Modeling the Mechanical Response of Fibrous Monolith Composites

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Introduction

Fibrous Monolith Composites (FMCs) are an exciting new class of structural ceramics that exhibit enhanced damage tolerance, high fracture energy associated with graceful failure characteristics and high toughness and R-curve behavior. FMCs have been used as wear materials for drilling and cutting tools, metal extrusion dies and other wear components for use in extreme environments.

In an effort to improve the crack growth resistance of wear materials, Fibrous Monolith Composite (FMC) microstructures are often organized into repeating regions of hard, wear resistant materials surrounded by a layer of more ductile, damage tolerant material. Figure 1 shows a typical fibrous monolith structure in which the primary extruded cell can be clad (right) or unclad (left) with another material if desired. The clad one is fabricated with fibrous monolith (hexagonal) architectures, the cells of predominantly "hard" materials (e.g. tungsten carbide) are surrounded by a cell wall of more ductile materials with a higher Co content in a regular and predictable pattern. This architecture significantly improves the damage tolerance of the surface. A series of button inserts were fabricated with FMCs as shown in Figure 2 for roller cone drill bit applications.

In the fabrication of FMCs, there are many variables which can be altered such as cell size, material composition, cell wall thickness etc., and there are presently no approaches other than by fabricating and testing the parts to evaluate their performance. Consequently, optimization of the material selection and FMC architecture selection is difficult and somewhat arbitrary. The objective of the modeling research is to enable the fabrication of FMCs with optimally designed microstructure for superior stiffness and strength. The effects of the FMC microstructure on the apparent resistance to crack growth will be studied elsewhere [1].

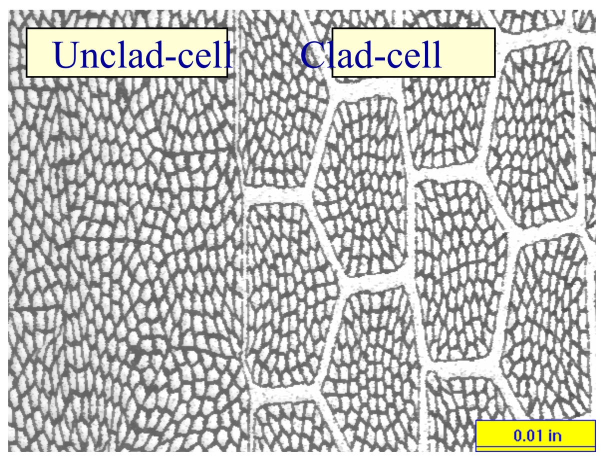

Figure 1: A micrograph showing a FMC microstructure. Several architectures are possible and their effects are investigated elsewhere [1].

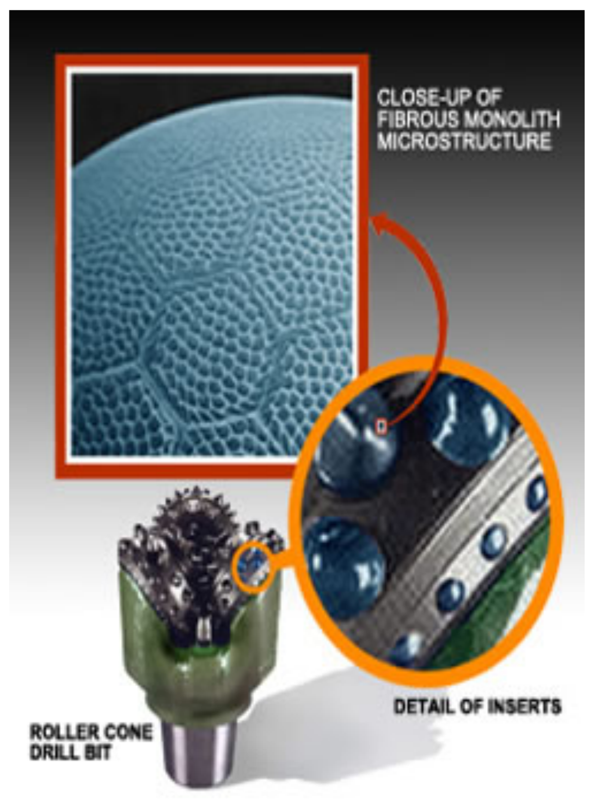

Figure 2: FM button inserts and a roller cone drill bit.

Model Development

The modeling of the mechanical response of FMCs includes establishing a finite element geometry mesh and determining the in-plane effective elastic response and the proportional limit of FMCs. A representative microstructure of a FMC is shown in Figure 3. Planes of symmetry exist along the x and y directions, and as a result, a representative unit cell can now be extracted from the FMC microstructure as shown in Figure 3 (right).

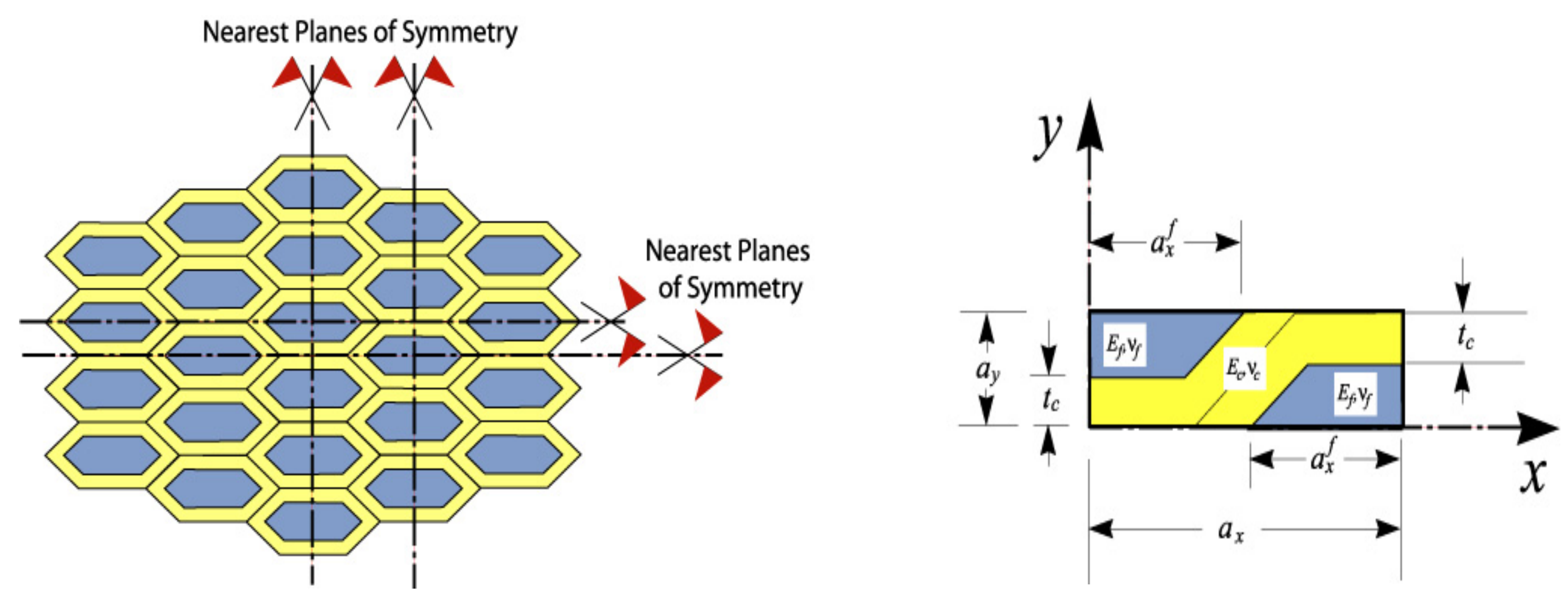

Figure 3: Microstructure of a fibrous monolith composite (FMC). Nearest plane of symmetry are shown for both x and y directions (left) and a heterogeneous unit-cell extracted from a FMC microstructure (right).

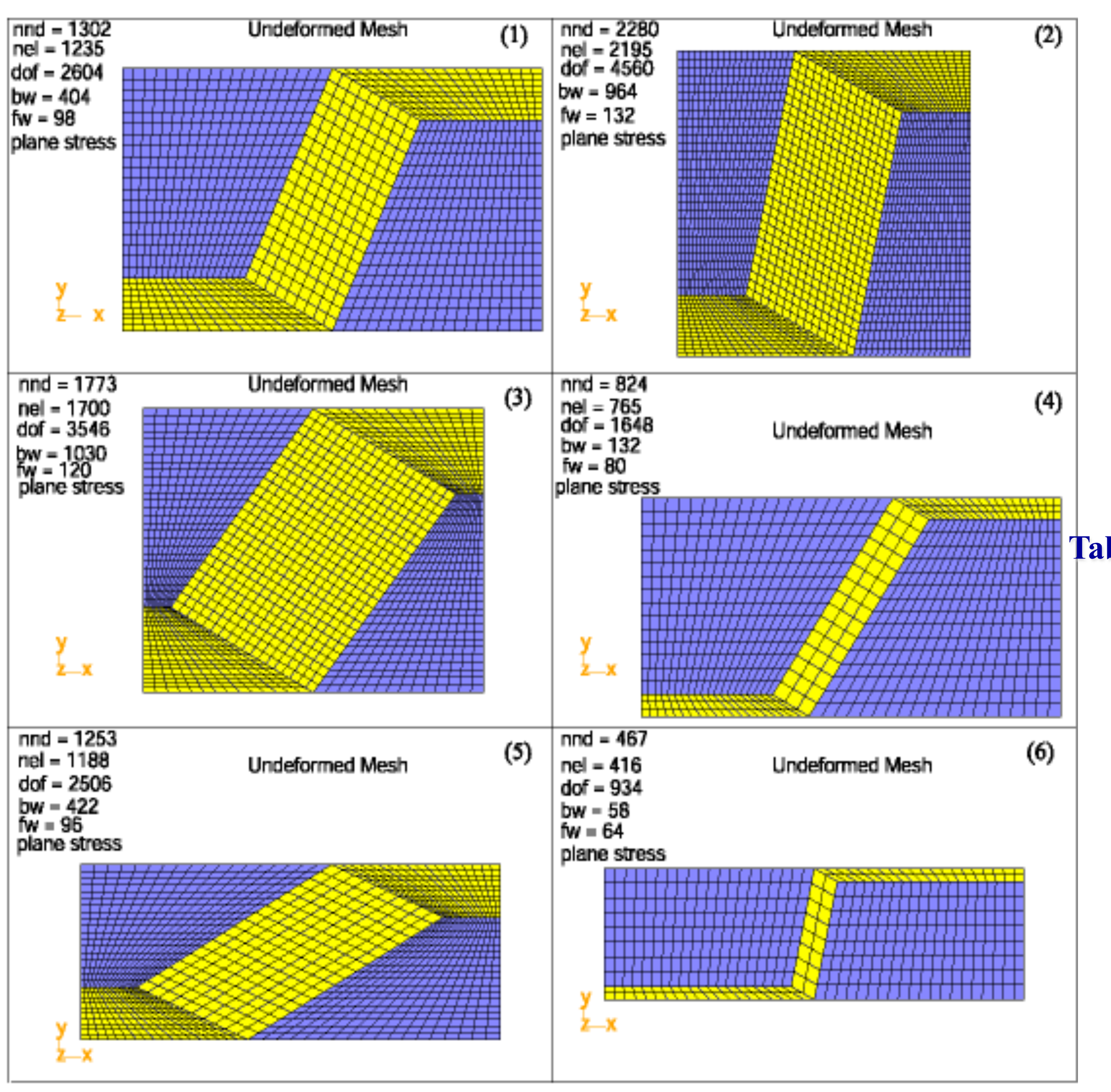

Figure 4: Geometry meshes corresponding to different geometry parameters. The parameters and material modulus are listed in the Table 1.

Table 1:

Mesh	a_y/a_x	t_c/a_y	a_x^f/a_x	E_f/E_m
(1)	0.6	0.2	0.5	2
(2)	1	0.2	0.4	5
(3)	0.8	0.3	0.5	3
(4)	0.5	0.1	0.6	3
(5)	0.4	0.3	0.6	4
(6)	0.3	0.1	0.5	4

In-plane Effective Elastic Response of FMCs

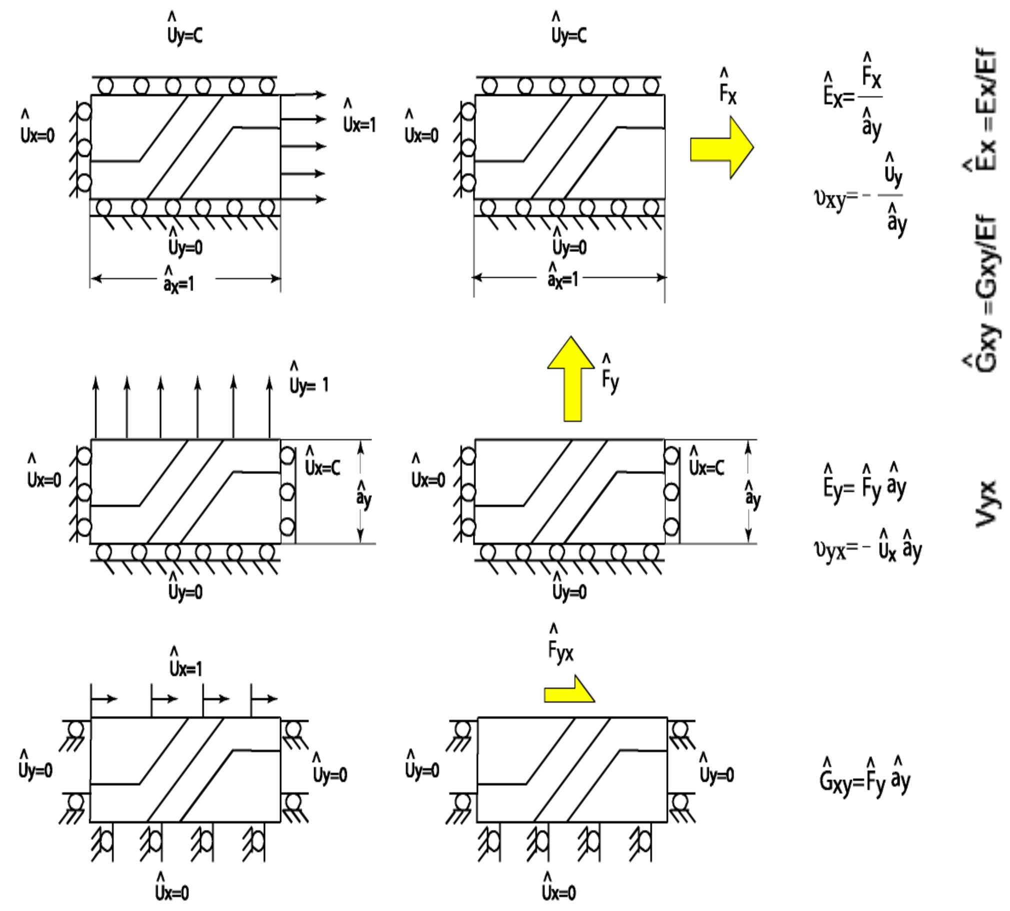

Figure 5: Three boundary value problems simulating the application of stress on a FMC unit cell.

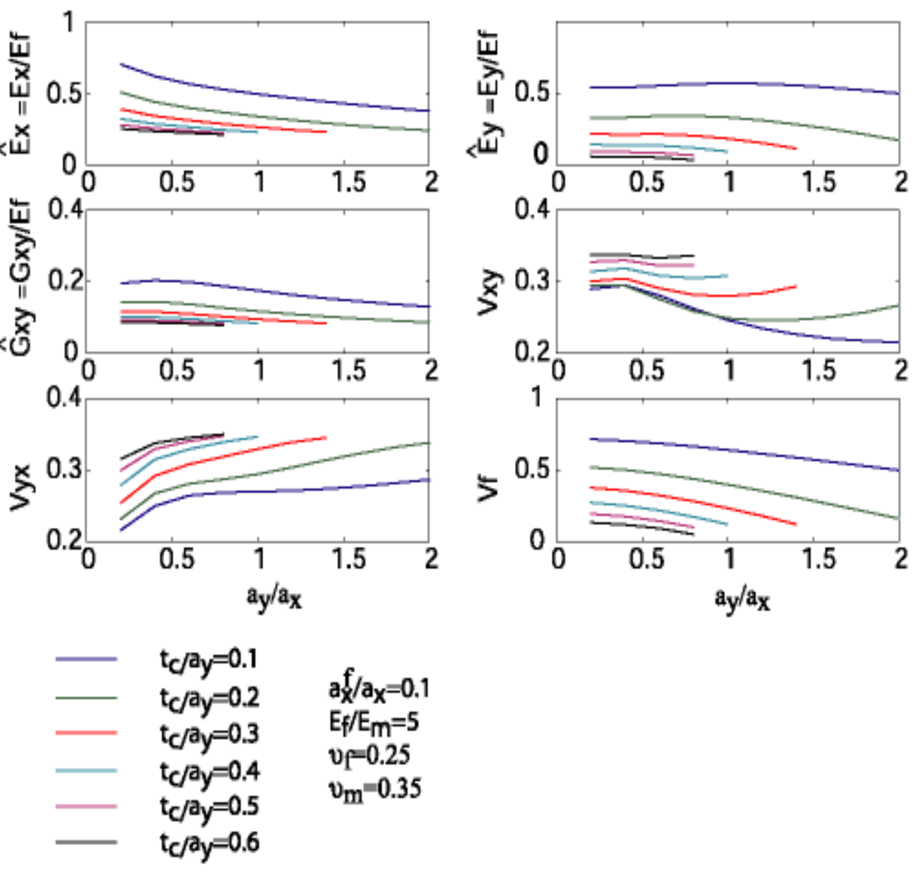

Figure 6: The in-plane effective elastic modulus and Poisson's ratio plotted against the FMC unit-cell aspect ratio a_y/a_x.

Modeling the Proportional Limit of FMCs

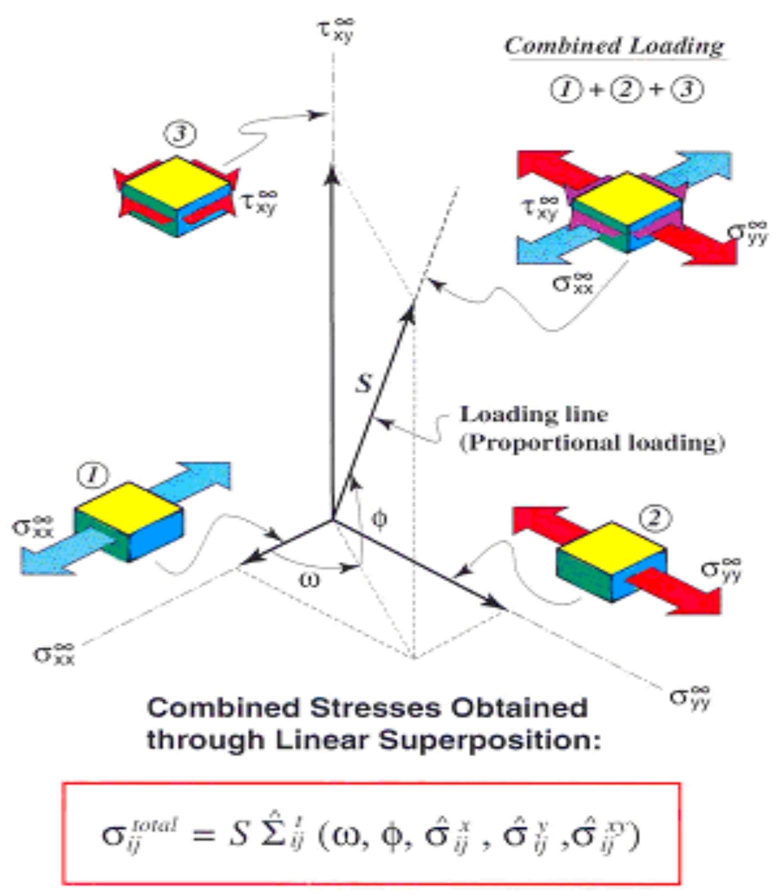

Figure 7: A schematic of a general in-plane loading stress vector.

Maximum normal stress criterion

$$\sigma_{p1} = \sigma_f$$

$$\frac{\sigma_f}{S} = \Phi_1(\omega, \phi, \hat{\sigma}_{ij}^x, \hat{\sigma}_{ij}^y, \hat{\sigma}_{ij}^{xy})$$

Effective stress criterion

$$\sigma_e = \sqrt{\sigma_{ij}^t \sigma_{ij}^t} = \sigma_c$$

$$\frac{\sigma_c}{S} = \Phi_2(\omega, \phi, \hat{\sigma}_{ij}^x, \hat{\sigma}_{ij}^y, \hat{\sigma}_{ij}^{xy})$$

The maxima Φ_1^{max} and Φ_2^{max} are used to establish a failure locus point in the normalized space $\sigma_{xx}^\infty - \tau_{xy}^\infty$ as shown in Figure 10 as discussed in [2].

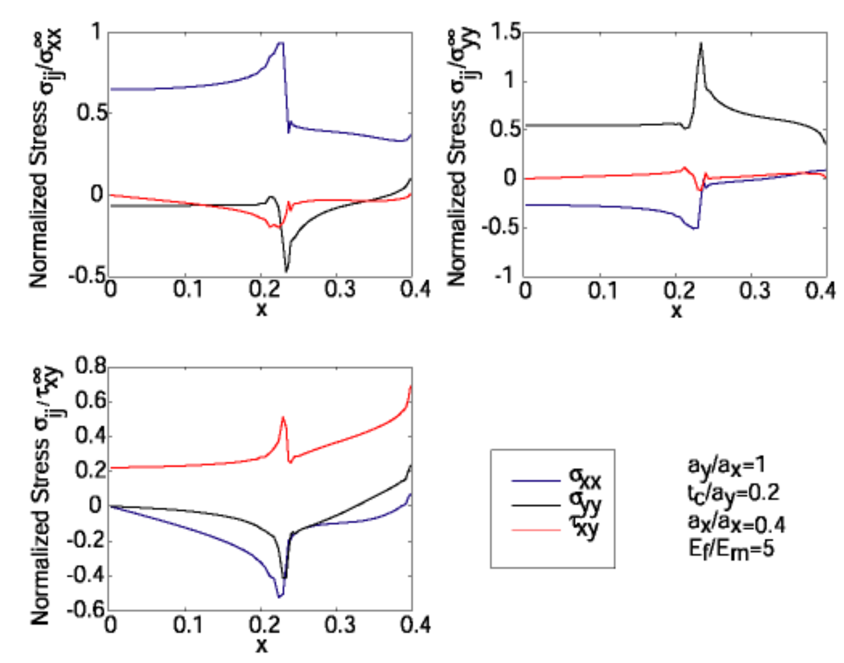

Figure 8: Fundamental micro-stress profiles obtained at the interface between fiber and matrix phases obtained by solving the three independent in-plane boundary value problems.

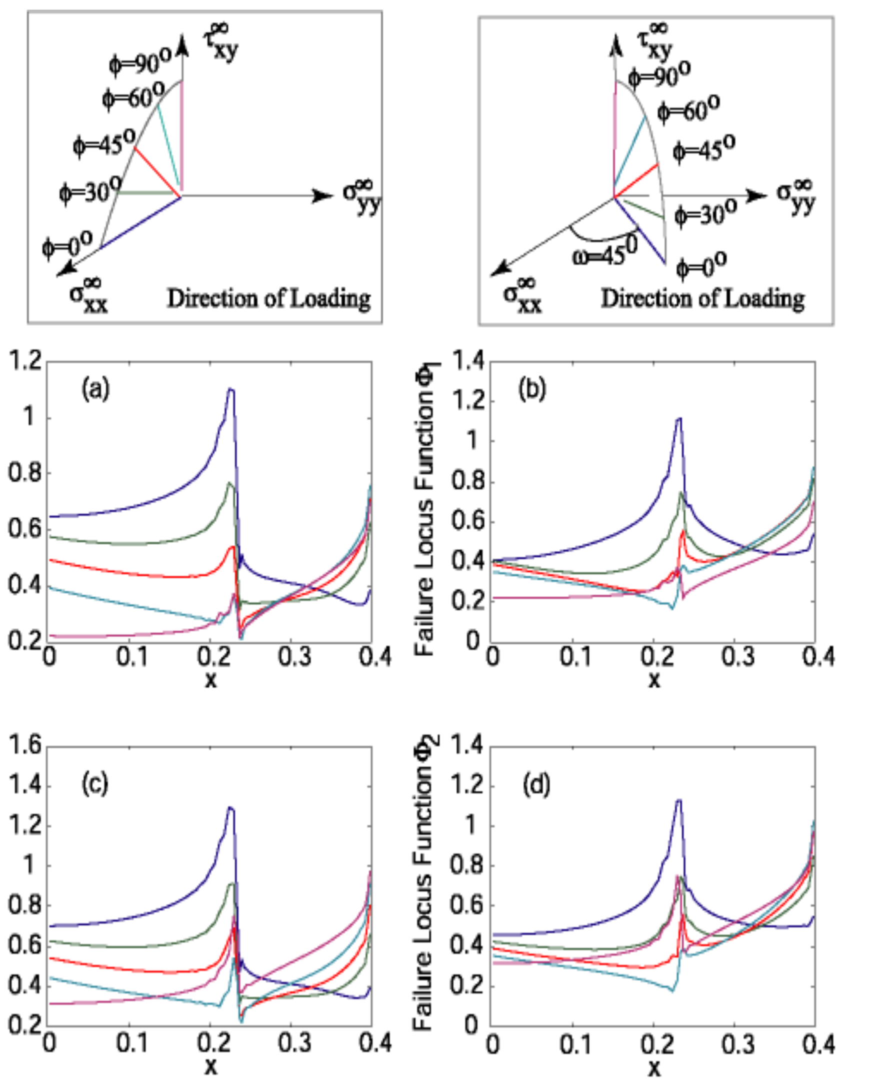

Figure 9: Failure locus functions for a given geometry and material parameter combination.

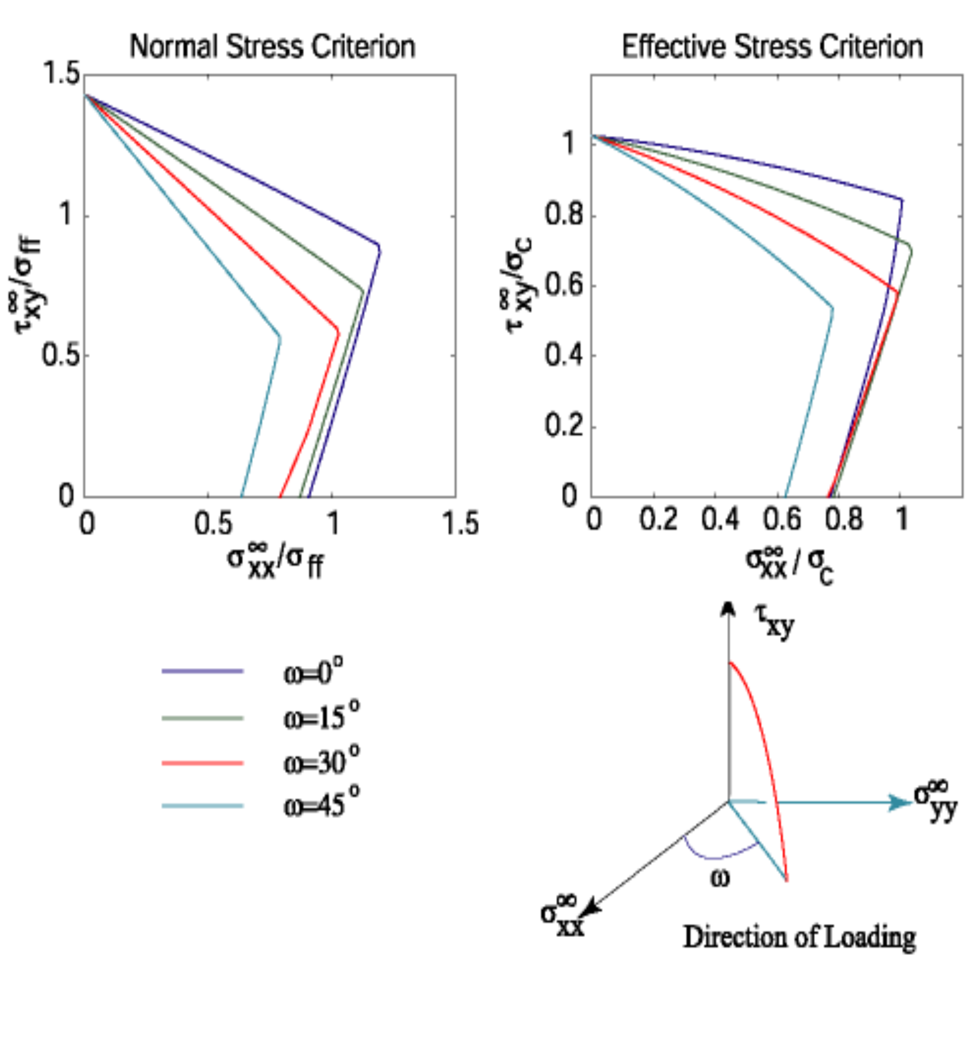

Figure 10: First cracking stress loci. The associated FMC microstructure and micro-constituent properties are related to the geometry and material rations given in the figure.

Conclusion

Finite element models have been developed to analyze the mechanical response of FMCs. The in-plane effective elastic responses of FMCs are established. Failure loci, predictive of the first matrix cracking stress have been obtained. The above results form the foundation for non-linear studies aiming at establishing the crack growth and wear resistance of FMCs.

Acknowledgment

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Reference

[1]. Liwei Lu, "Modeling the Mechanical Response of Fibrous Monolith Composites", Ph.D. Research, in progress.

[2]. S.I. Haan, "Modeling of the Mechanical Response of Plain Weave Composites", Doctor of Philosophy thesis, University of Maryland, Baltimore County, 2000.