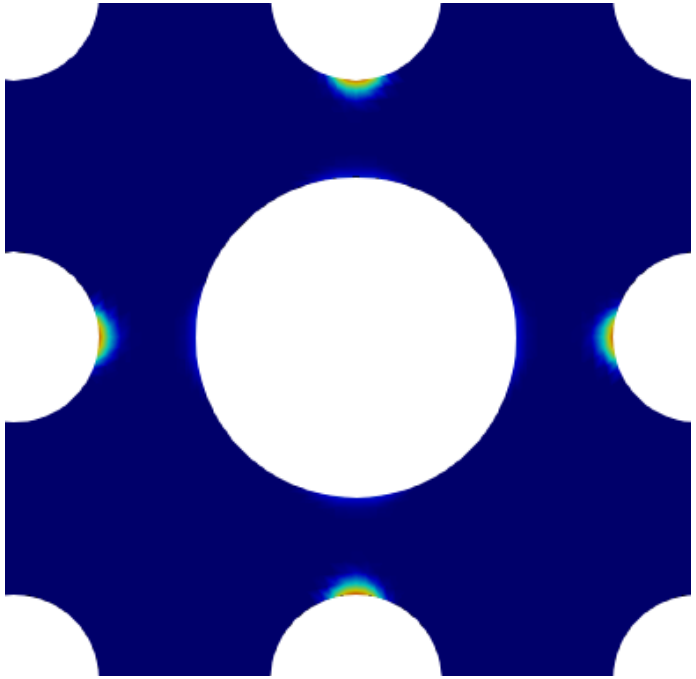
Reference

GFEM^{gl}

Equivalent Plastic Strain

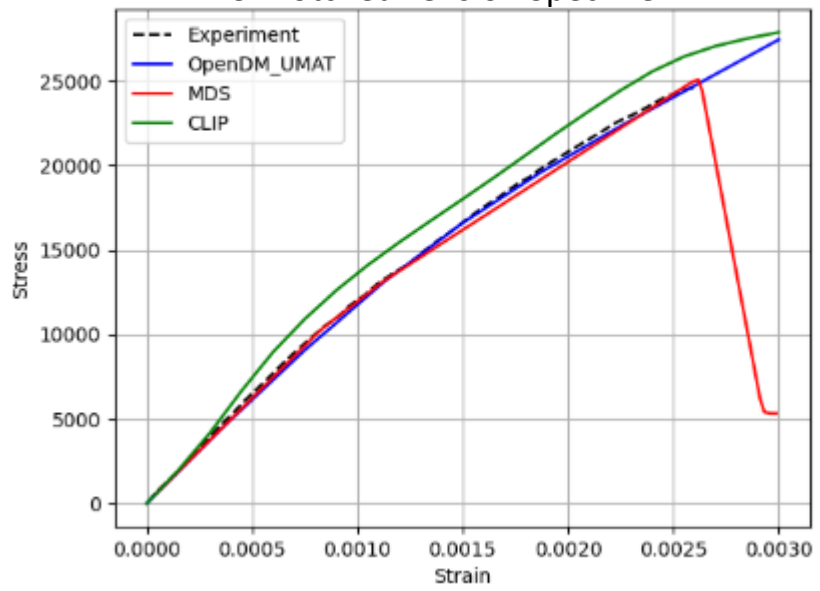




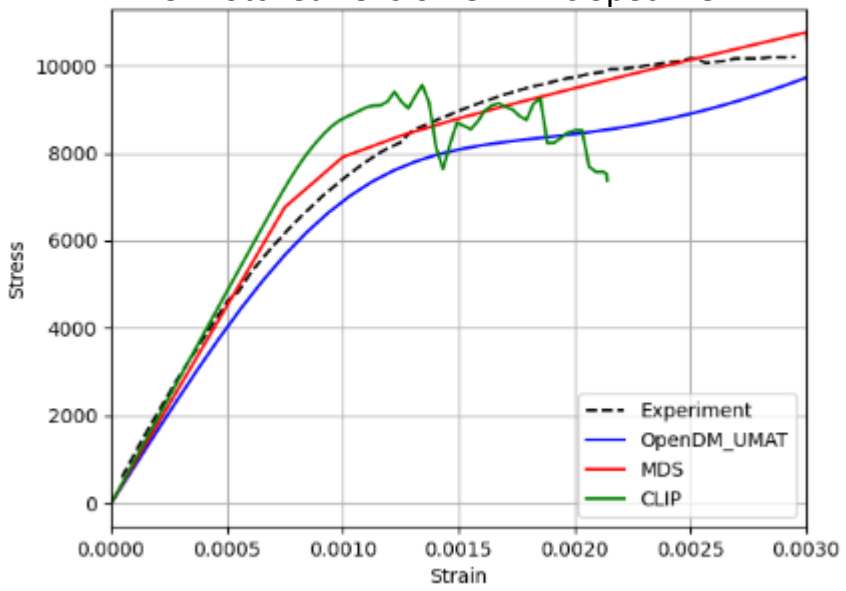


Calibration of Damage Models

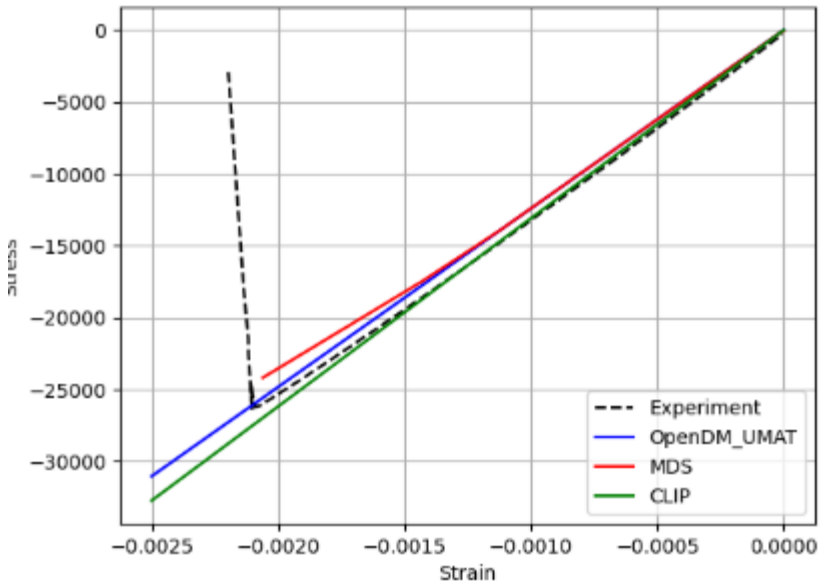
Unnotched Tension Specimen



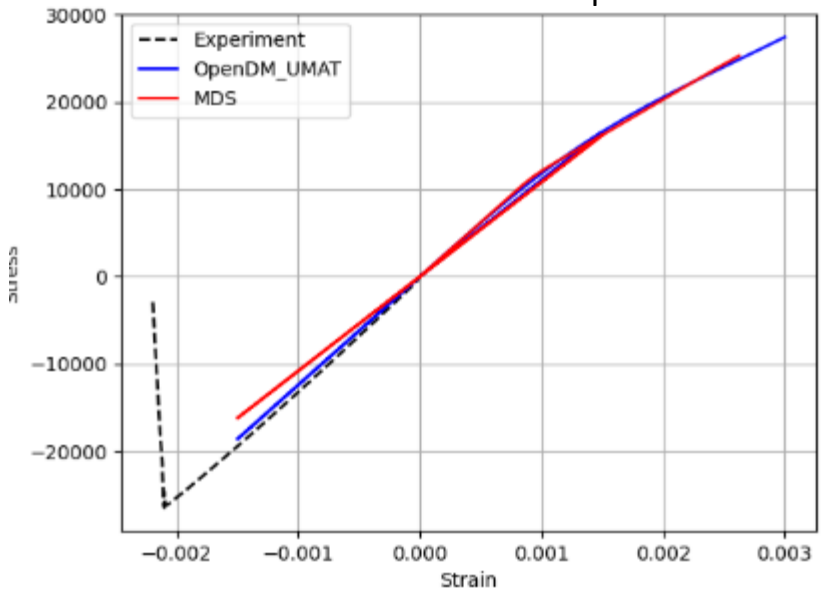
Unnotched Tension Off-Axis Specimen



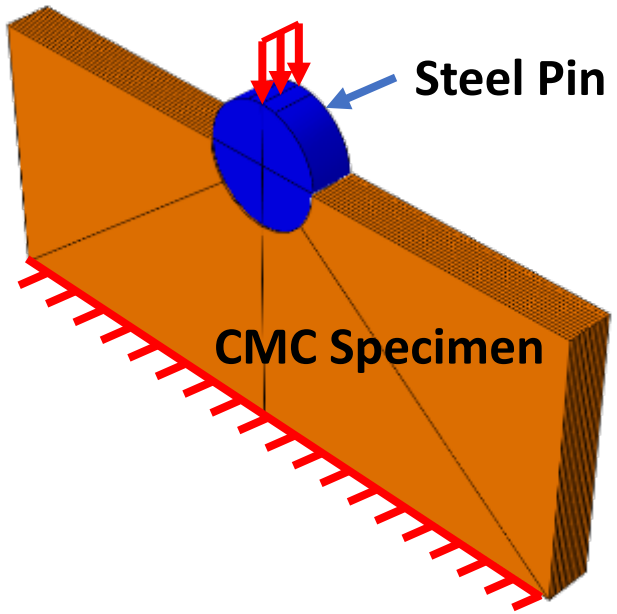
Unnotched Compression Specimen



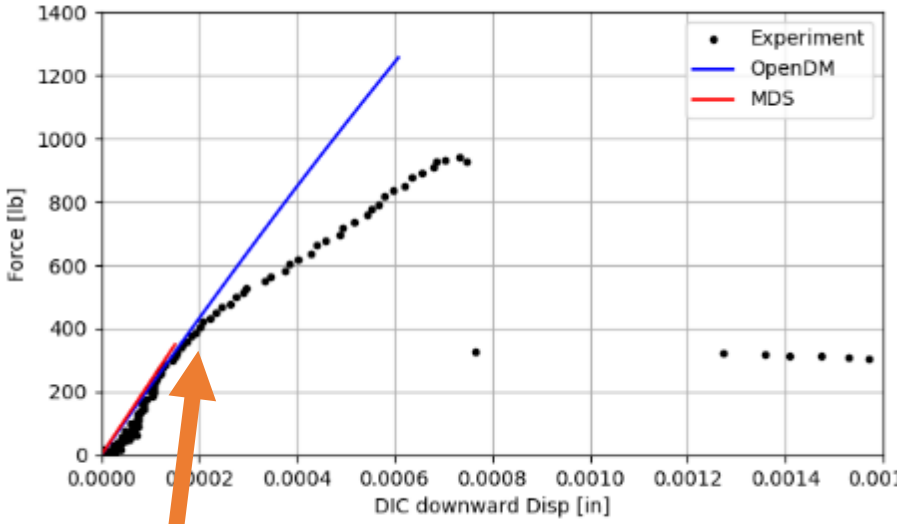
Unnotched Load-Unload Specimen



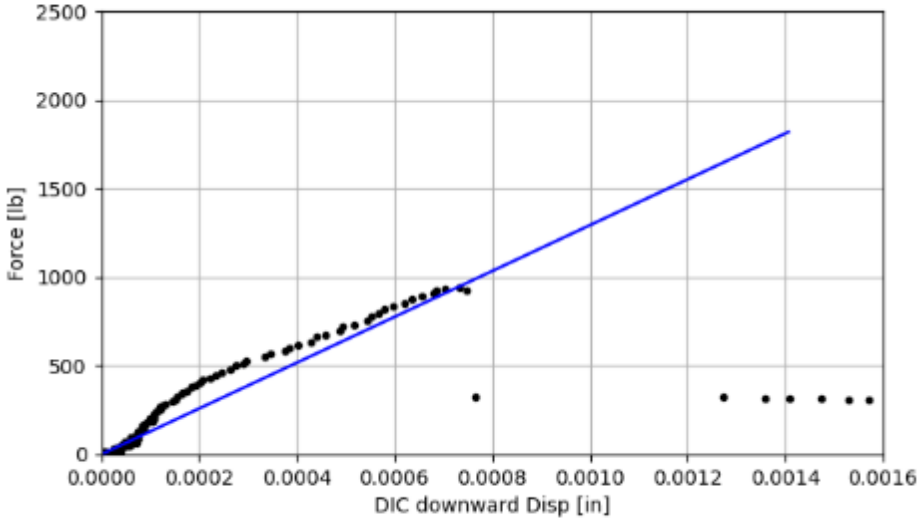
Validation Experiments



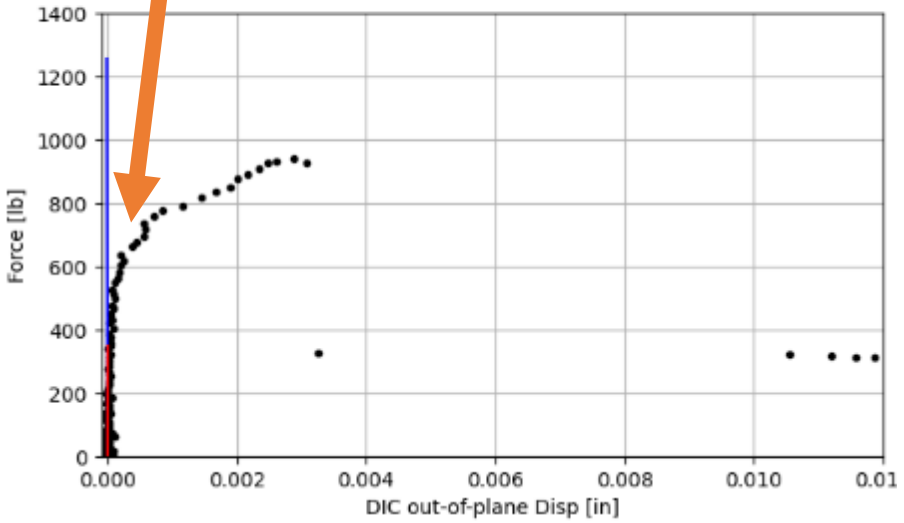
Delamination

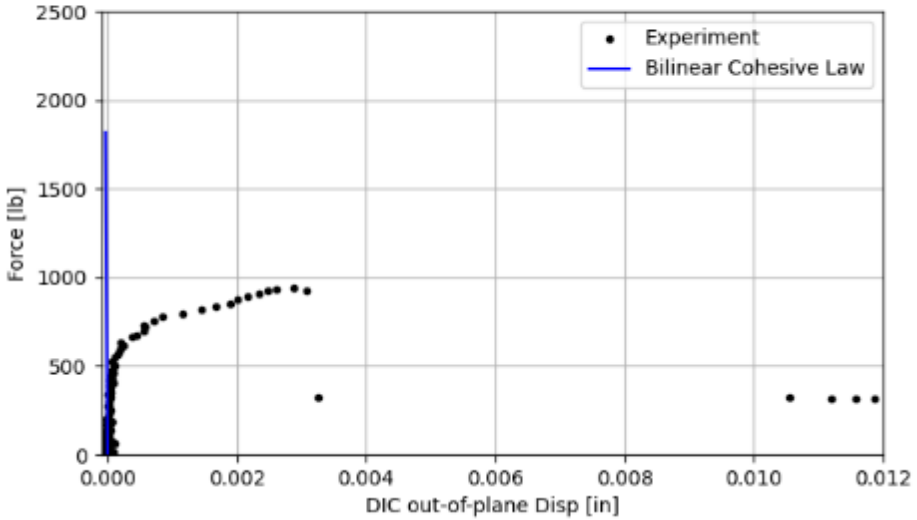


Damage models only



Cohesive delamination only





Conclusions

- GFEM^{gl} can recover localized nonlinear material when majority of global domain uses homogenized linear elastic material
- Damage models can capture coupon-level behavior of CMCs

Future Work

- Verification and validation of CMC damage models
- Add microstructure-informed damage models into GFEM^{gl}
- Use GFEM^{gl} in an IGL-GFEM^{gl} scheme to capture realistic structures
- Test on other composite materials