COMPARISON OF MICROMECHANICS THEORIES FOR MODELING CHOPPED CARBON FIBER POLYMER MATRIX COMPOSITES

Evan J. Pineda[1*], Ibrahim Kaleel[2], Brett A. Bednarcyk[1] and Sandi G. Miller[3]

[1] Multiscale and Multiphysics Modeling Branch, NASA Glenn Research Center, Cleveland, U.S.A.,
[2] NASA Postdoctoral Program, Oak Ridge Associated Universities, Cleveland, U.S.A.,
[3] Ceramic and Polymer Composites Branch, NASA Glenn Research Center, Cleveland, U.S.A.

*Corresponding author (evan.j.pineda@nasa.gov)

Presented at the International Conference on Composite Materials 2023
Multiscale Modelling – Session 2
Belfast, United Kingdom
30 July – 4 August, 2023

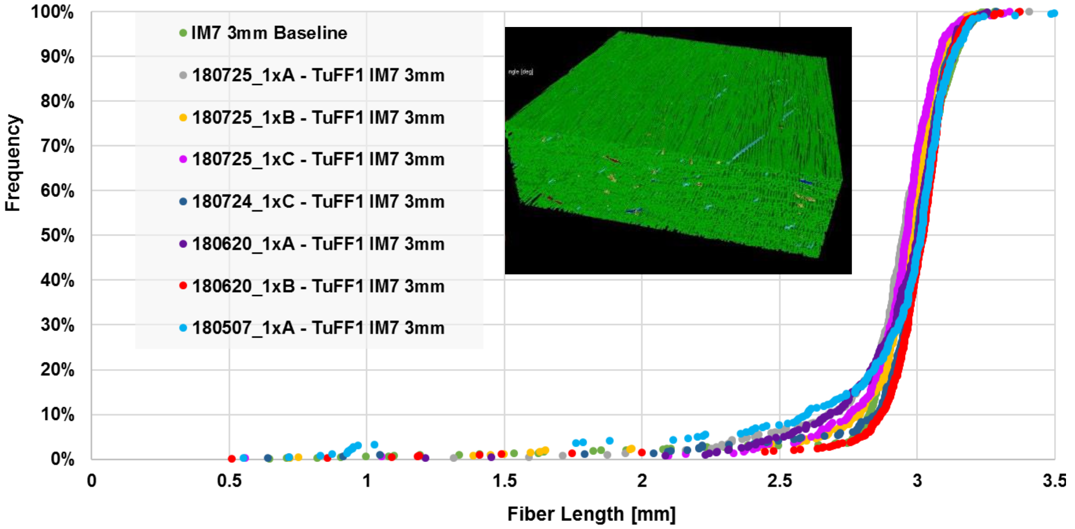
Outline

- Overview of Tailored Universal Feedstock for Forming (TuFF)
- Objective
- Micromechanics
  - High fidelity generalized method of cells (HFGMC)
  - Carrera Unified Formulation (CUF)
- Simple single fiber Repeating Unit Cell (RUC) model
- Results
- Conclusion/Future Work

Tailored Universal Feedstock for Forming (TuFF)

Yarlagadda, et al. (2019), SAMPE, Charlotte, NC;

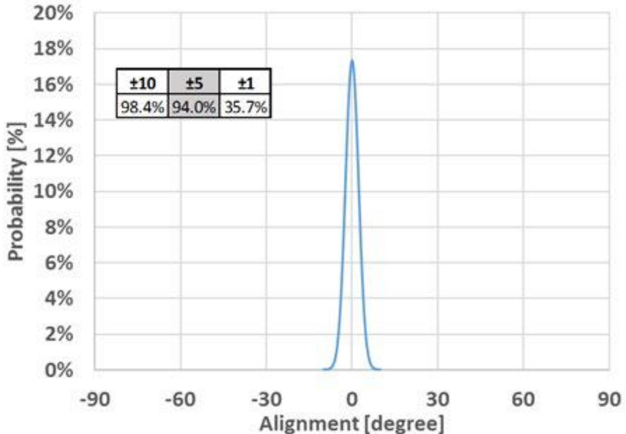
Discrete Long Fibers (Len./Dia ≥ 600



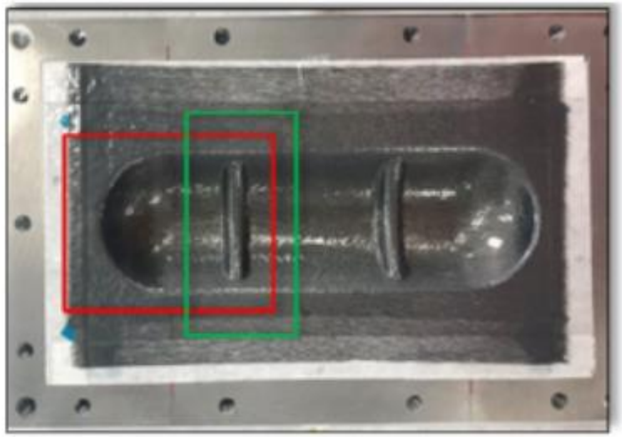
In-plane properties similar to continuous fiber composites

Sample	Fiber	Length (mm)	Resin	E_{11} (GPa)	CV (%)	X_T (MPa)	CV (%)	ε_{11}	FVF
IM7/8552	IM7	Cont	8552	162	2.27	2558	4.1	1.58%	57.30%
180507_1xA_6:1	IM7	3	PEI	143	1.61	2255	2.01	1.51%	52%
180620_1xA_8:1	IM7	3	PEI	168	1.46	2503	3.19	1.42%	61%
180620_1xB_9:1	IM7	3	PEI	173	1.71	2668	2.96	1.49%	63%
180724_1xC_7:1	IM7	3	PEI	161	1.36	2579	3.67	1.51%	58%
180724_1xB_8:1	IM7	3	PEI	168	1.78	2551	5.86	1.48%	61%
Commercial (Cytec)	AS4	Cont	PEI	134	1.3	2406	4.8	1.64%	55.5%
Cytec AS4/PEI 2-ply	AS4	Cont	PEI	137	5.46	2289	7.82	1.54%	55.5%

Highly Aligned



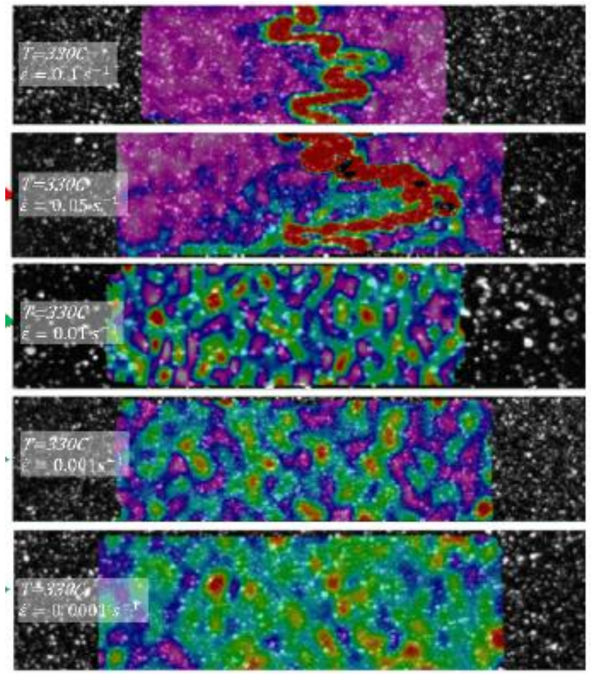
Formability

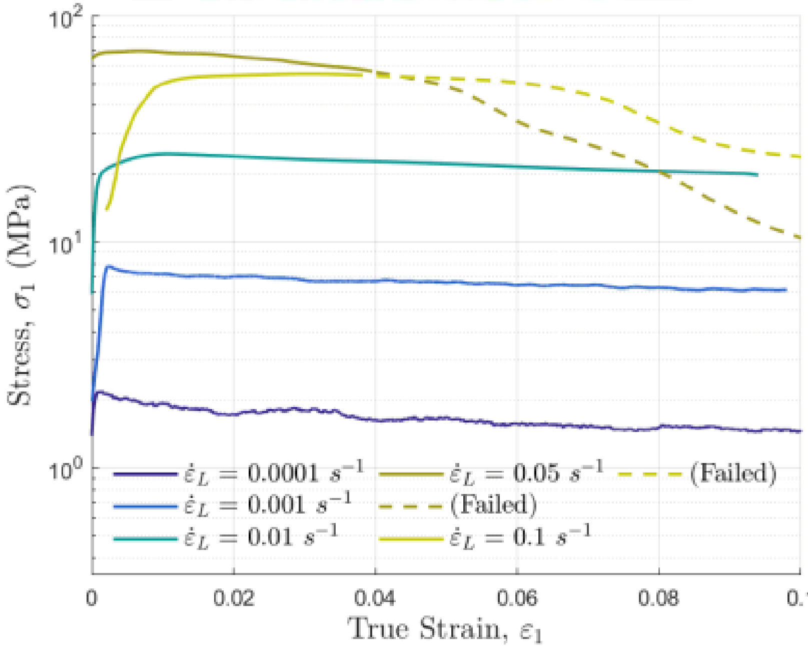


- Enabling Technology!
  - Rapid and advanced manufacturing
    - Stretch forming, stamping, tow steering, AFP
  - Complex parts
  - Recyclability (thermoplastic matrix)

Why Model TuFF?

- Composite behavior highly dependent on microstructure
- Virtual manufacturing, testing and progressive damage and failure analysis (PDFA)
  - Rapid product development
  - Improved material design
  - Improved material performance
- Micromechanics and multiscale modeling is a useful tool
  - Can relate microstructure to properties
  - Can understand the local physics that drive the global phenomena





Cender, et al. (2022). SAMPE 2022, Charlotte, NC

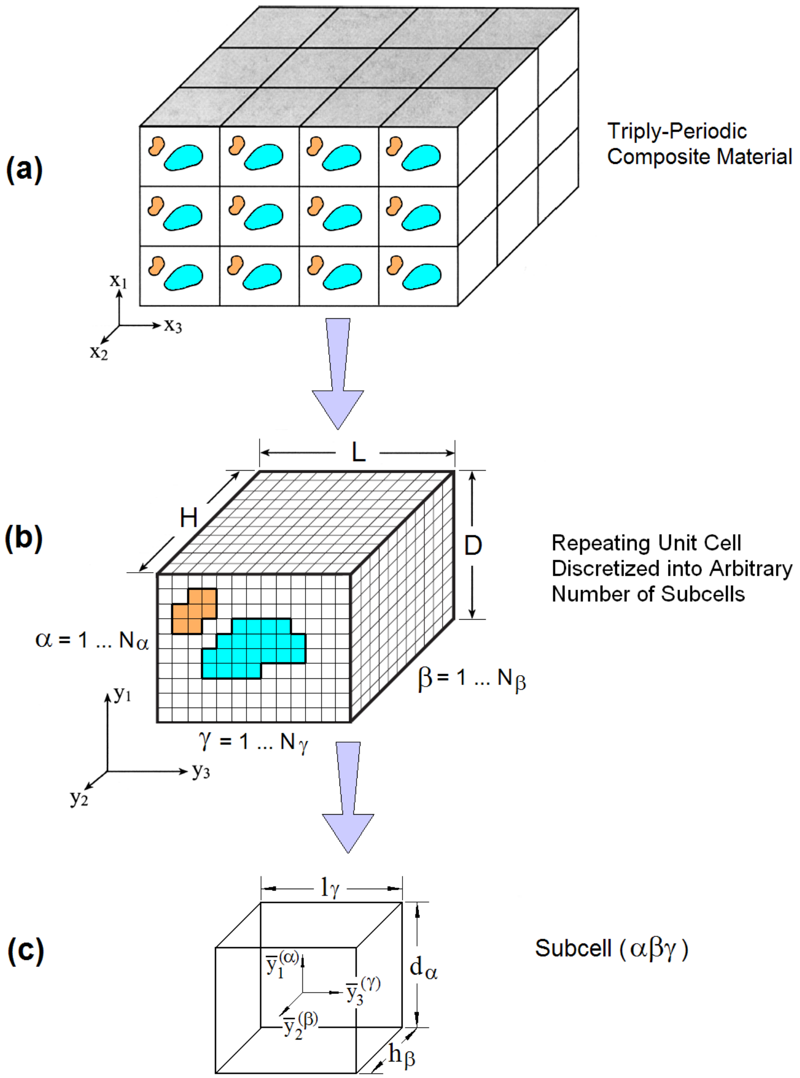
Objective

- Evaluate micromechanics theories
  - Potential for modeling multi-fiber representative volume elements (RVE)
  - Nonlinear modeling – PDFA, process modeling
  - Accuracy – must be able to capture shear lag effect
  - Efficiency – RVE simulations will be large

- Preliminary work – study single fiber repeating unit cell (RUC)

- Two micromechanics theories considered here
  - HFGMC – faster than traditional FEA
    - Amenable to multiscale modeling
  - CUF – based on arbitrary order beam theory
    - Suitable for modeling discrete fibers explicitly

HFGMC – Theory Overview



- Microstructure idealized with a discretized repeating unit cell (RUC)
  - Microstructure and material behavior are arbitrary
- Subcell displacements are assumed quadratic

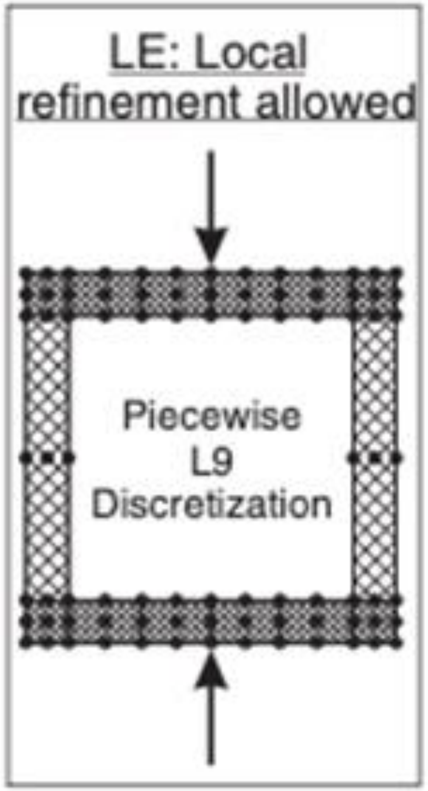
$$u_i^{(\alpha\beta\gamma)} = \bar{\varepsilon}_{ij} x_j + W_{i(000)}^{(\alpha\beta\gamma)} + \bar{y}_1^{(\alpha)} W_{i(100)}^{(\alpha\beta\gamma)} + \bar{y}_2^{(\beta)} W_{i(010)}^{(\alpha\beta\gamma)} + \bar{y}_3^{(\gamma)} W_{i(001)}^{(\alpha\beta\gamma)}$$
$$+ \frac{1}{2}\left(3\bar{y}_1^{(\alpha)2} - \frac{d_\alpha^2}{4}\right) W_{i(200)}^{(\alpha\beta\gamma)} + \frac{1}{2}\left(3\bar{y}_2^{(\beta)2} - \frac{h_\beta^2}{4}\right) W_{i(020)}^{(\alpha\beta\gamma)} + \frac{1}{2}\left(3\bar{y}_3^{(\gamma)2} - \frac{l_\gamma^2}{4}\right) W_{i(002)}^{(\alpha\beta\gamma)}$$

- Efficient semi-analytical solution
  - Continuity of traction and displacements
    - Enforced in an integral sense at subcell interfaces
- Strain concentration matrix maps global strains to local strains
  - Piecewise linear, 3D local stresses and strains

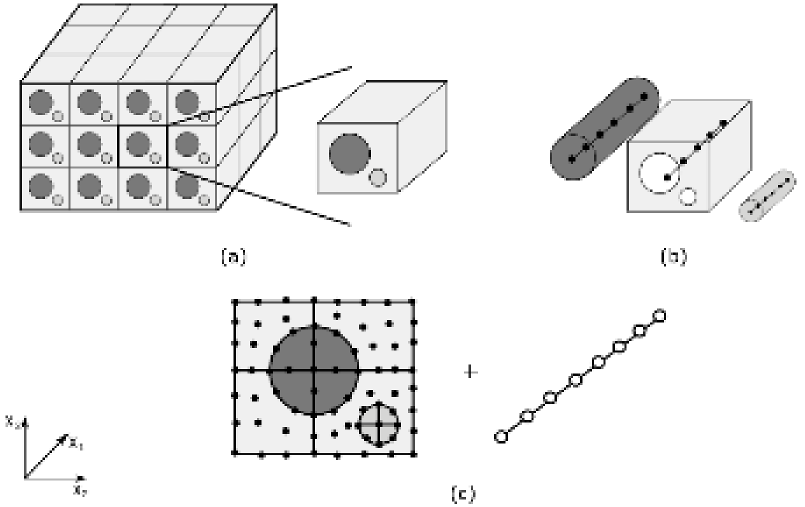
CUF – Theory Overview

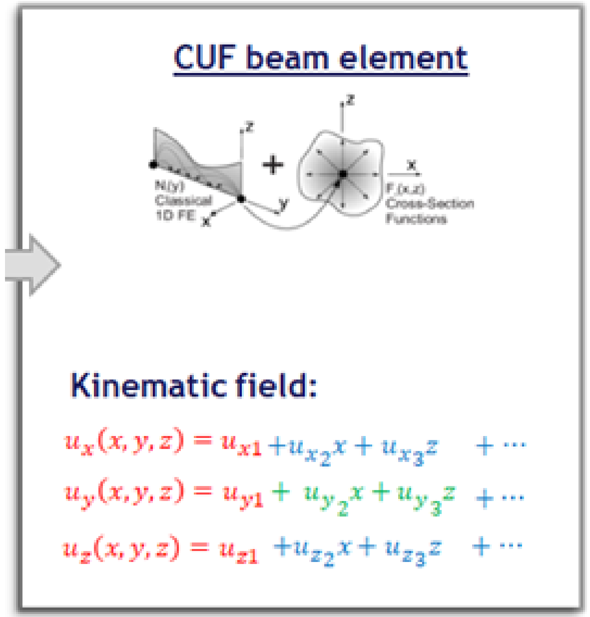
- Arbitrary choice for the type and order (number of terms) of the expansion

CUF Kinematic field: $u(x, y, z) = F_\tau(x, z)\, u(y)$



- Formulated as an invariant through Fundamental nuclei - same implementation for different classes of models
- Formulated within the context of finite element using standard shape function:





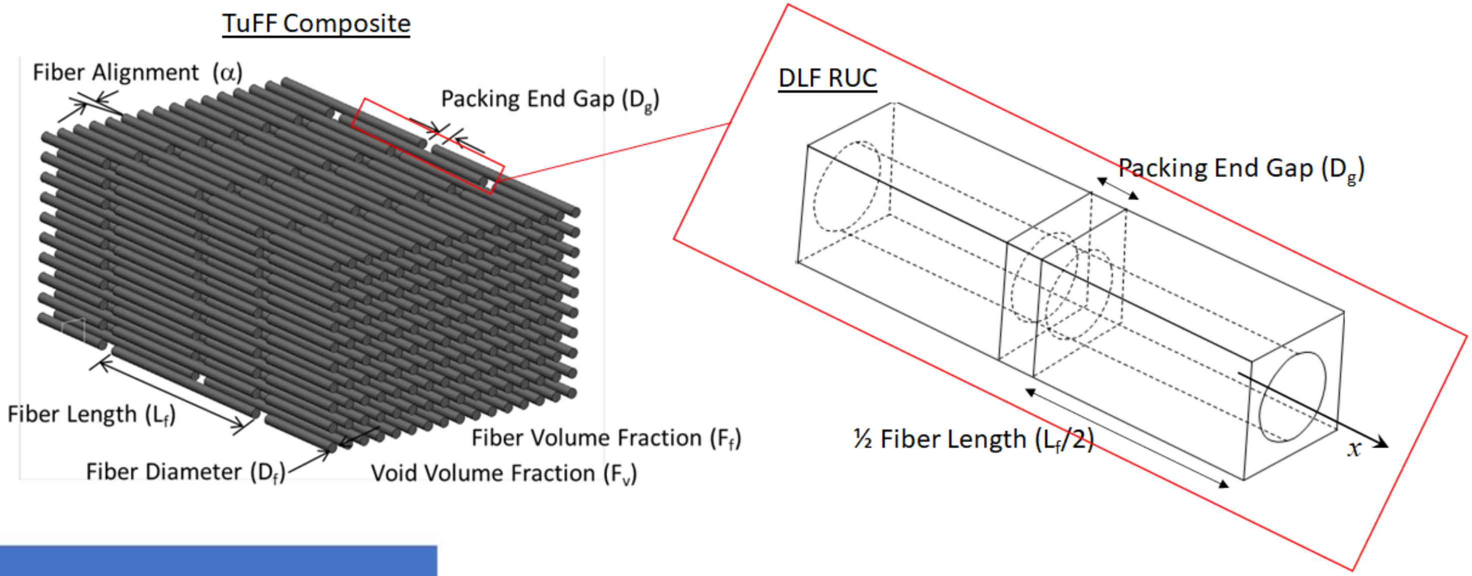
$$F_\tau = \frac{1}{2}(r^2 + r r_\tau)(s^2 + s s_\tau) \qquad \tau = 1,3,5,7$$

$$F_\tau = \frac{1}{2}r_\tau^2(r^2 + r r_\tau)(1 - s^2) + \frac{1}{2}s_\tau^2(s^2 + s s_\tau)(1 - r^2) \qquad \tau = 2,4,6,8$$

$$F_\tau = (1 - r^2)(1 - s^2) \qquad \tau = 9$$

RUC Model Details

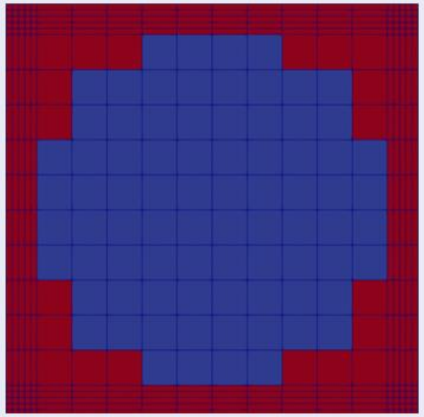
Aspect Ratio (Lf/Df)	600
Gap Ratio (Dg/Lf)	0.005 – 0.05
Fiber Volume Fraction (Ff)	0.58

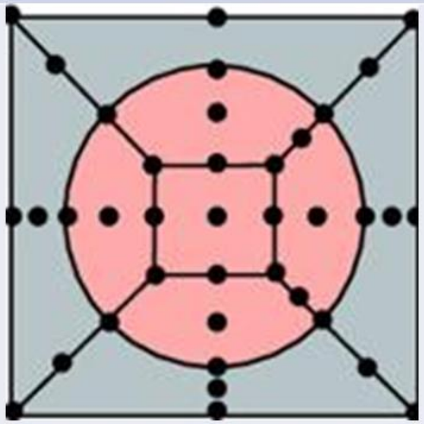


Axial Discretization

Cross Section Discretization

HFGMC	CUF

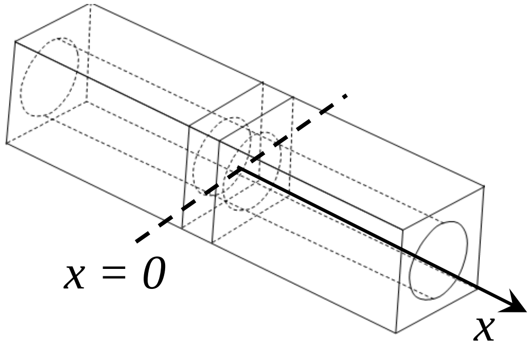




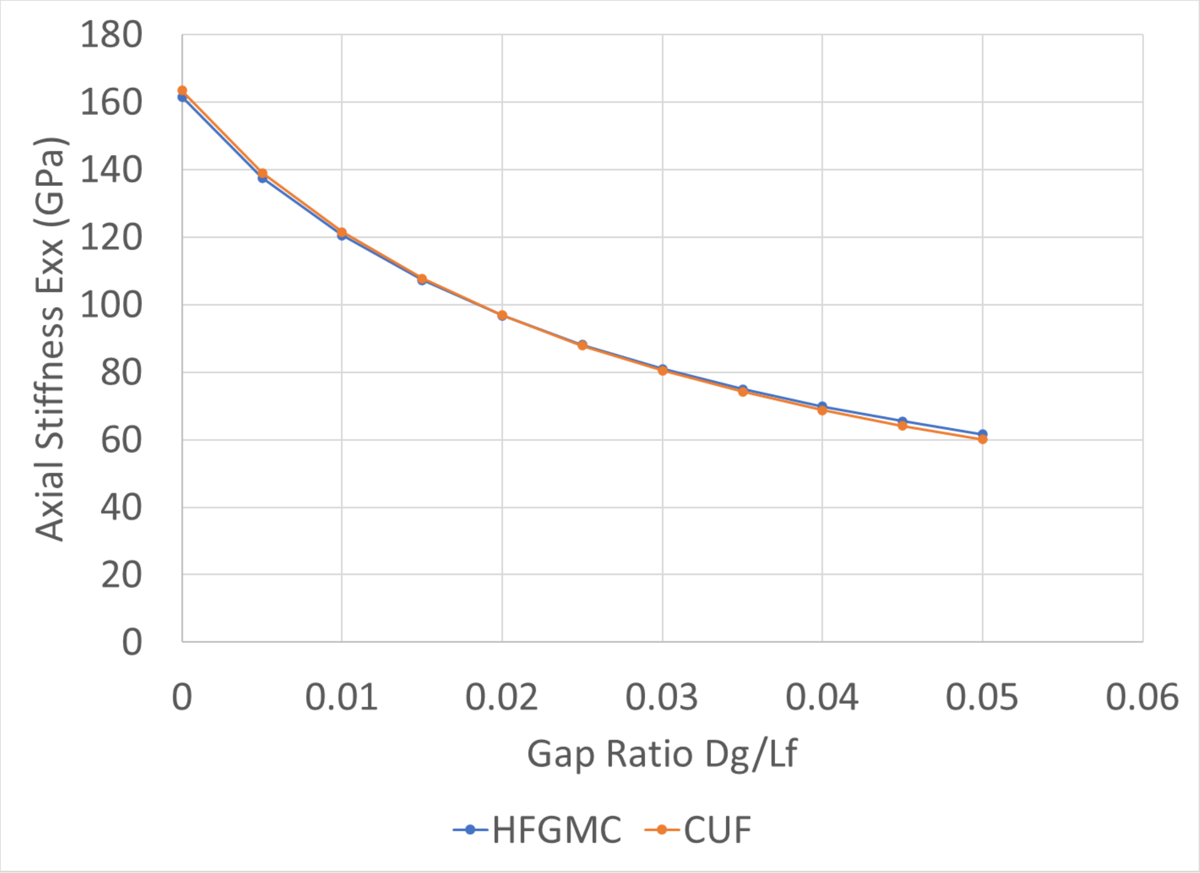
- Periodic boundary conditions
- Uniaxial strain ε_x applied in the longitudinal direction

Runtimes (Single CPU on a Laptop)	
HFGMC	CUF
~ 12 mins	~ 6 mins

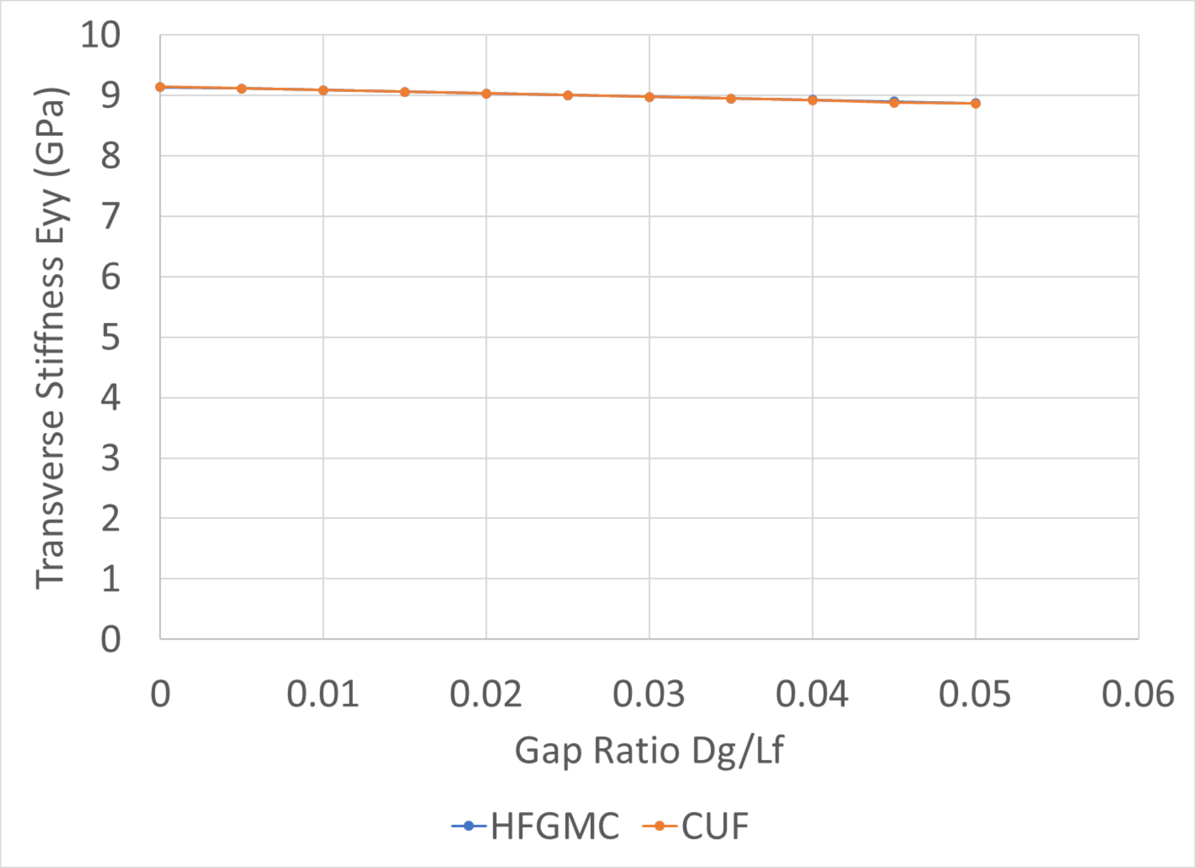
Stiffness as a Function of Gap Ratio



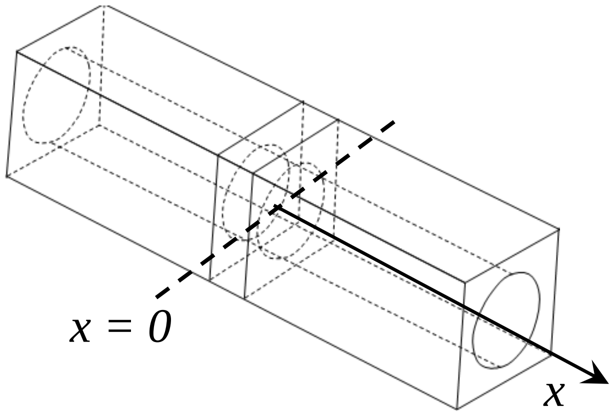
E_{xx}

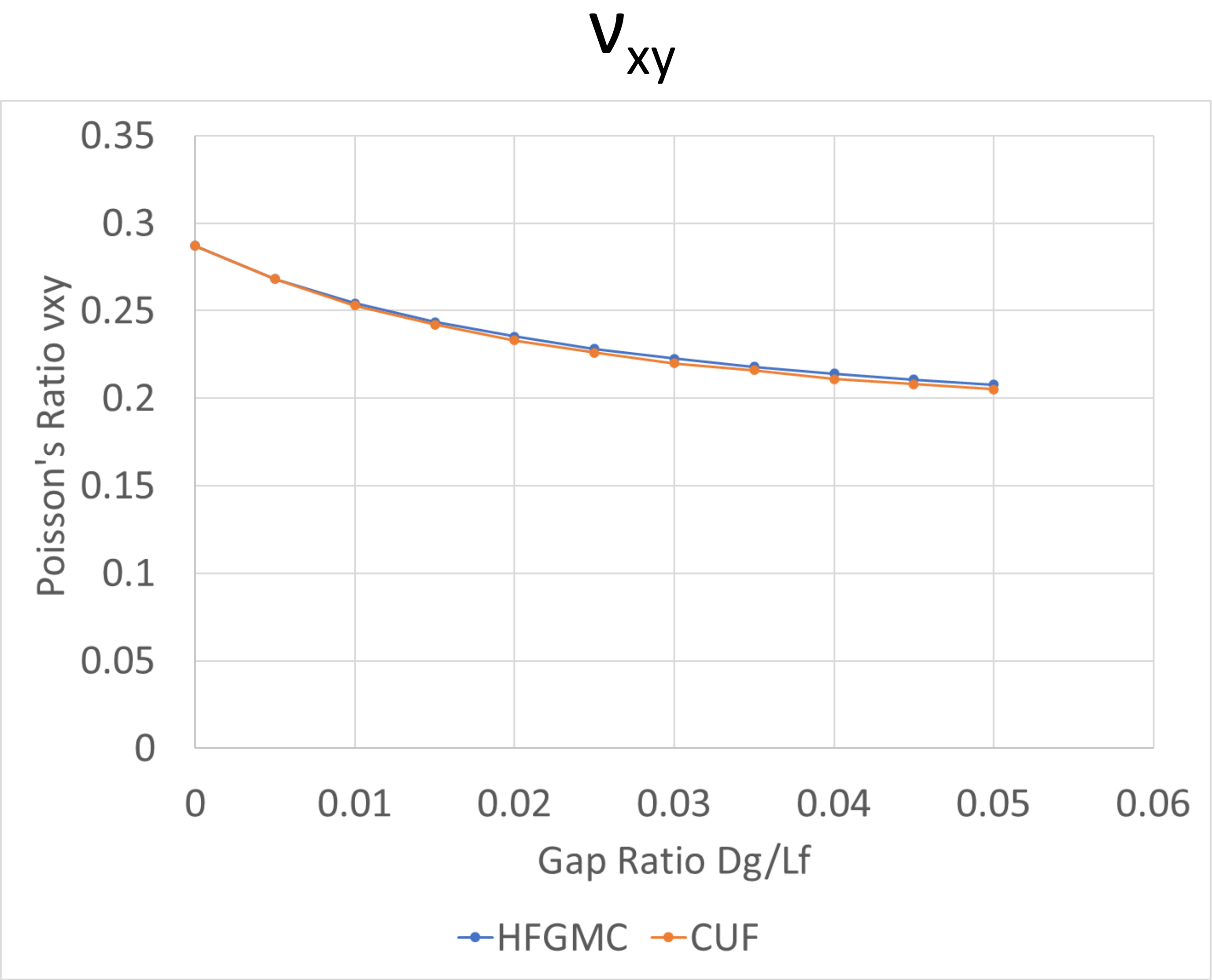


E_{yy}

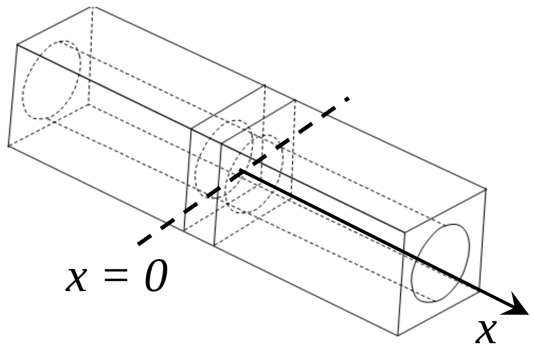


Poisson’s Ratio as a Function of Gap Ratio

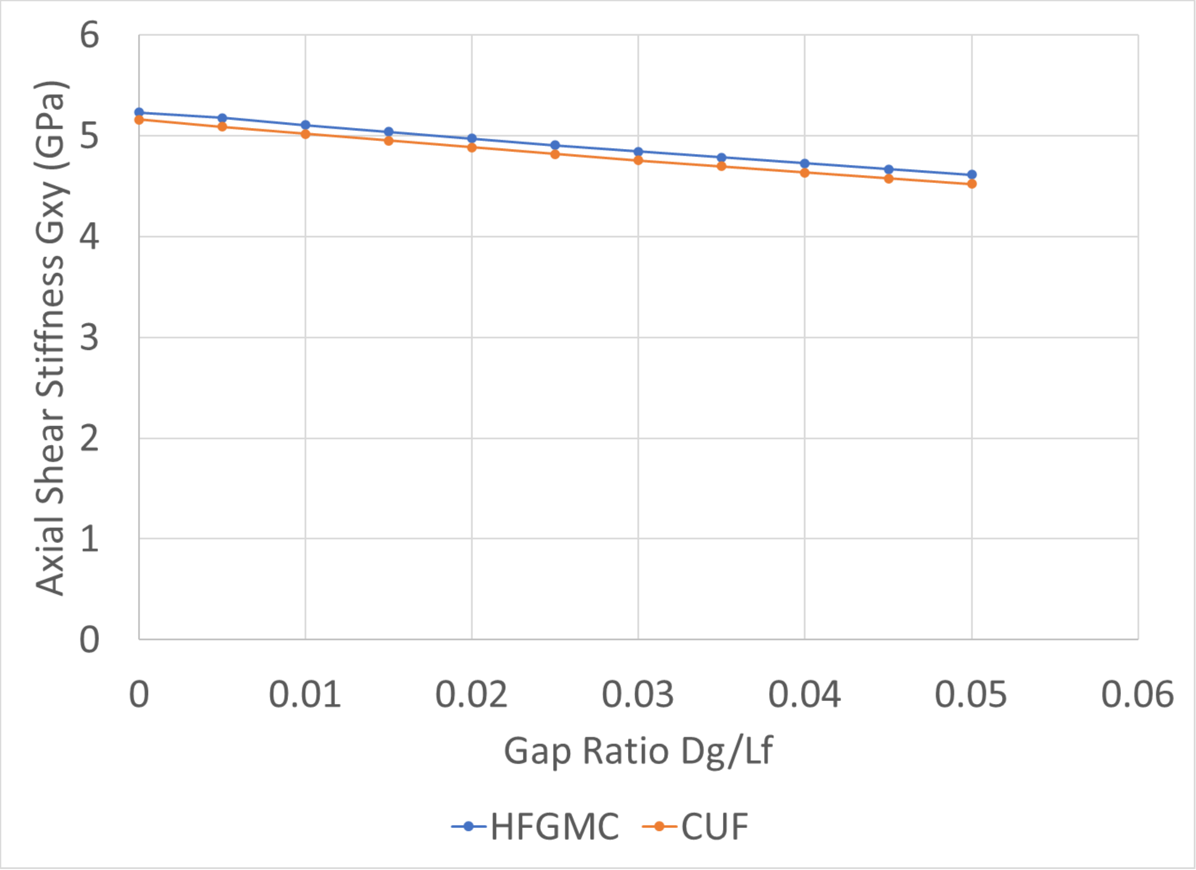




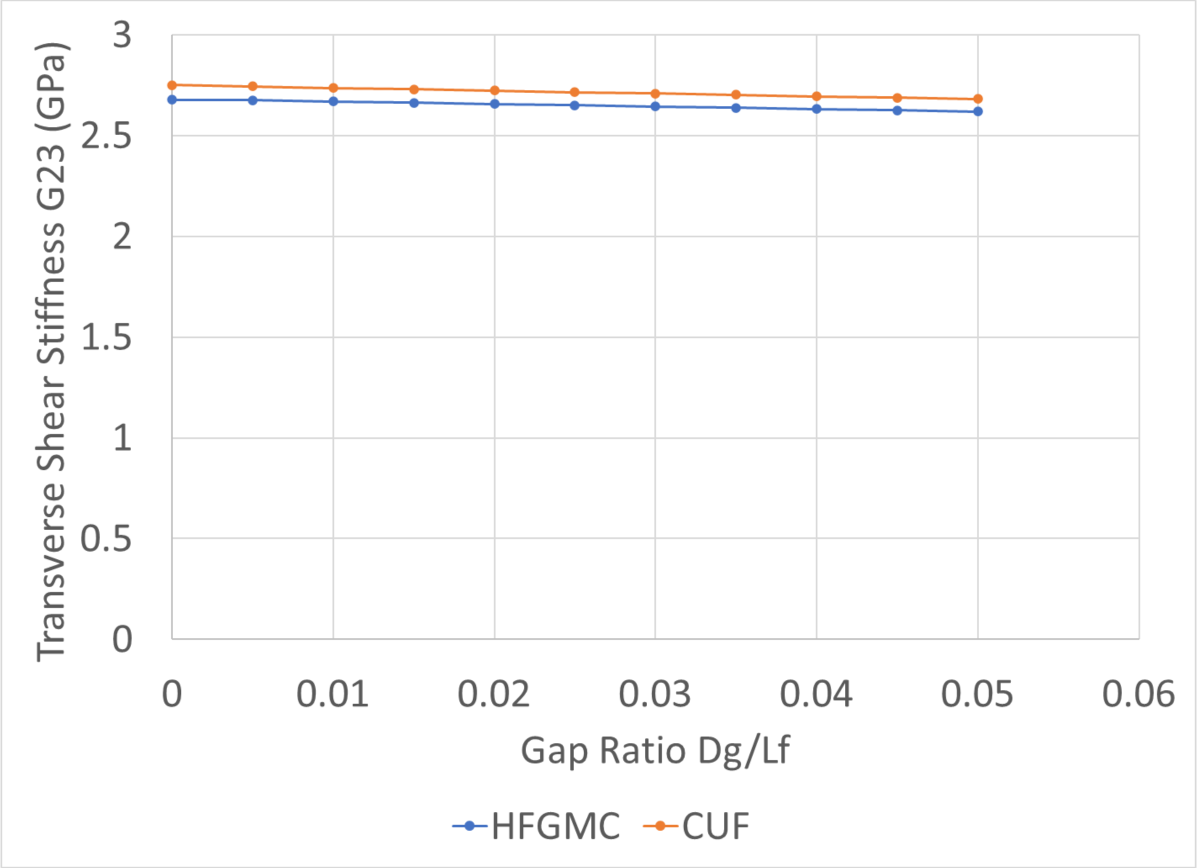
Shear Stiffness as a Function of Gap Ratio



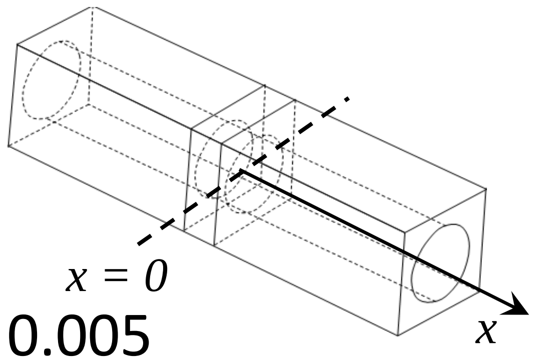
G_{xy}



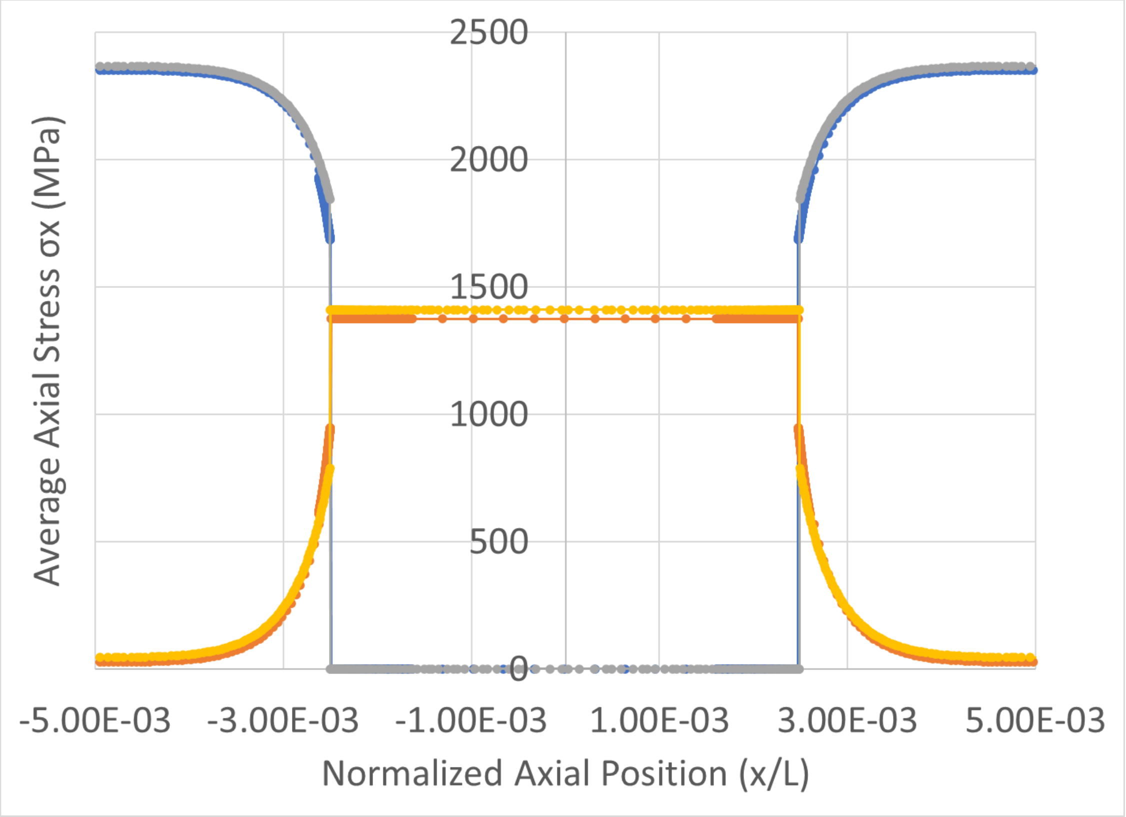
G_{yz}



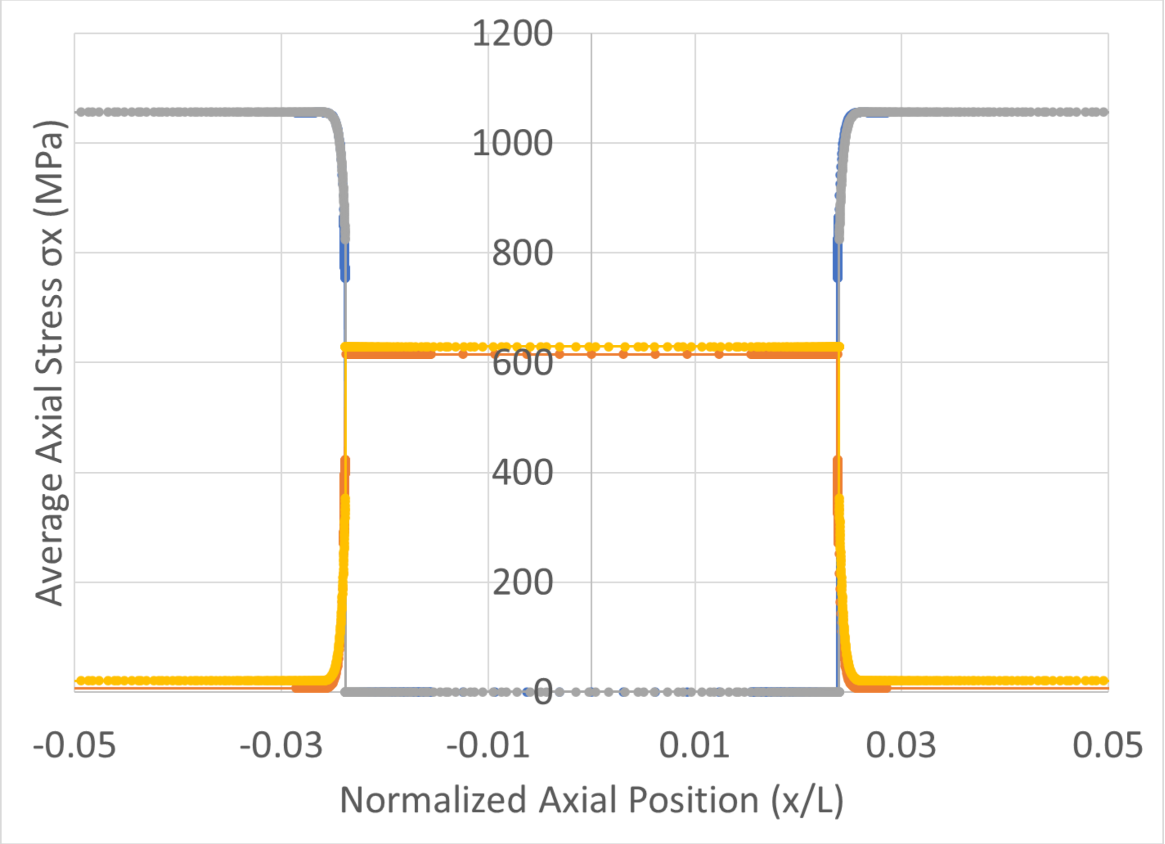
Average Stress in Fiber and Matrix



Gap Ratio Dg/Lf = 0.005

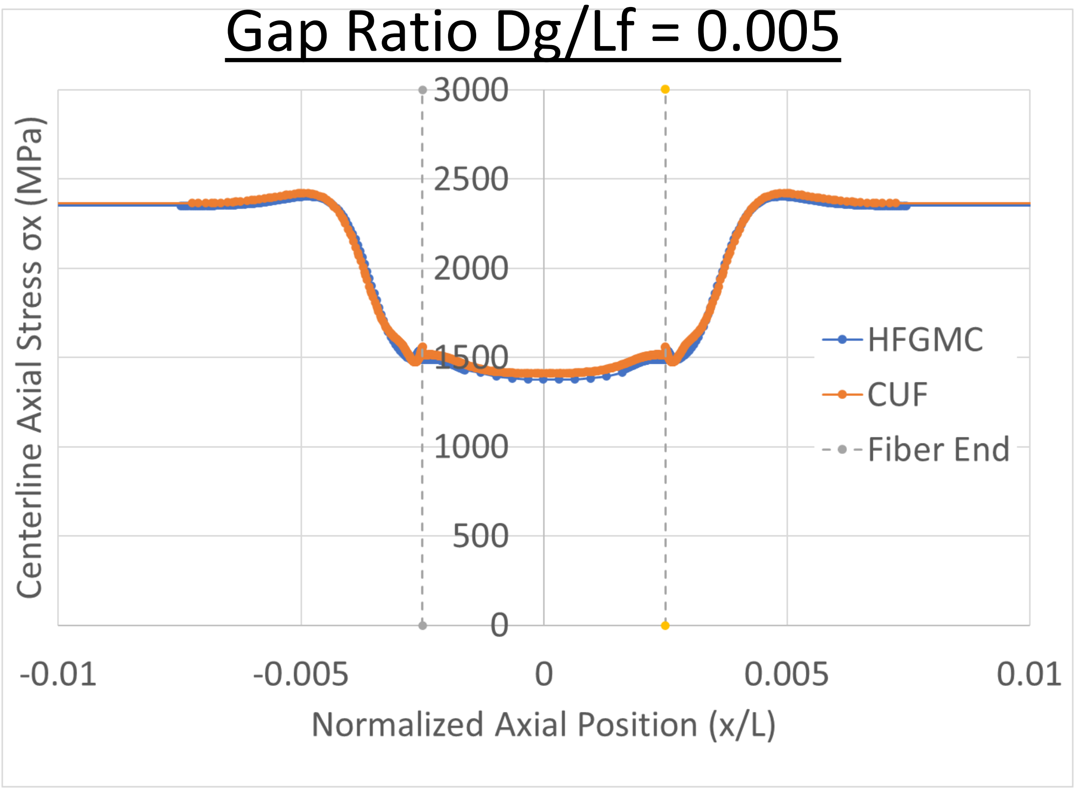


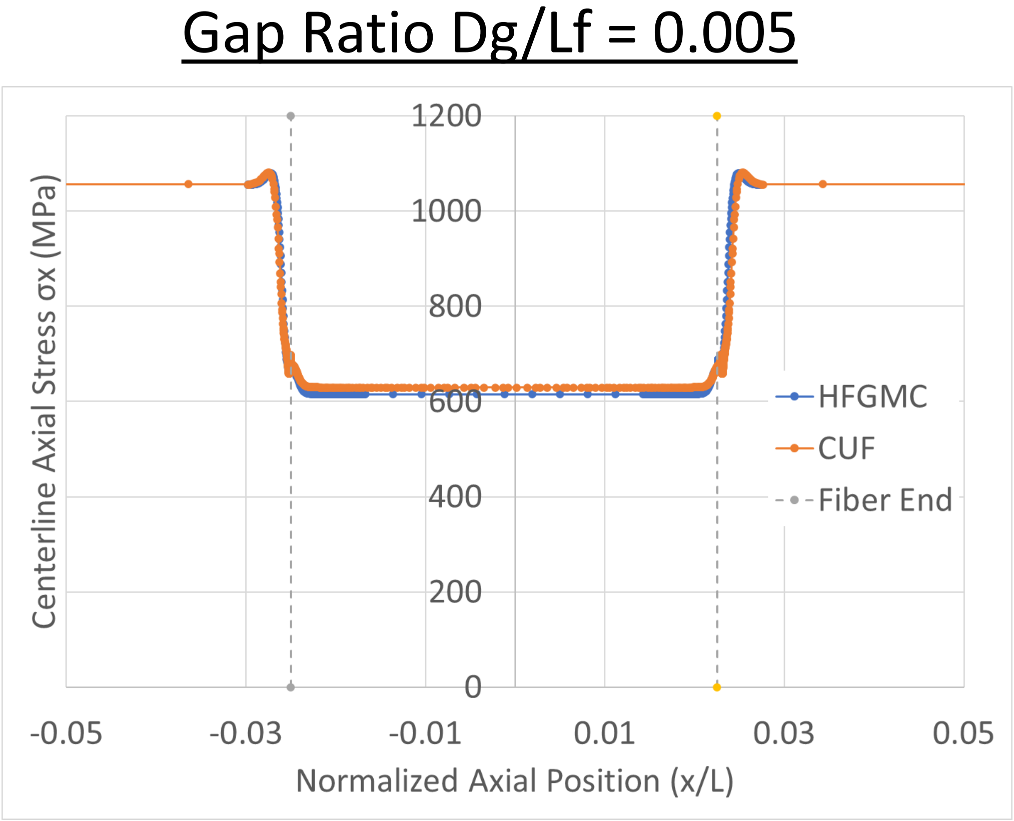
Gap Ratio Dg/Lf = 0.005

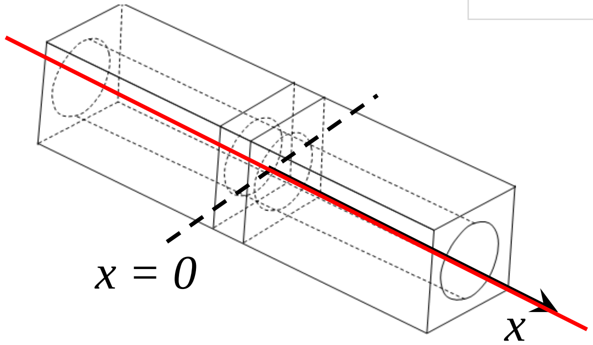


HFGMC - Fiber · HFGMC - Matrix · CUF - Fiber · CUF - Matrix

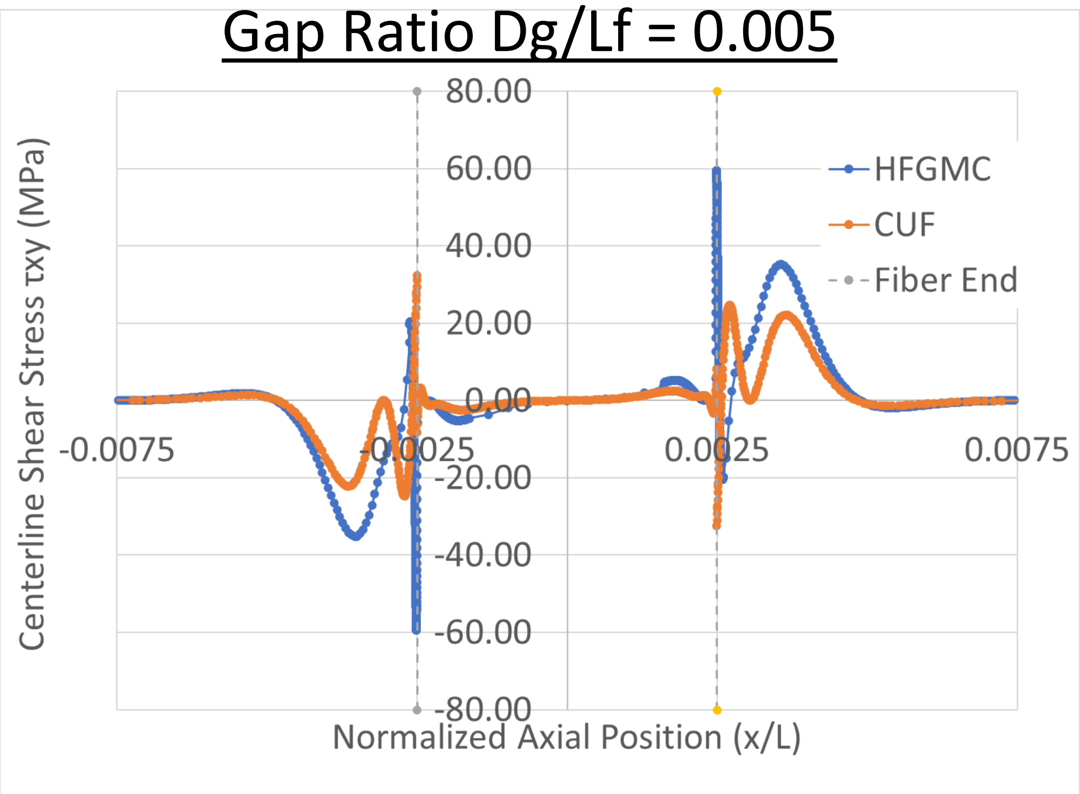
Axial Stress Along Centerline

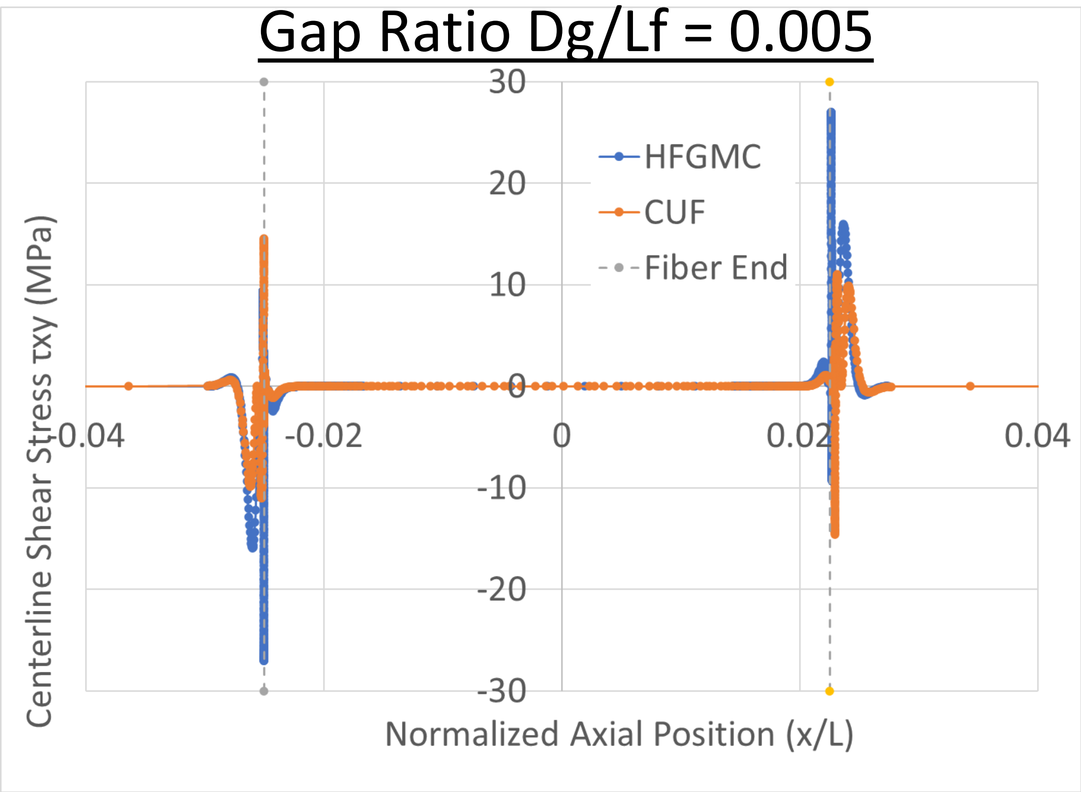


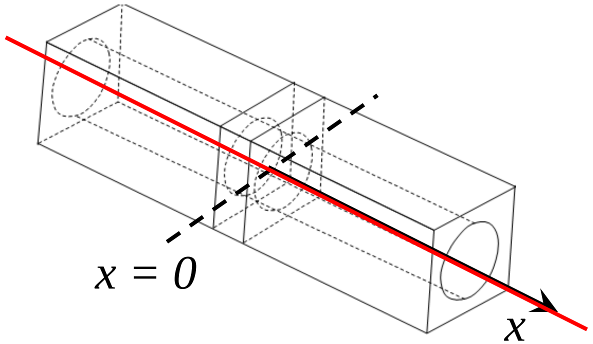




Shear Stress Along Centerline







Conclusion

- Single fiber RUC for a discrete long fiber composite modeled with HFGMC and CUF
  - Length to diameter aspect ratio = 600
- Axial stiffness sensitive to gap size
- Calculation of average stress in fiber and matrix match well between models
  - Local stress fields are complex
    - Large gradients and stress spikes
  - Discrepancy between models in shear stress along centerline

Future Work

- Understand reason for discrepancy in shear stresses
- Develop strategy for modeling multiple fibers
  - Computational requirements will pose a problem
- Incorporate damage model
- Incorporate rate dependent constitutive model to capture stretch forming at high temperatures
- Integrate multiscale model for semi-crystalline thermoplastic

Acknowledgement

This work was funded by an Interagency Agreement with the Office of Naval Research

Questions/Comments/Suggestions?