Fatigue, Damage and Failure of Composite Materials: Mechanisms, Fatigue Life Diagrams and Life Prediction

Ramesh Talreja
Department of Aerospace Engineering
Department of Materials Science and Engineering
Texas A&M University, College Station, Texas, USA

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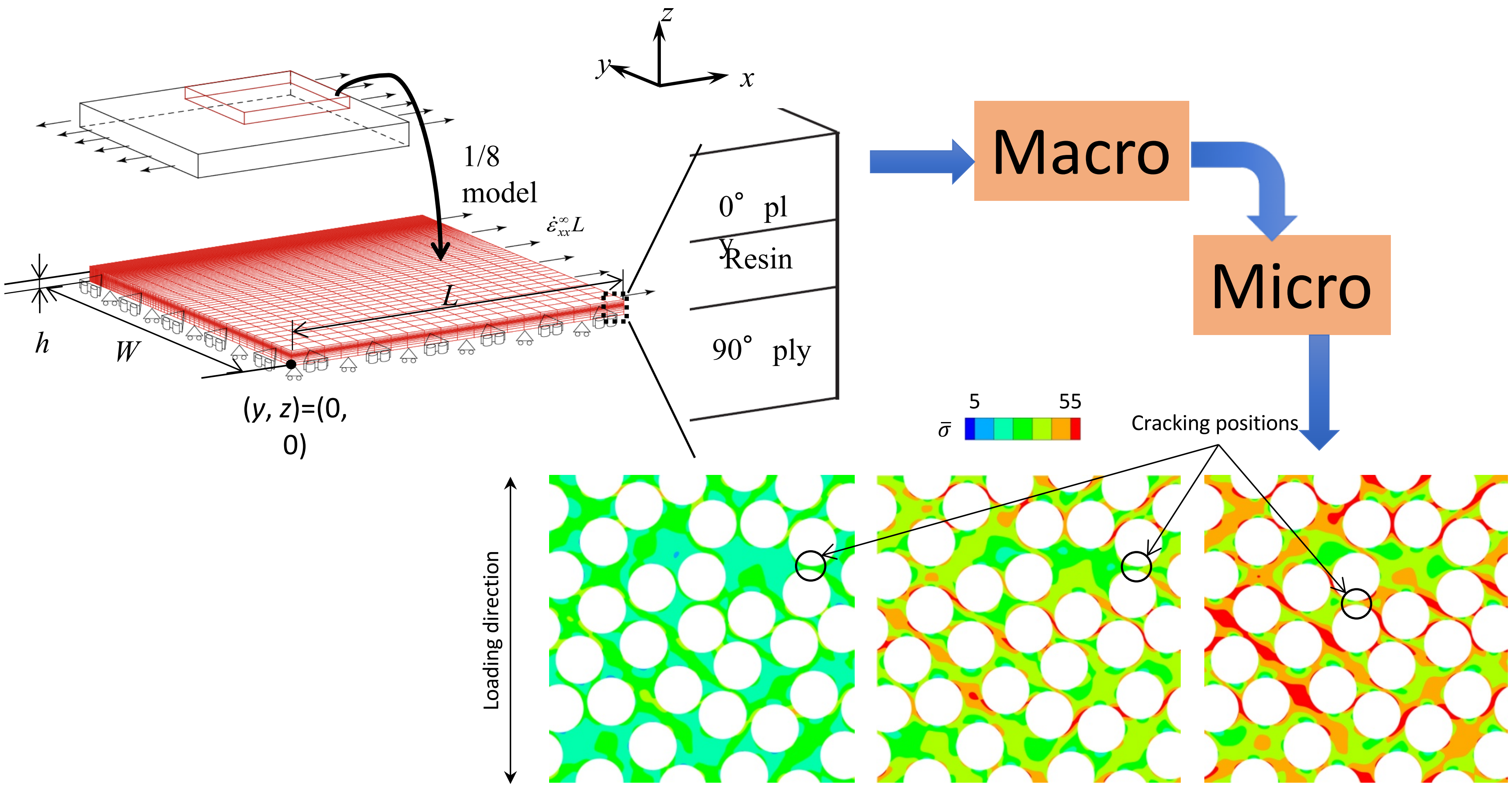
Lecture 5 : DAMAGE MECHANICS

Contents

- Multiscale approach to damage and failure
- Macro damage mechanics
- Micro damage mechanics
- Synergistic damage mechanics
- Defect damage mechanics
- Virtual testing, computational micromechanics

Multi-scale analysis - Methodology

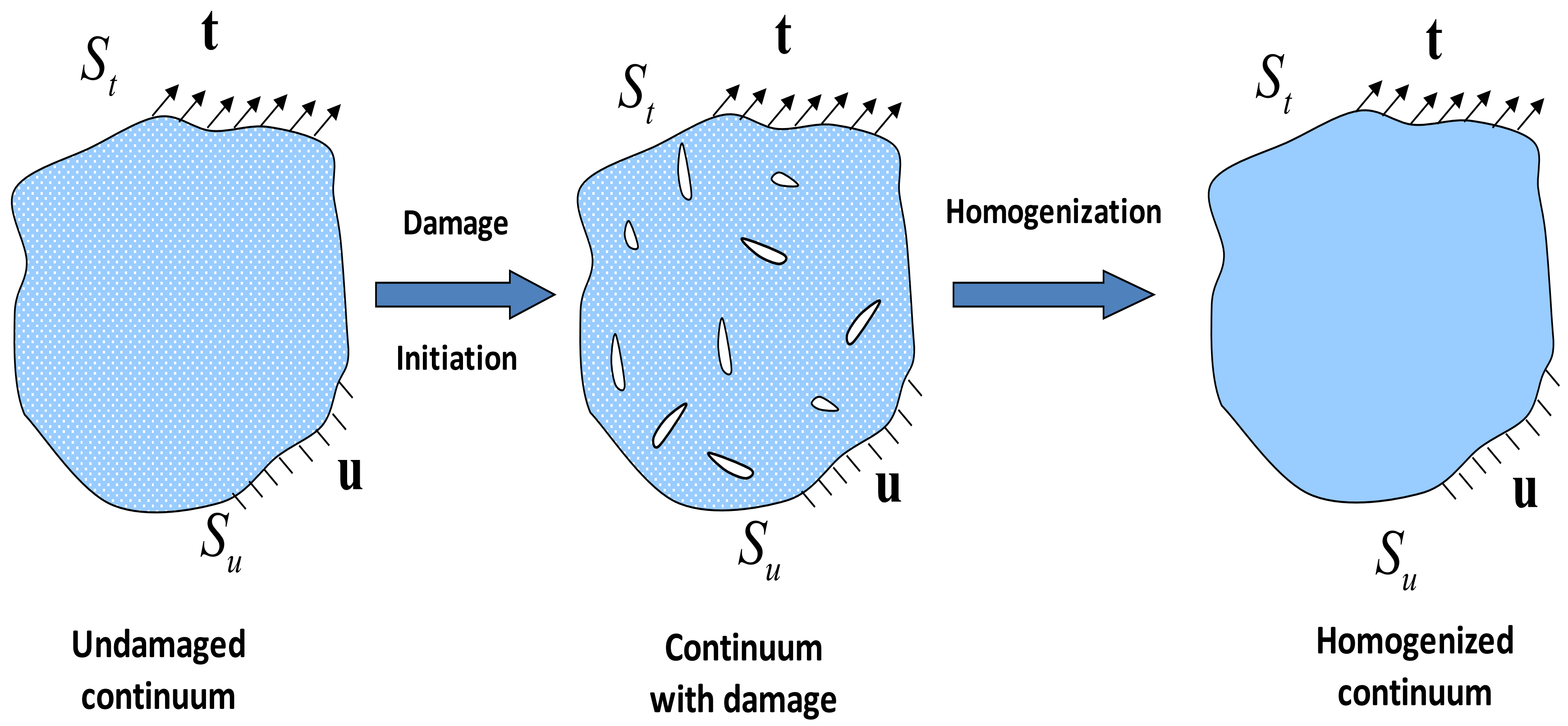


Near the 0° ply at the free edge ((*y*, *z*)=(*W*, *h*))

Central plane of the free edge ((*y*, *z*)=(*W*, 0))

Internal section ((*y*, *z*)=(0, 0))

Macro damage mechanics (also called continuum damage mechanics, CDM)



Early concepts of damage as an "internal state", Kachanov (1958)

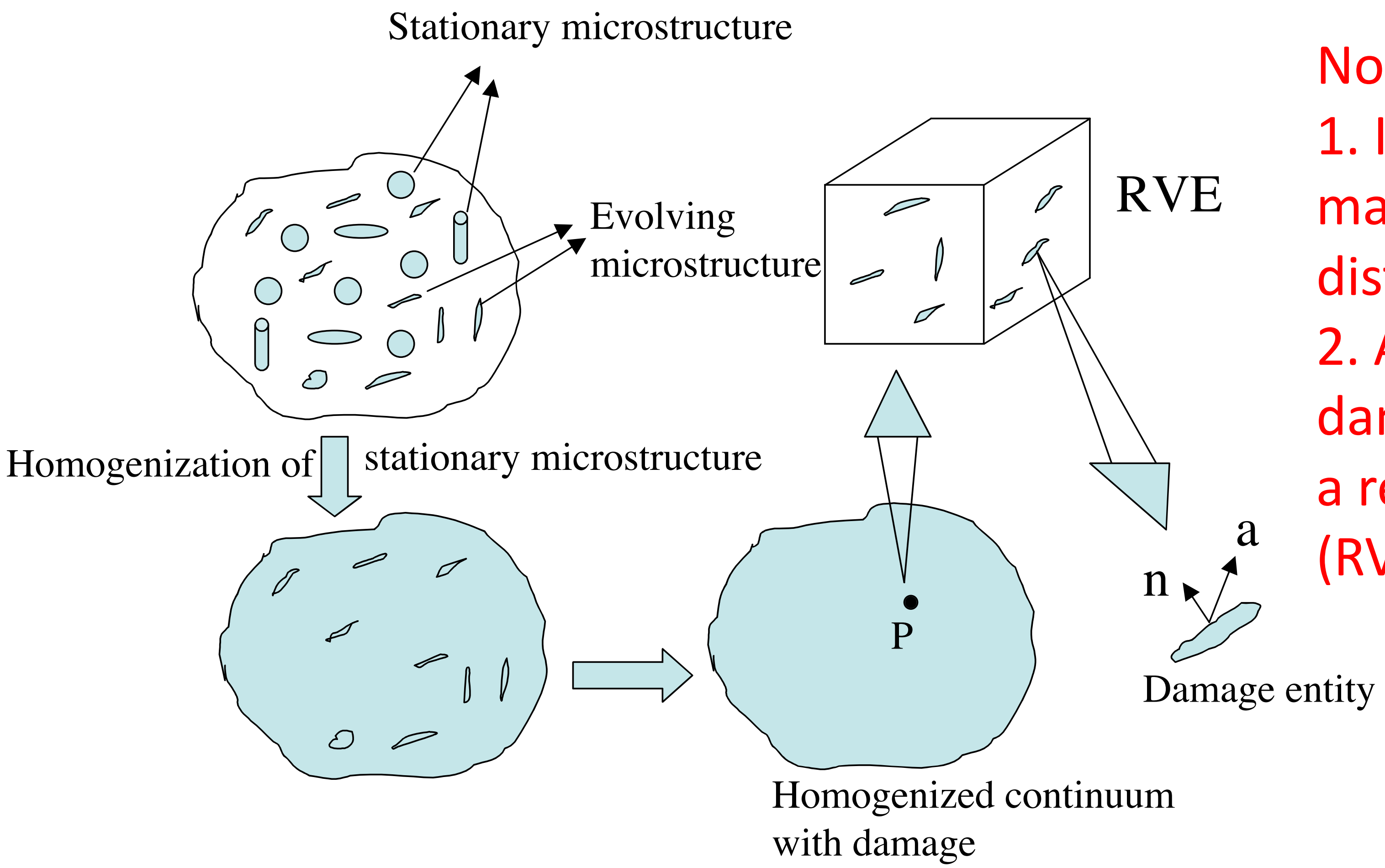
Kachanov considered creep rupture of metals. He assumed the internal structure was degrading in time (becoming discontinuous) and introduced an internal variable called discontinuity, ϕ, $\phi = 1$ at t = 0, whose rate of change was assumed as a power law:

$$\frac{\mathrm{d}\phi}{\mathrm{d}t} = -A\left(\frac{\sigma}{\phi}\right)^{m}$$

Robotnov later (1969) defined damage as $\omega = 1 - \phi$ as a damage parameter representing net area reduction. Thus, $0 < \omega < 1$ was born as an internal state variable.

Today, "damage" denoted by D has become an abused concept, and D is used arbitrarily as needed, mostly driven by convenience.

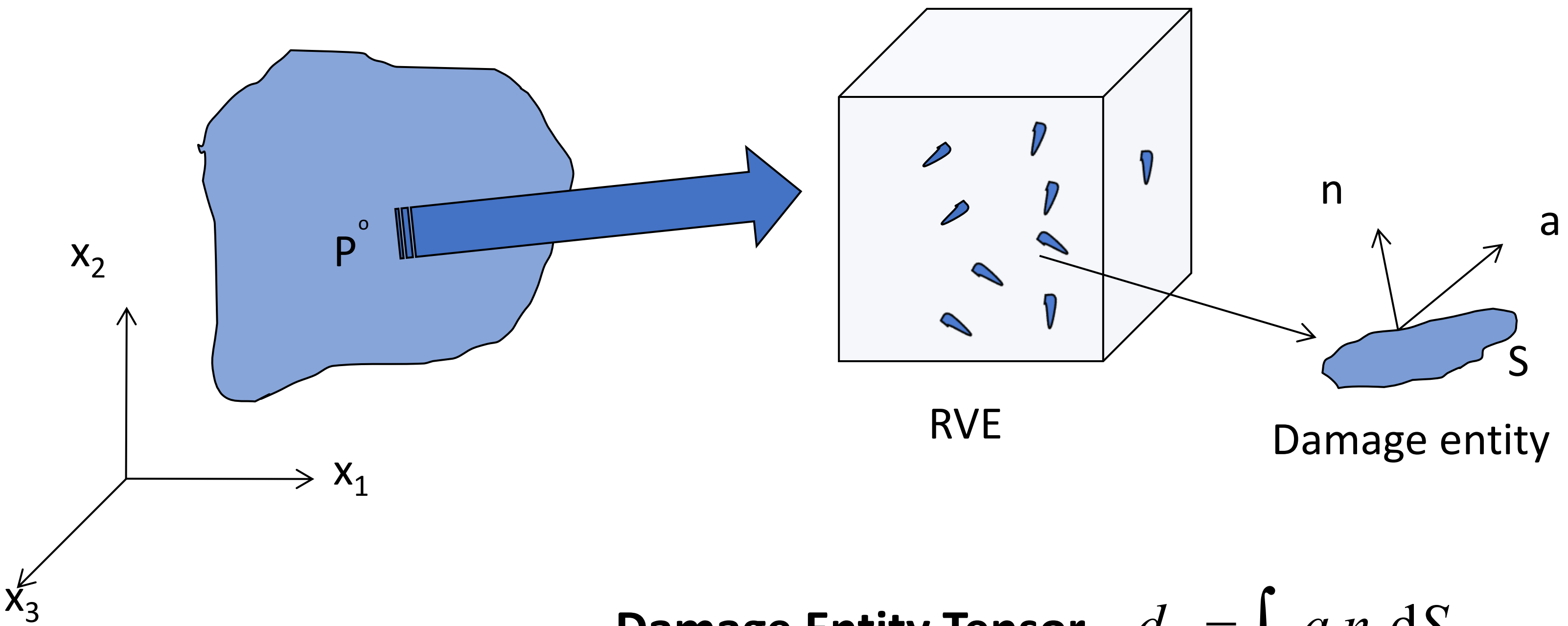
Damage as an internal variable for composite materials (Talreja, 1985)



Note:

1. Internal damage in composite materials is in the form of distributed, ***oriented*** microcracks.
2. All variables, stress, strain and damage must be described using a representative volume element (RVE).

Damage characterization for composites



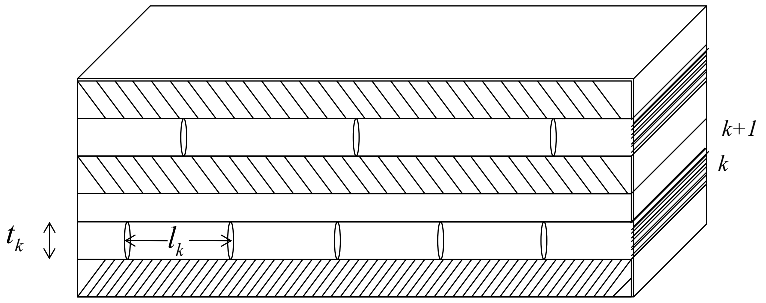
Damage Entity Tensor $d_{ij} = \int_S a_i n_j \mathrm{d}S$

Damage Mode Tensor

$$D_{ij}^{(\alpha)} = \frac{1}{V} \sum_{k_\alpha} \left(d_{ij} \right)_{k_\alpha}$$

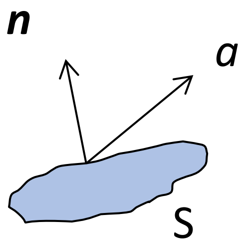
Note: Instead of a tensor a vector can be used (see Talreja, Proc. R. Soc, 1985)

Damage Mode Tensors



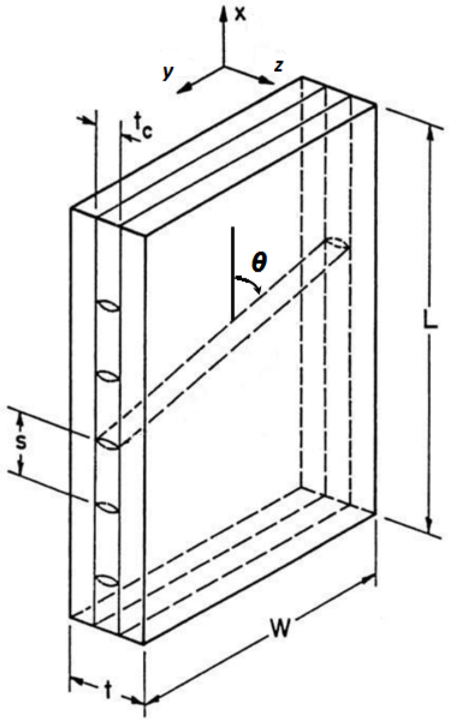
RVE of volume V

$$d_{ij} = \int_S a_i n_j \mathrm{d}S$$



$$D_{ij}^{(\alpha)} = \frac{1}{V} \sum_{k_\alpha} \left(d_{ij} \right)_{k_\alpha}$$

where k_α is the number of damage entities in the α^{th} mode



$$a_i = a n_i + b m_i \qquad n_i m_i = 0$$

a: crack opening displacement

b: crack sliding displacement

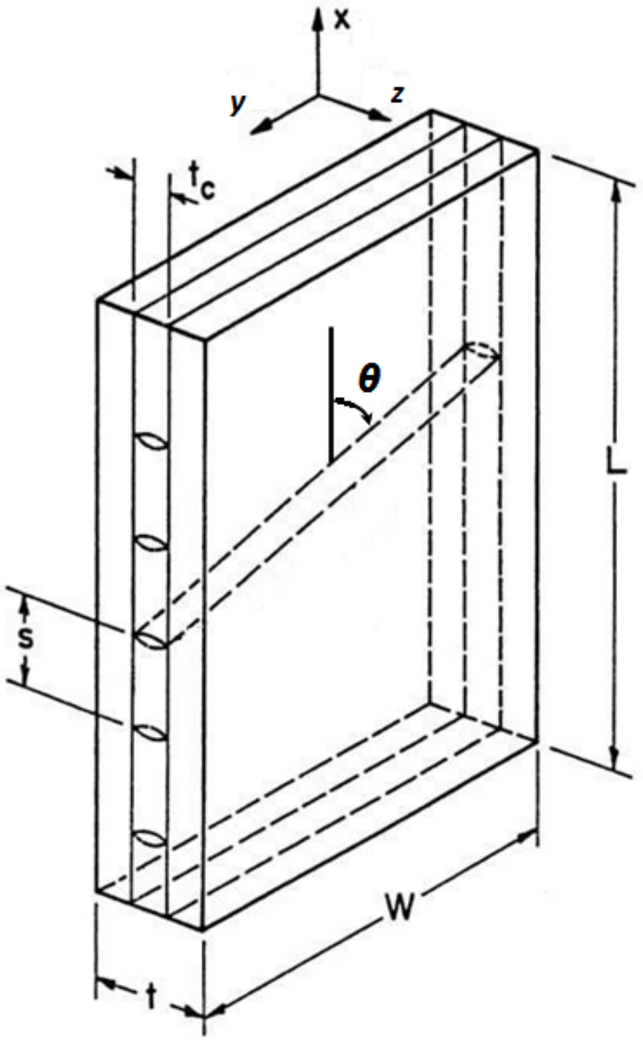
$$d_{ij} = d_{ij}^1 + d_{ij}^2 \qquad d_{ij}^1 = \int_S a n_i n_j \mathrm{d}S, \qquad d_{ij}^2 = \int_S b m_i n_j \mathrm{d}S$$

$$D_{ij}^{(\alpha)} = D_{ij}^{1(\alpha)} + D_{ij}^{2(\alpha)} \qquad D_{ij}^{1(\alpha)} = \frac{1}{V} \sum_{k_\alpha} \left(d_{ij}^1 \right)_{k_\alpha}, \quad D_{ij}^{2(\alpha)} = \frac{1}{V} \sum_{k_\alpha} \left(d_{ij}^2 \right)_{k_\alpha}.$$

Assume *b* = 0 →

$$D_{ij}^{(\alpha)} = D_{ij}^{1(\alpha)} = \frac{1}{V} \sum_{k_\alpha} \left[\int_S a n_i n_j \mathrm{d}S \right]_{k_\alpha}.$$

Damage Tensor Components (One Damage Mode)



$$D_{ij}^{(\alpha)} = D_{ij}^{1(\alpha)} = \frac{1}{V}\sum_{k_\alpha}\left[\int_S a n_i n_j \, \mathrm{d}S\right]_{k_\alpha} .$$

$$V = L.W.t$$

$$S = \frac{W.t_c}{\sin\theta}$$

$$a = \kappa t_c$$

$$n_i = (\sin\theta, \quad \cos\theta, \quad 0)$$

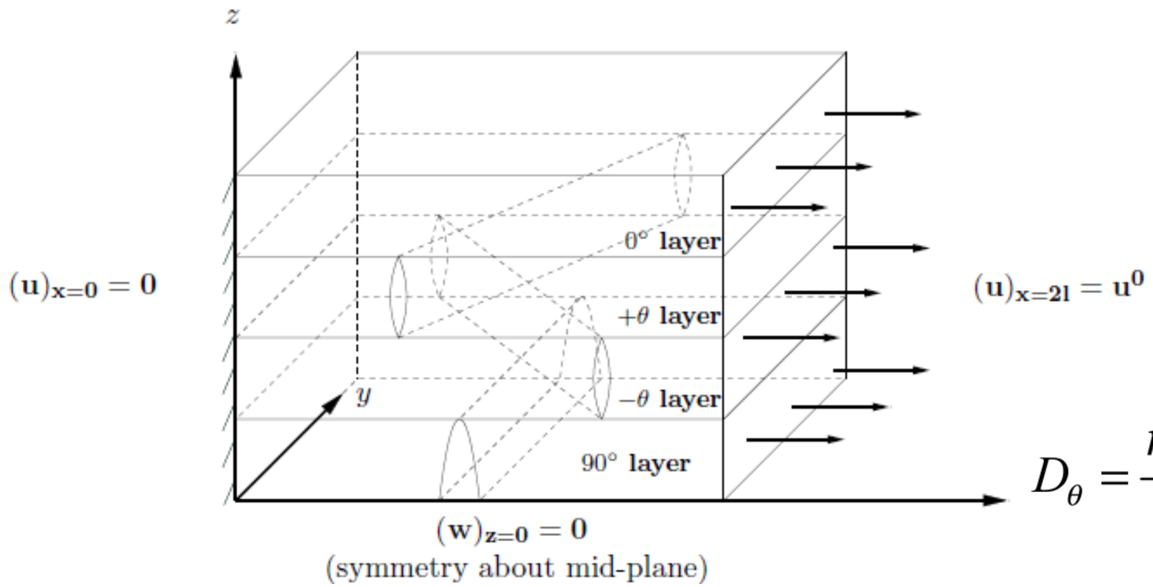
$$D_{ij}^{(\alpha)} = \frac{\kappa t_c^2}{st\sin\theta} n_i n_j$$

$$\alpha = 1$$

(one damage mode)

κ (kappa): Constraint parameter

Three Damage Modes: Cracking in θ, -θ, and 90° Plies



$$D_1^{(3)} = \frac{\kappa_{90} t_{90}^2}{s^{90} t}, \quad D_2^{(3)} = D_6^{(3)} = 0 .$$

$$\mathbf{C_{pq}} = \mathbf{C_{pq}^0} + \mathbf{C_{pq}^{(1)}} + \mathbf{C_{pq}^{(2)}} + \mathbf{C_{pq}^{(3)}}$$

$$D_\theta = \frac{\kappa_\theta (2nt_0)^2}{s_n^\theta t}; \qquad D_{90} = \frac{\kappa_{90} (2rt_0)^2}{s^{90} t}$$

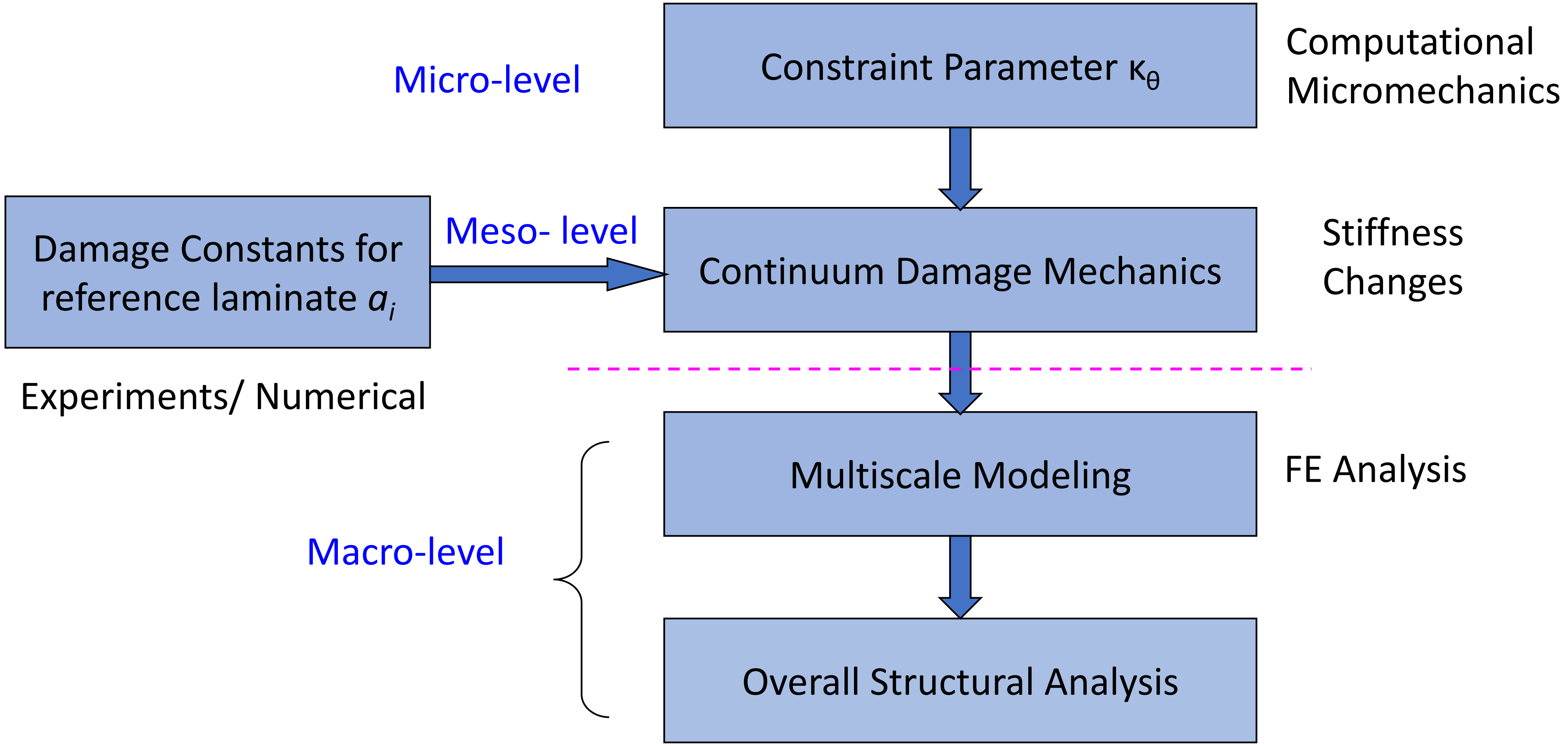
$[0_m/\pm\theta_n/90_r]_s$ laminate

$$\kappa_\theta = \frac{\left(\overline{\Delta u_y}\right)_{\pm\theta_{2n}}}{2nt_0}; \qquad \kappa_{90_{4n+2r}} = \frac{\left(\overline{\Delta u_y}\right)_{90_{4n+2r}}}{(4n+2r)t_0}; \qquad \kappa_{90} = \frac{\left(\overline{\Delta u_y}\right)_{90_{2r}}}{2rt_0} .$$

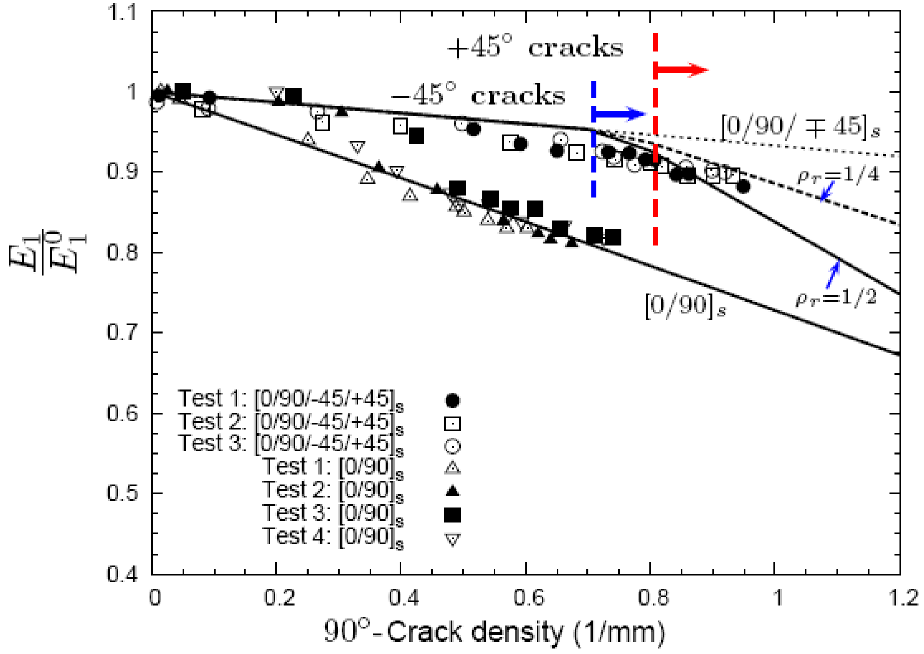
$$\Delta\mathbf{C_{pq}} = 2D_\theta \begin{bmatrix} 2a_1 & a_4 & 0 \\ & 2a_2 & 0 \\ Symm & & 2a_3 \end{bmatrix} + D_{90} \begin{bmatrix} 2a_1' & a_4' & 0 \\ & 2a_2' & 0 \\ Symm & & 2a_3' \end{bmatrix}$$

Singh and Talreja, 2013

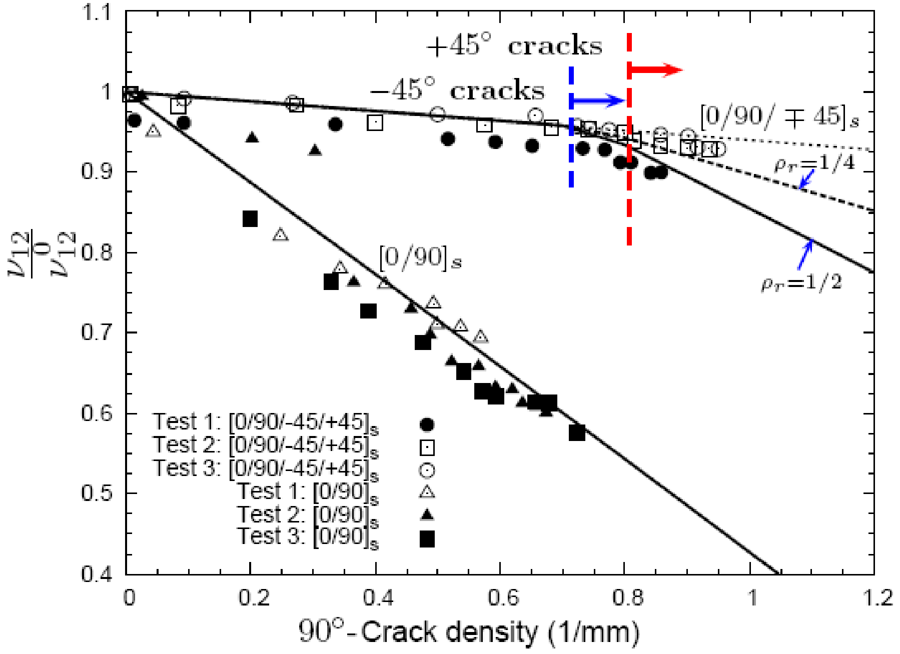
Multiscale Synergistic Damage Mechanics (SDM)



Results: quasi-isotropic laminate



Longitudinal Modulus



Poisson's Ratio

Steps

1. Fit the damage model with experimental data for crossply laminate

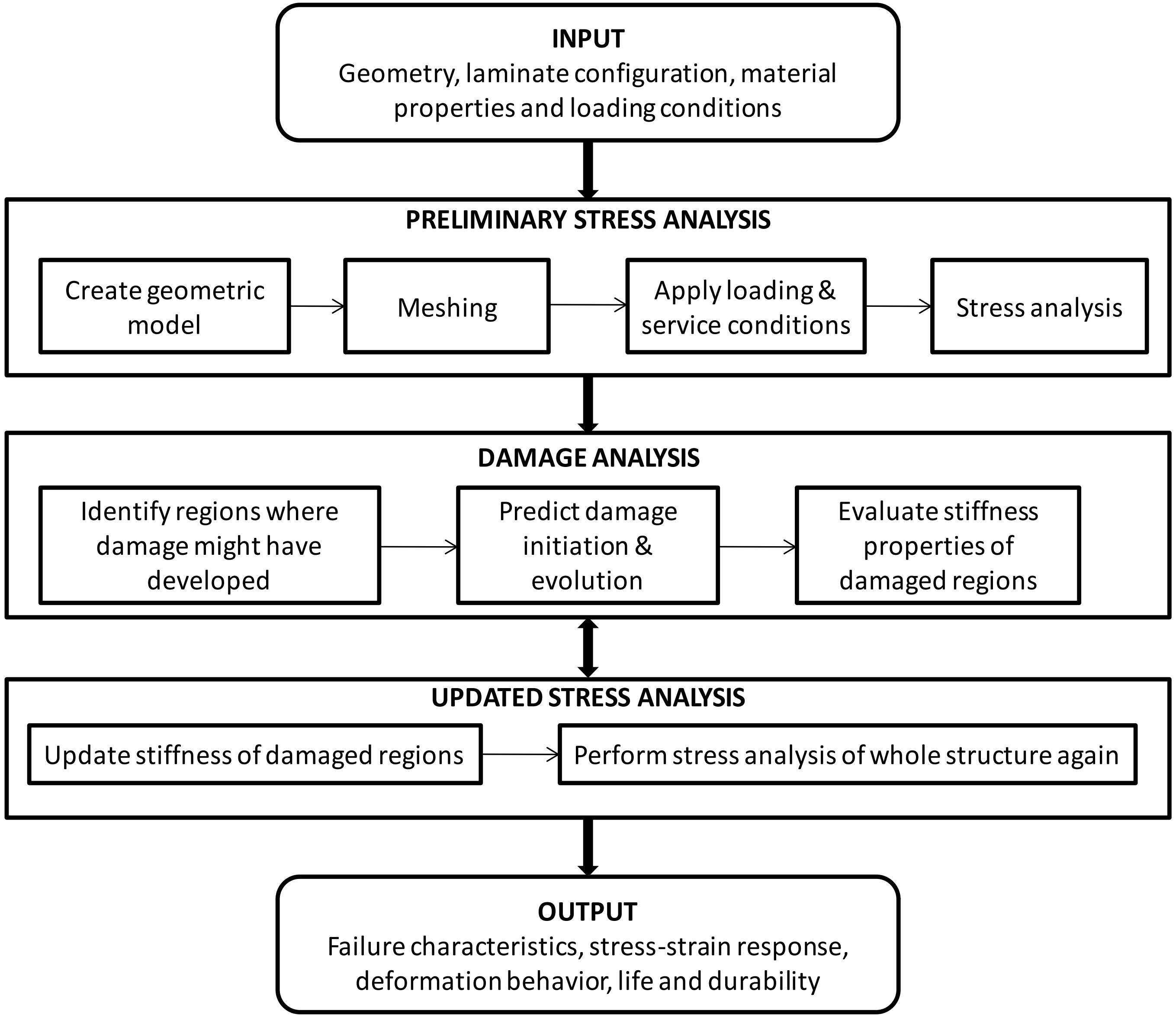
➔Gives us phenomenological constants a_i

2. Compute constraint parameters by calculating CODs from FEM

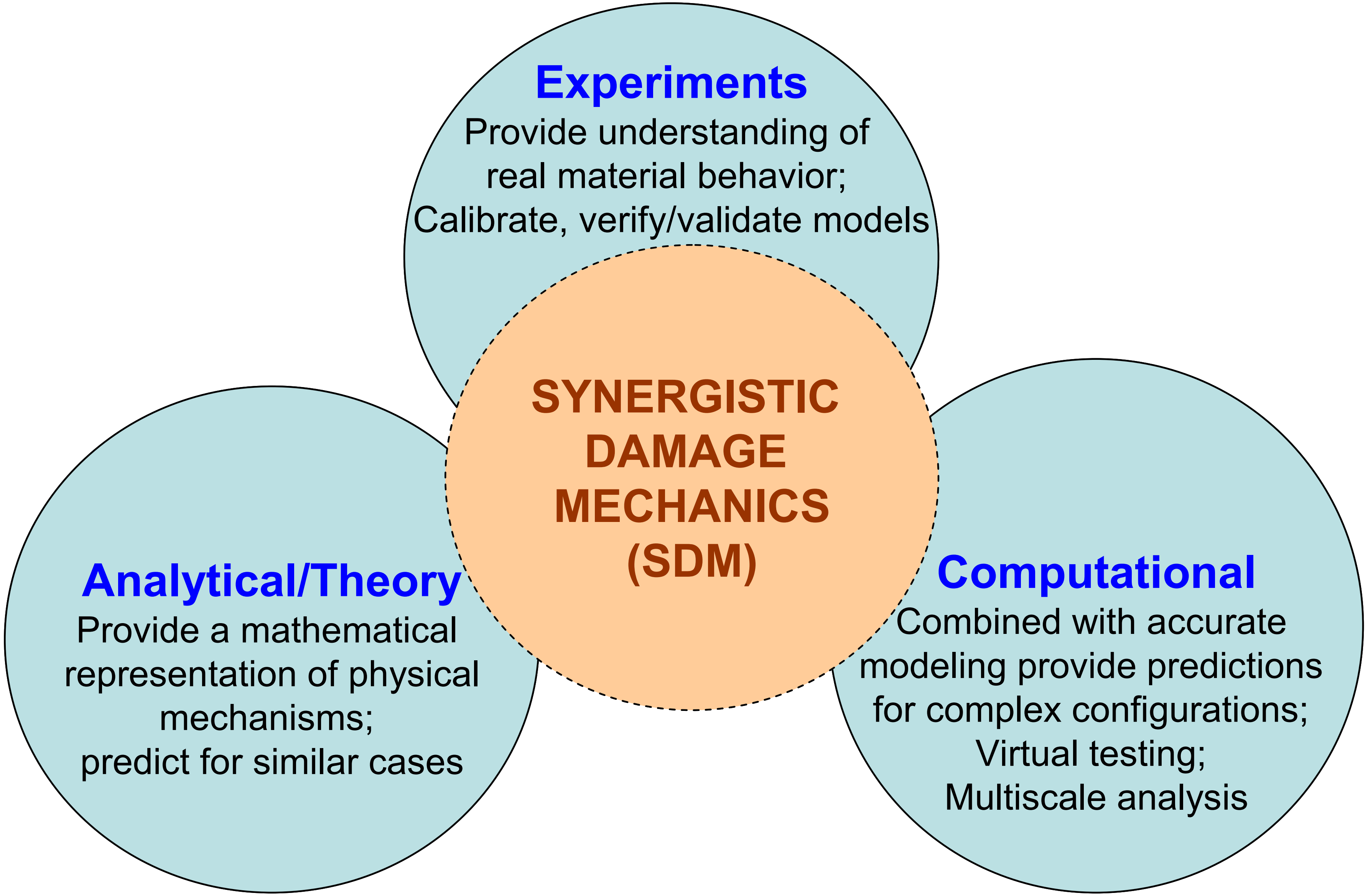
3. Employ the model for quasi-isotropic laminate.

Refs. Singh & Talreja, Mech Mat (2009) ; Singh & Talreja, Int J Solids Struct (2008)

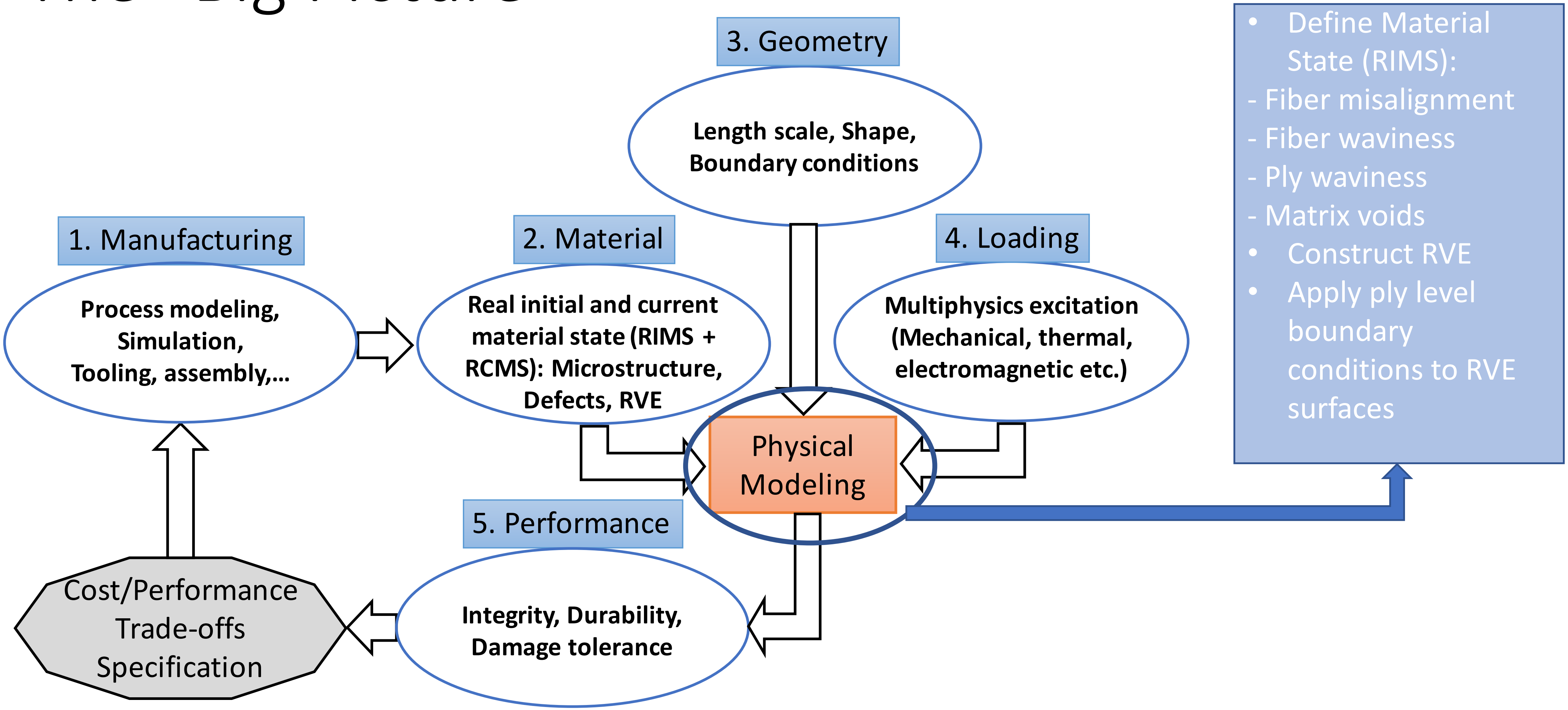
Computational structural analysis



SDM methodology



The "Big Picture"



Defect Damage Mechanics

Idealized models:

Heterogeneities, no defects

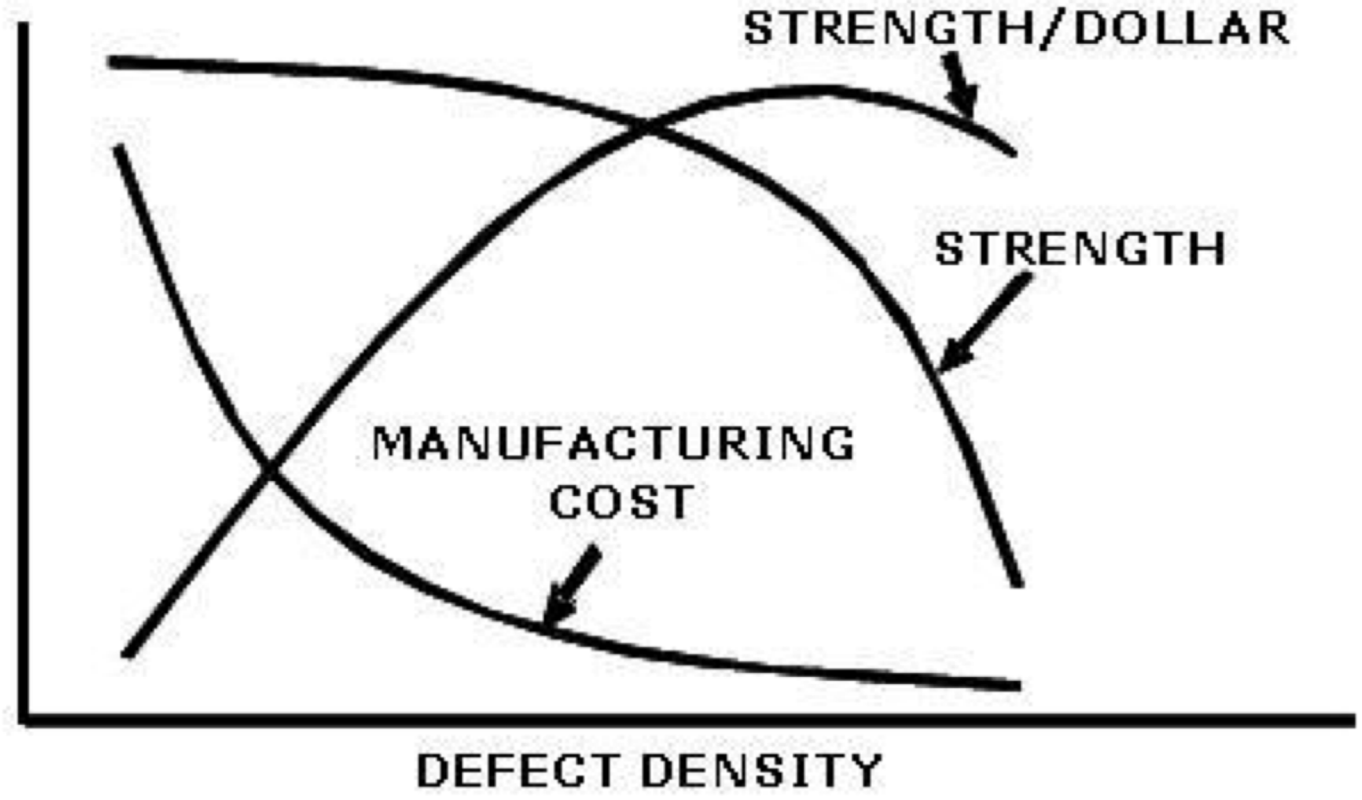
- Fiber volume fraction
- Fiber Distribution
  - Length
  - Orientation

Real composites:

Defects

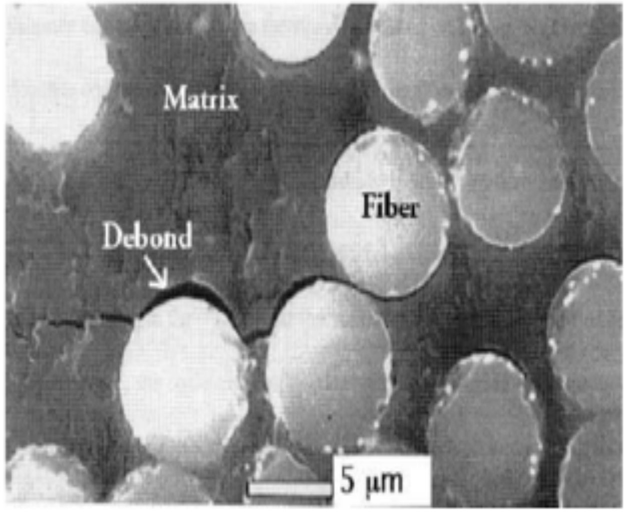
- Fiber Defects
  - Misalignment, waviness
  - Breakage
- Matrix Defects
  - Incomplete curing
  - Voids
- Interface Defects
  - Fiber/matrix disbonds
  - Delamination

Cost-performance trade-off

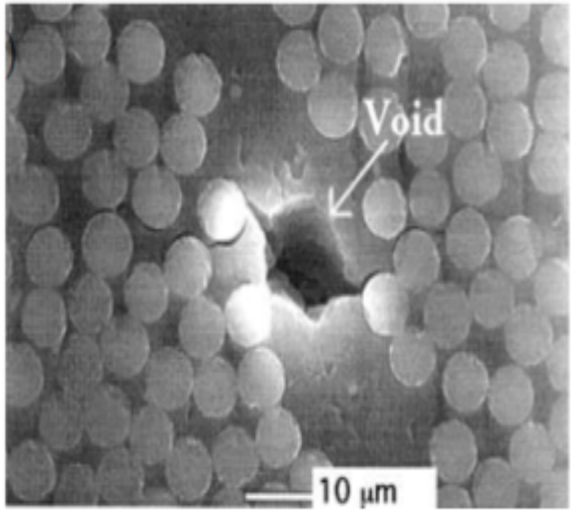


Manufacturing Defects: Nonuniform Fiber Distribution and Matrix Voids

(a

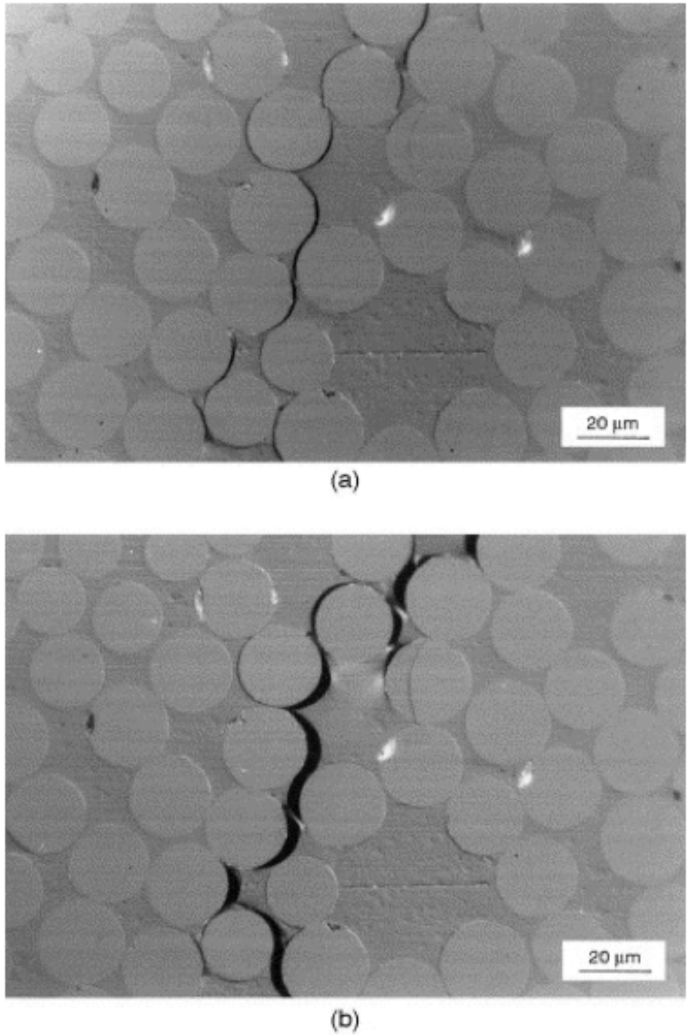


(b



Cracks initiating from weak planes

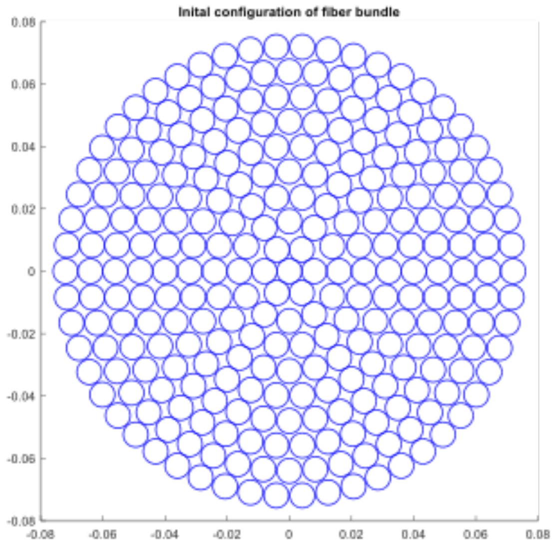
Cracks initiating from voids

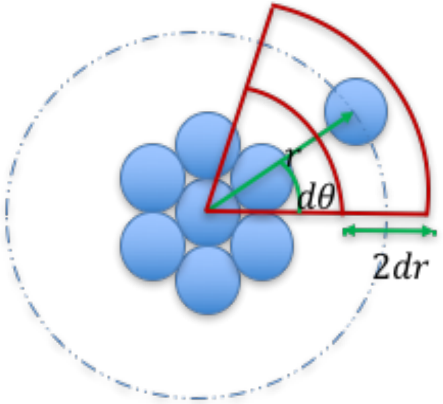


Debond link-up to transverse cracking

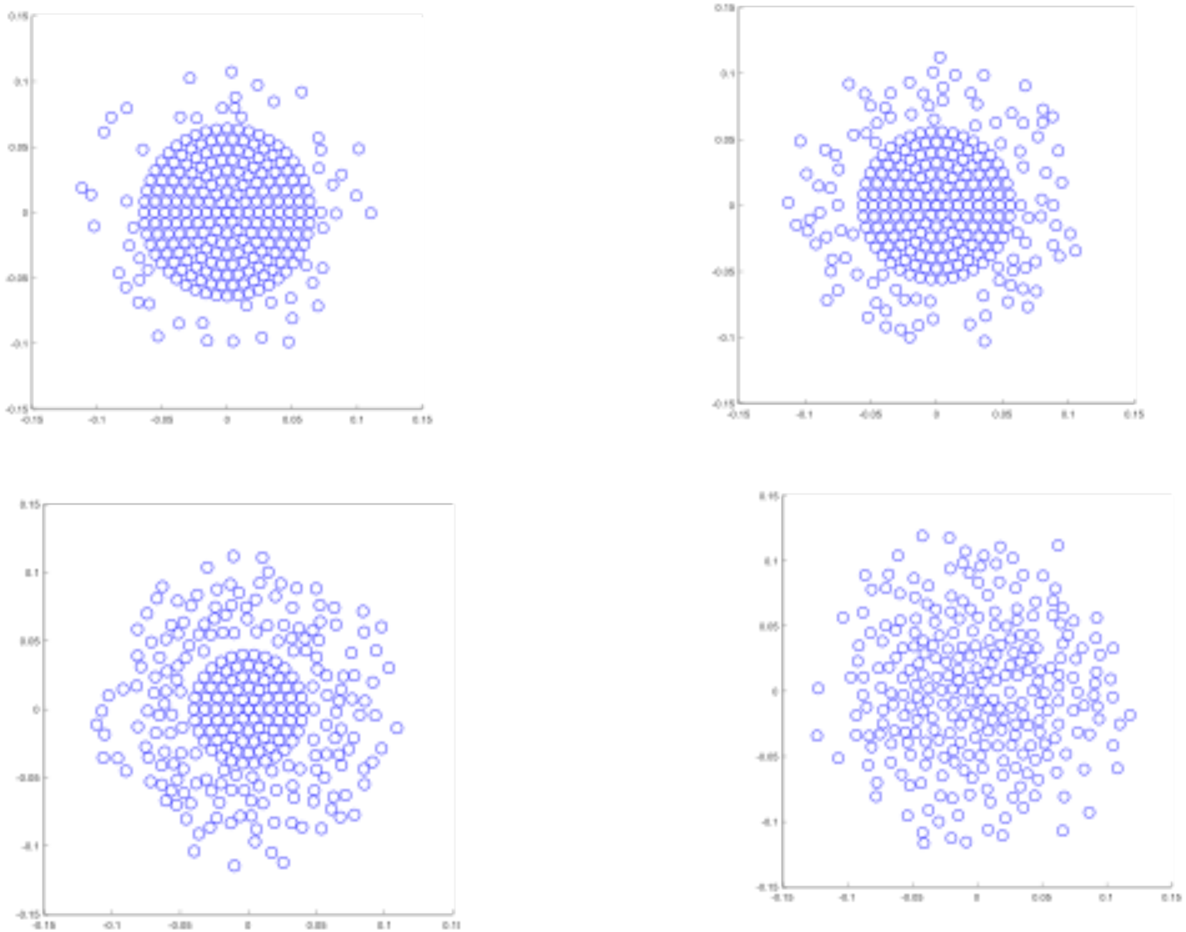
Simulation of manufacturing induced fiber distribution nonuniformity

Approach 1: Quantification of fiber mobility (radial and angular)





Resin infusion

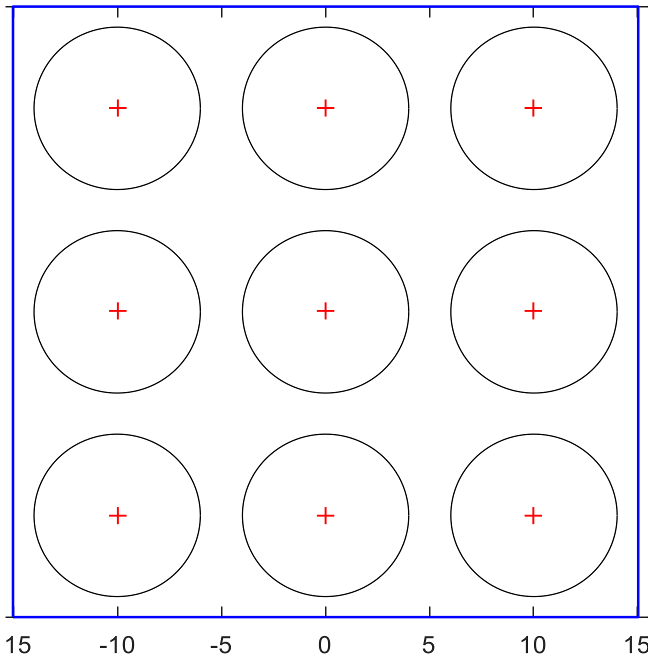


Dry fiber bundle

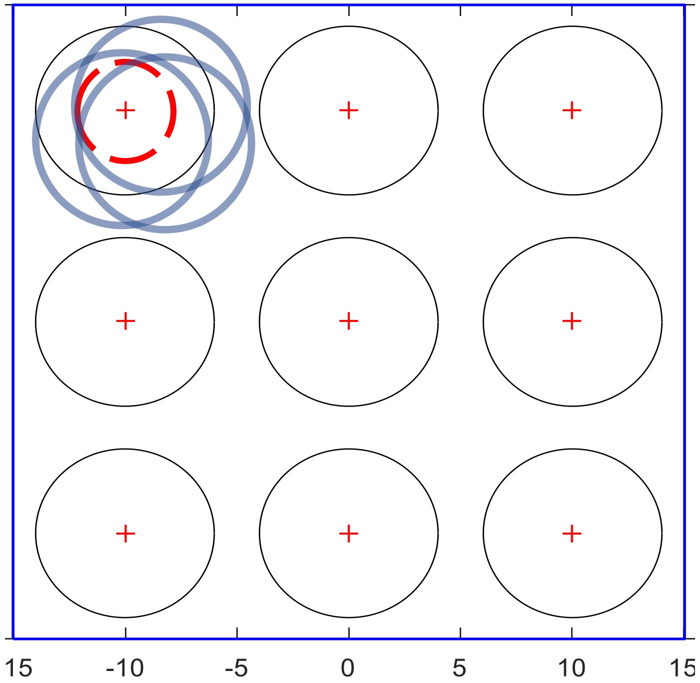
Sudhir and Talreja, ASC, 2017

Simulation of manufacturing induced fiber distribution nonuniformity

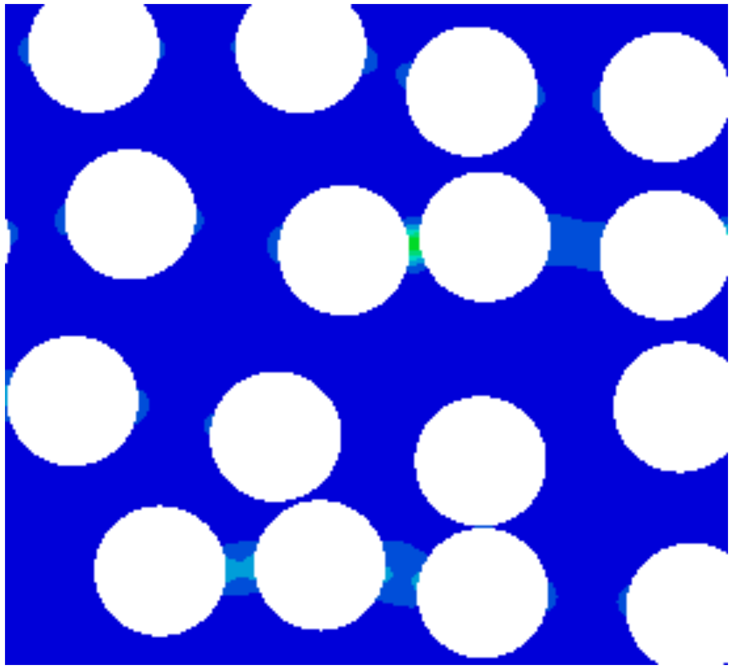
Approach 2: Quantification of degree of nonuniformity



Initial uniform pattern



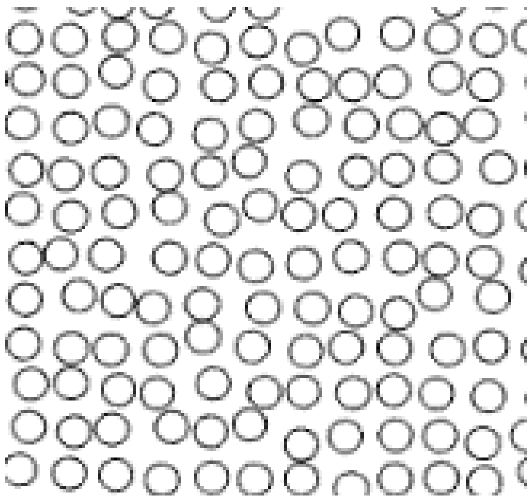
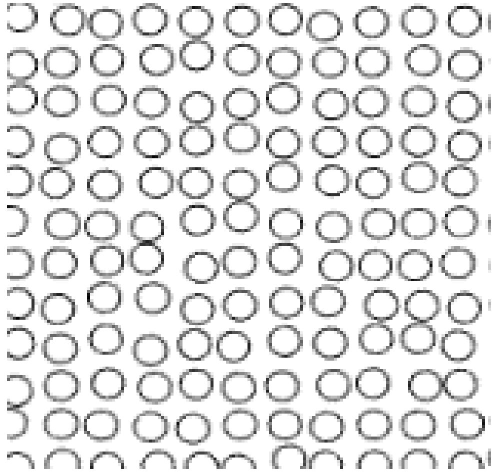
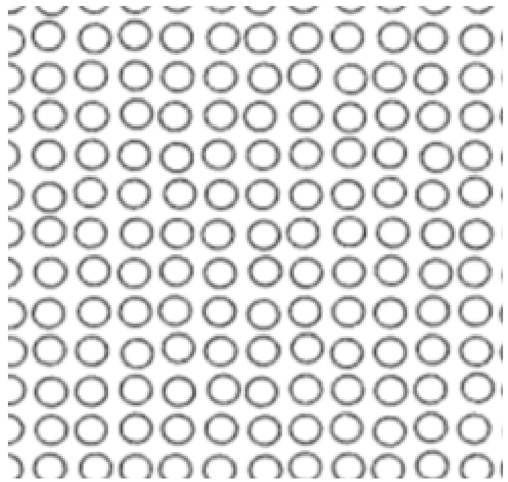
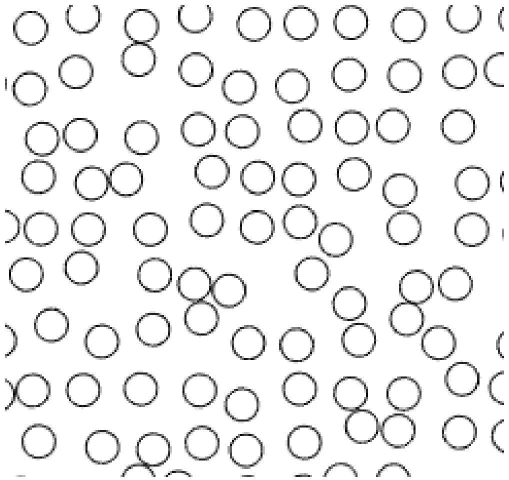
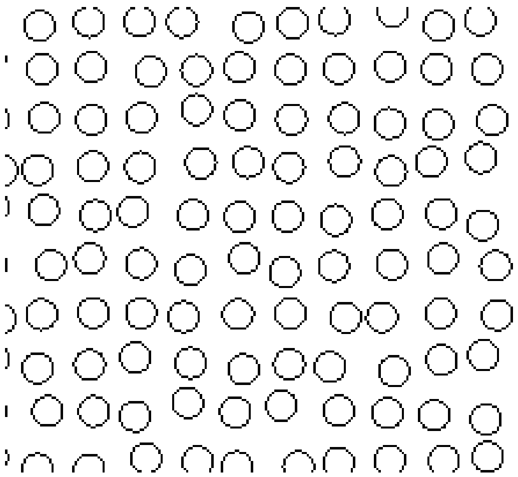
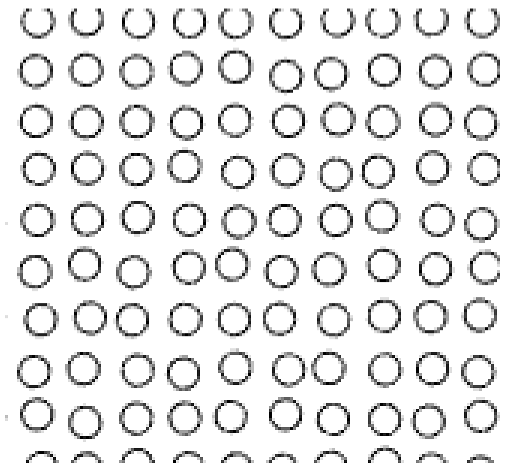
Intermediate steps to "shake" fibers



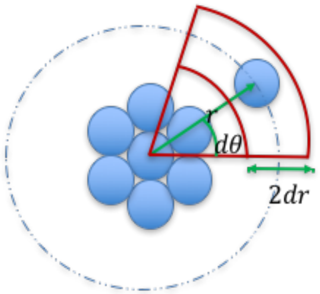
Final nonuniform pattern

Elnekhaily and Talreja, CST, 2018

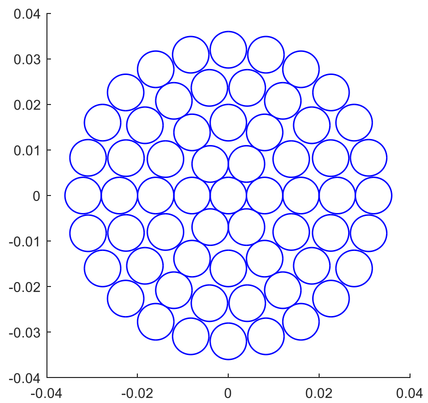
RVE realizations for different degrees of nonuniformity

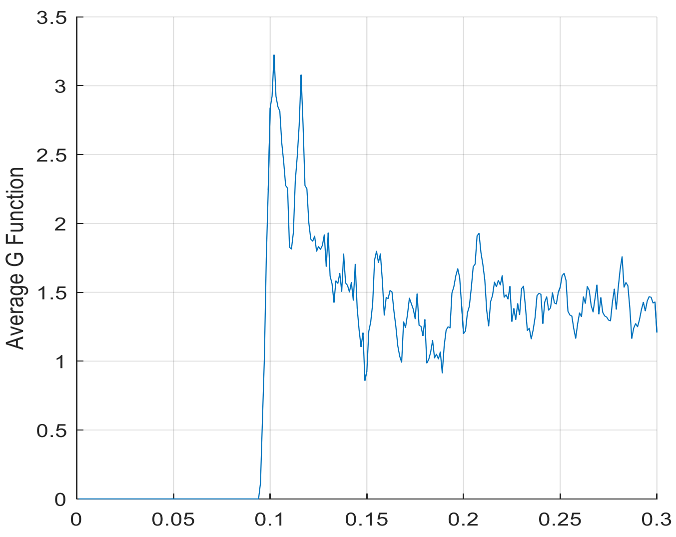
	100% Nonuniformity	60% Nonuniformity	30% Nonuniformity
(a) 40% fiber volume fraction			
(b) 30% fiber volume fraction			

Minimum RVE size
Approach 1: Pair distribution function G(r)

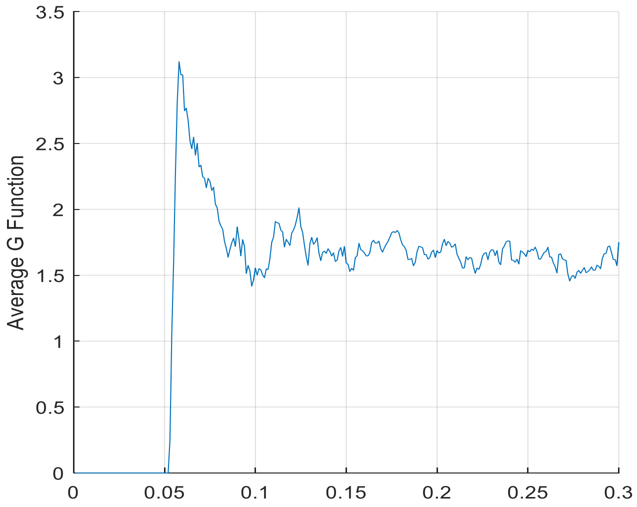


$$dr = \pm 0.25r$$
$$d\theta = \pm 15°$$





NOR=5



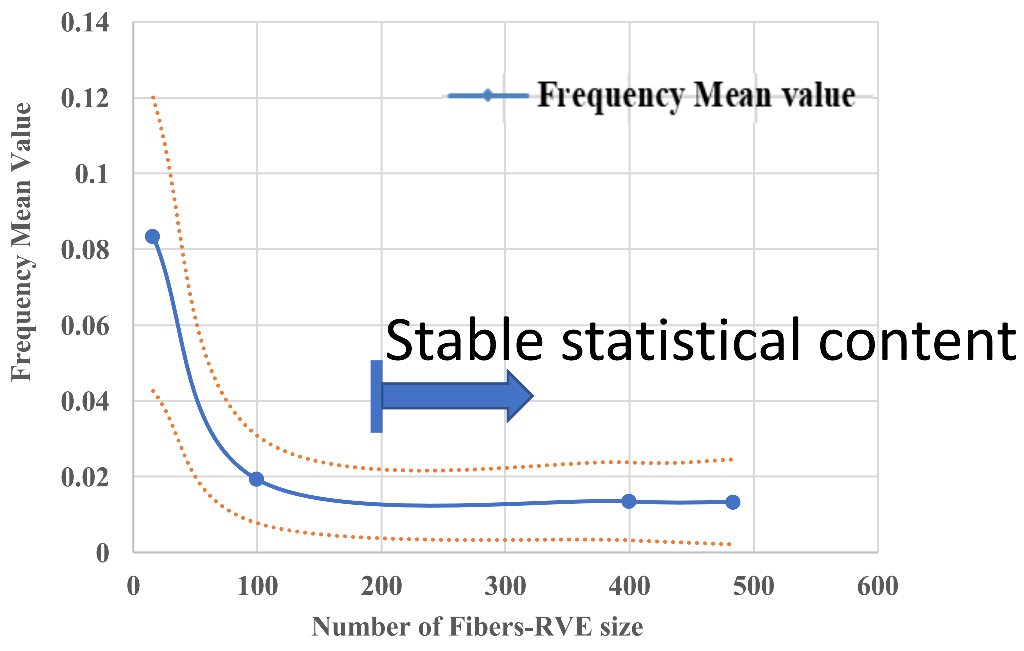
NOR=9

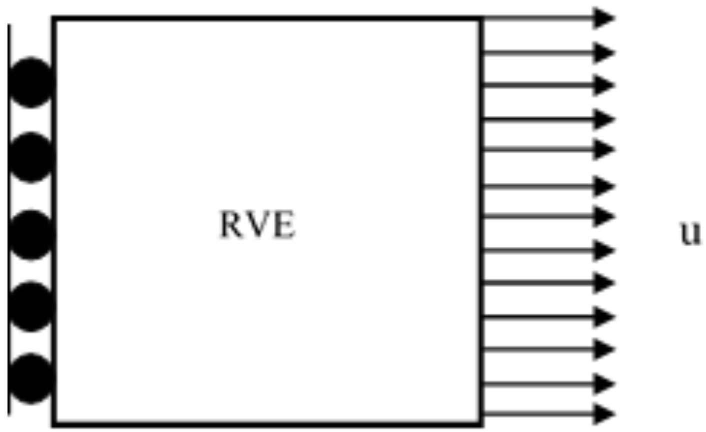
NOR: Number of Rings around the central fiber

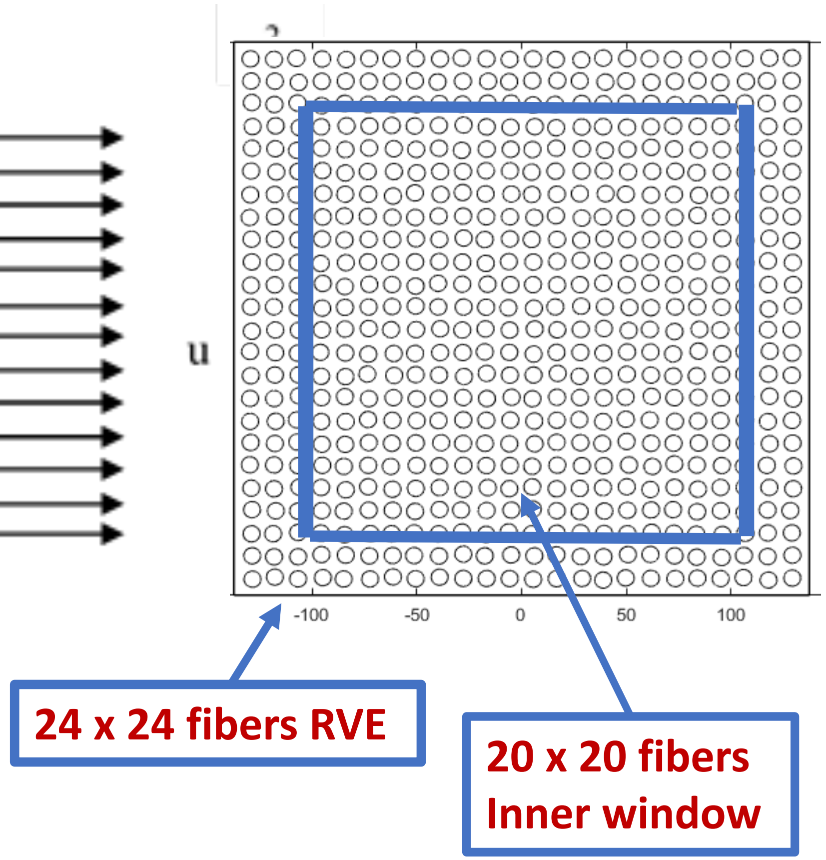
As NOR ≥ 9 the avg G function stabilizes ➔ the min size of RVEis NOR=9

Minimum RVE size

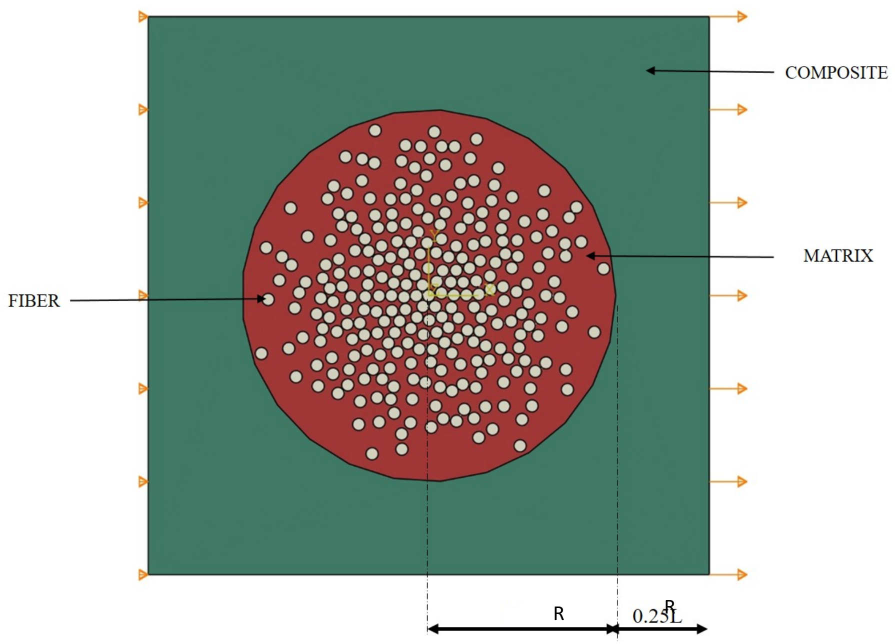
Approach 2: Stabilization of nearest neighbor statistics

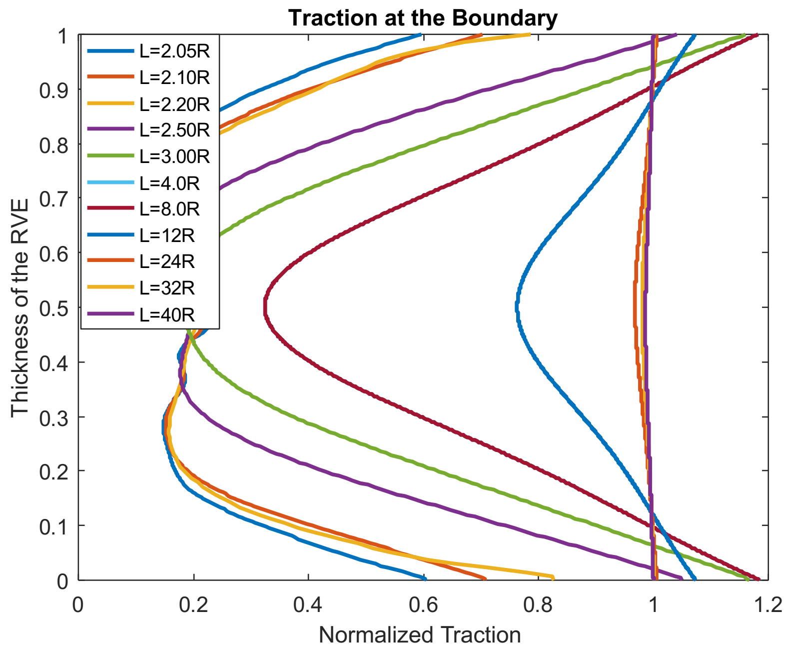






Stress analysis for Approach 1: Embedded cell method





$\Delta T = -82°\text{C}$,
Uniform boundary displacement

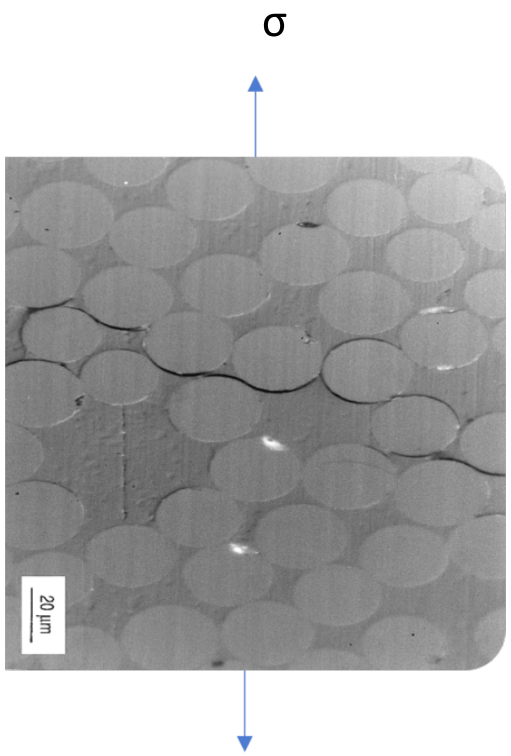
Size of the embedding composite determined by Hill's criterion: Uniform boundary traction

Failure analysis:
Multi level energy hierarchy approach

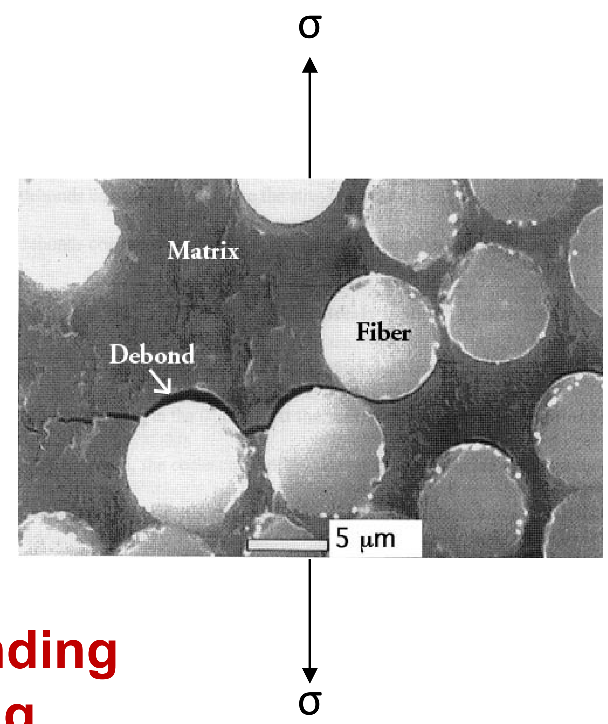
Assumptions (Statements of truths):

- The FIRST failure event occurs at the LOWEST critical energy level
- Local stress states are generally TRIAXIAL
- "Strength" criteria (max tension, max shear, "effective" stress, etc.) are not rational unless derived from energy criteria
- Progression of failure can be by a sequence of failure events or by incremental advance of already occurred failure (e.g. crack growth)

Failure under transverse tension



Gamstedt et al (1999)

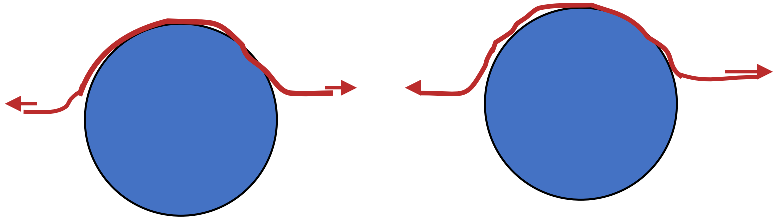


Wood & Bradley (1997)

Fiber/Matrix debonding and matrix cracking

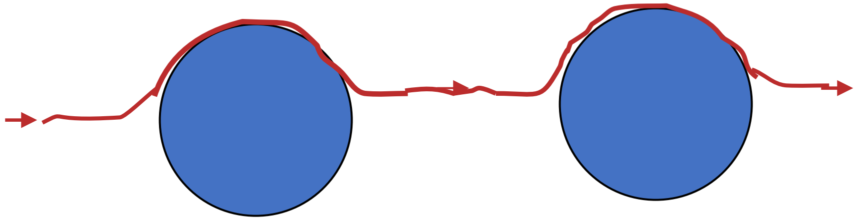
How is damage initiated under transverse tension?

Debonding induces matrix cracking

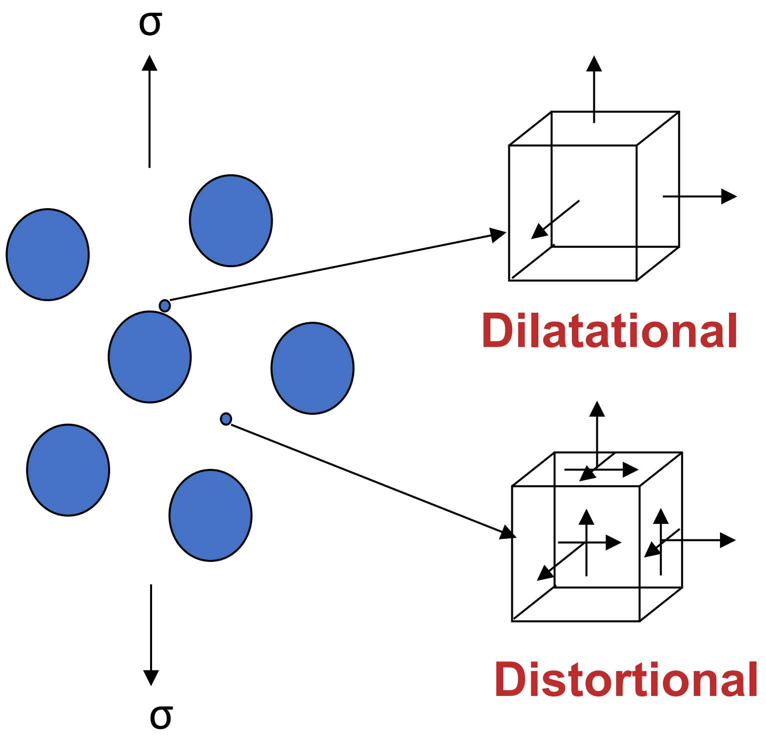


OR

Matrix cracking causes debonding



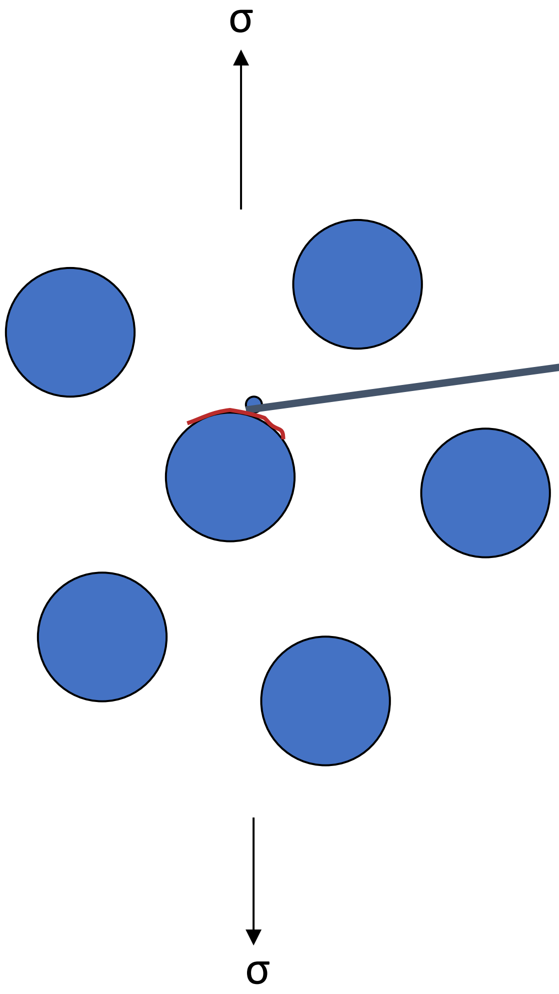
Failure under transverse tension



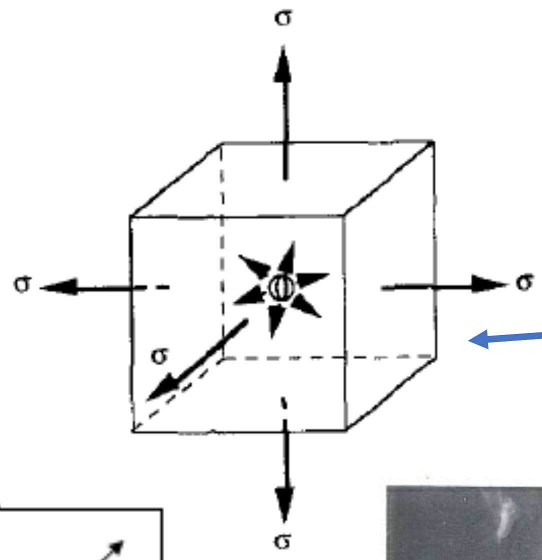
Total Stain Energy Density

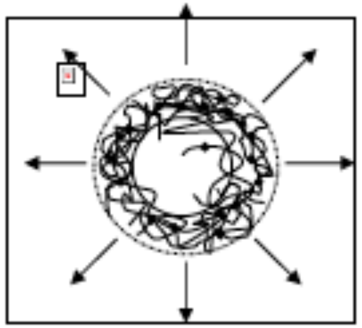
Dilatational Energy Density	Distortional Energy Density
Criticality:	Criticality:
Brittle cavitation	**Yielding**
Subsequent failure:	Subsequent failure:
Fiber/matrix debonding	**Shear bands, cavitation, cracking**

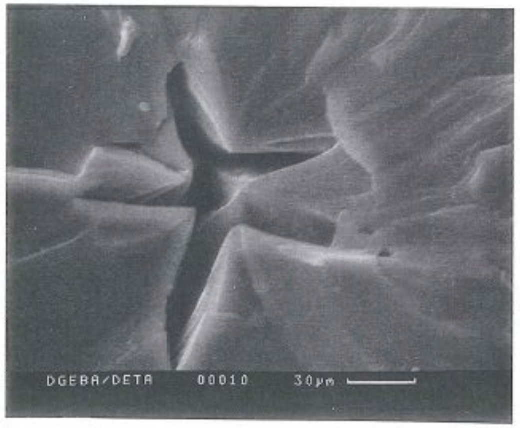
Failure analysis: Brittle cavitation

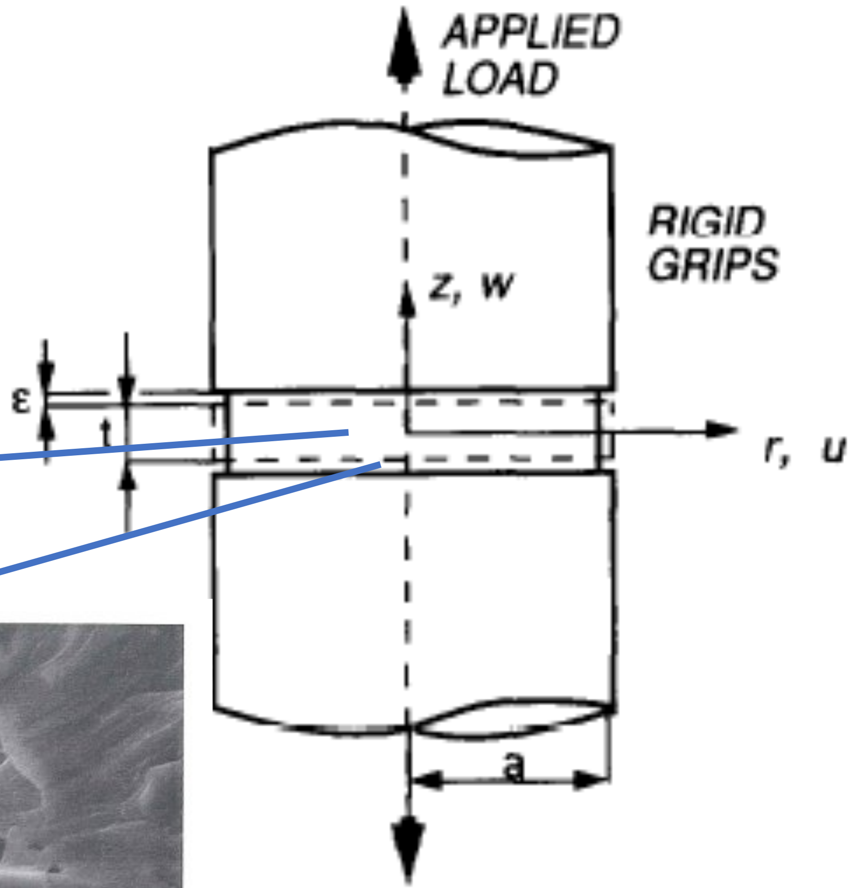


Asp, Berglund, Talreja (1996)









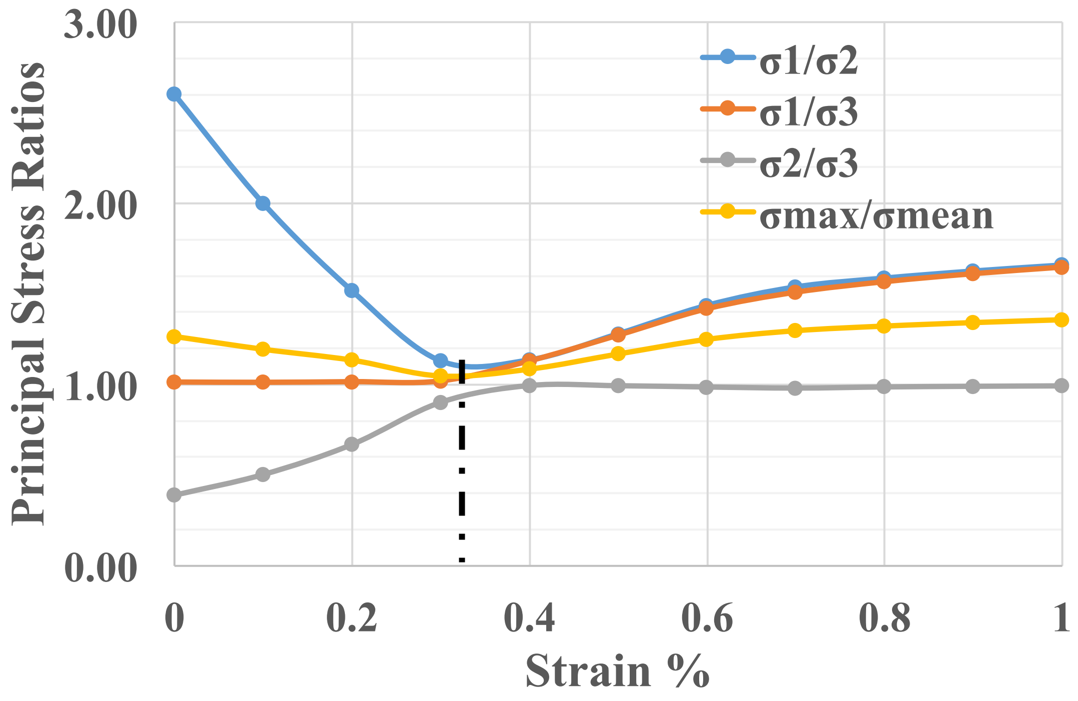
poker-chip test

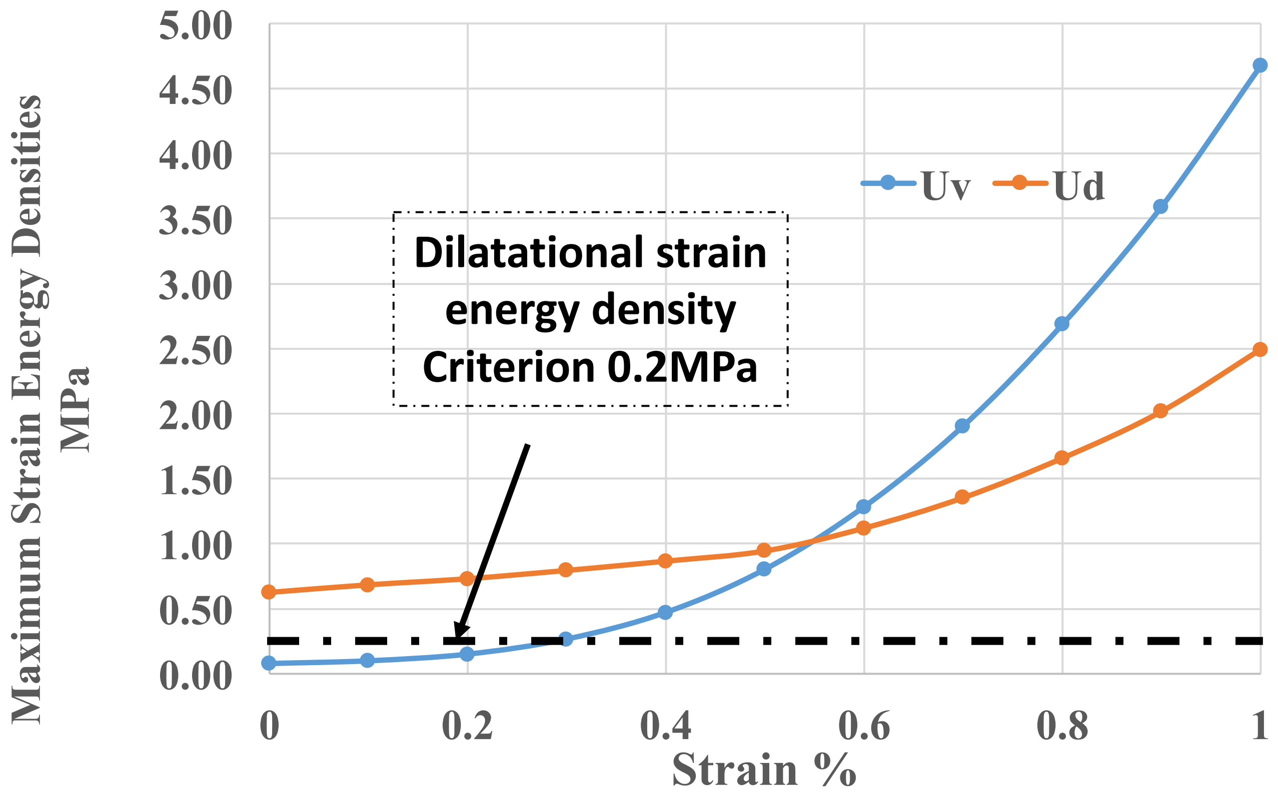
$$U_v = \frac{1-2\nu}{6E}(\sigma_1+\sigma_2+\sigma_3)^2 = U_{v,crit} \approx 0.2MPa$$ for epoxies

Much lower than energy for yielding

Brittle cavitation under transverse tension

Example: 50% fiber volume fraction and 100 % degree of nonuniformity

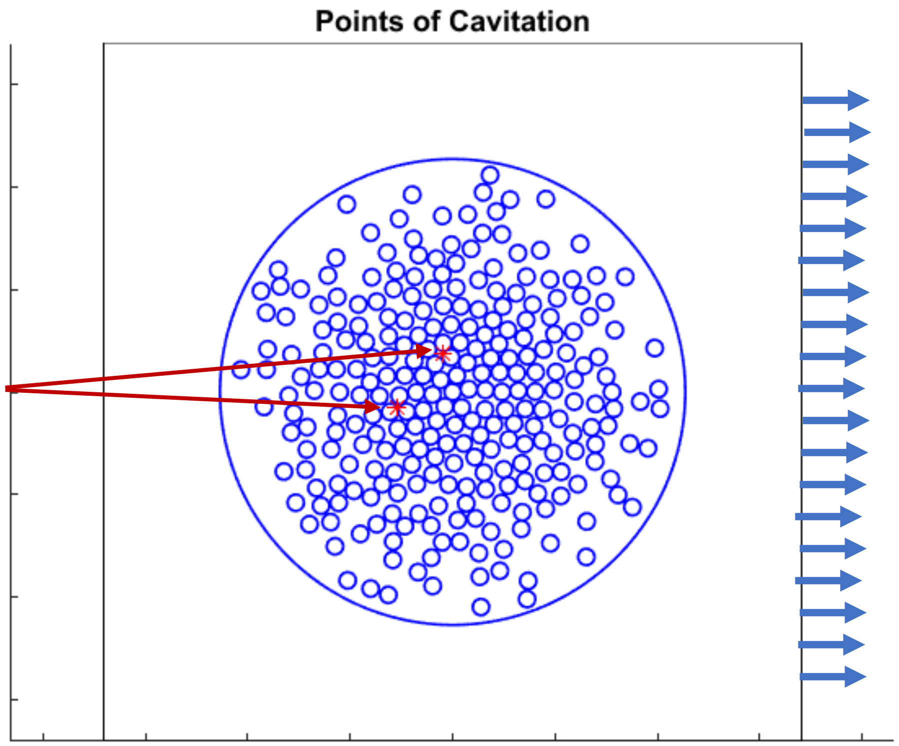




Location of Dilatation Induced Brittle Cavitation

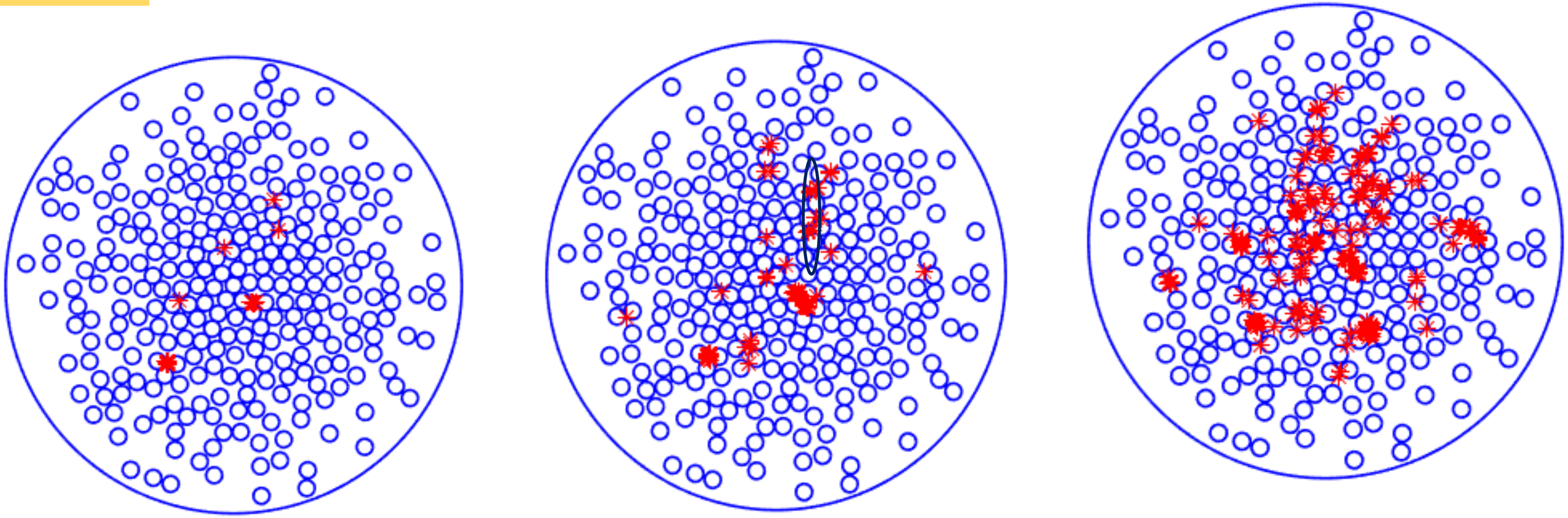
$$dr = \pm 0.25r$$
$$d\theta = \pm 15°$$

Point of damage initiation (cavitation) by dilatational energy density criteria



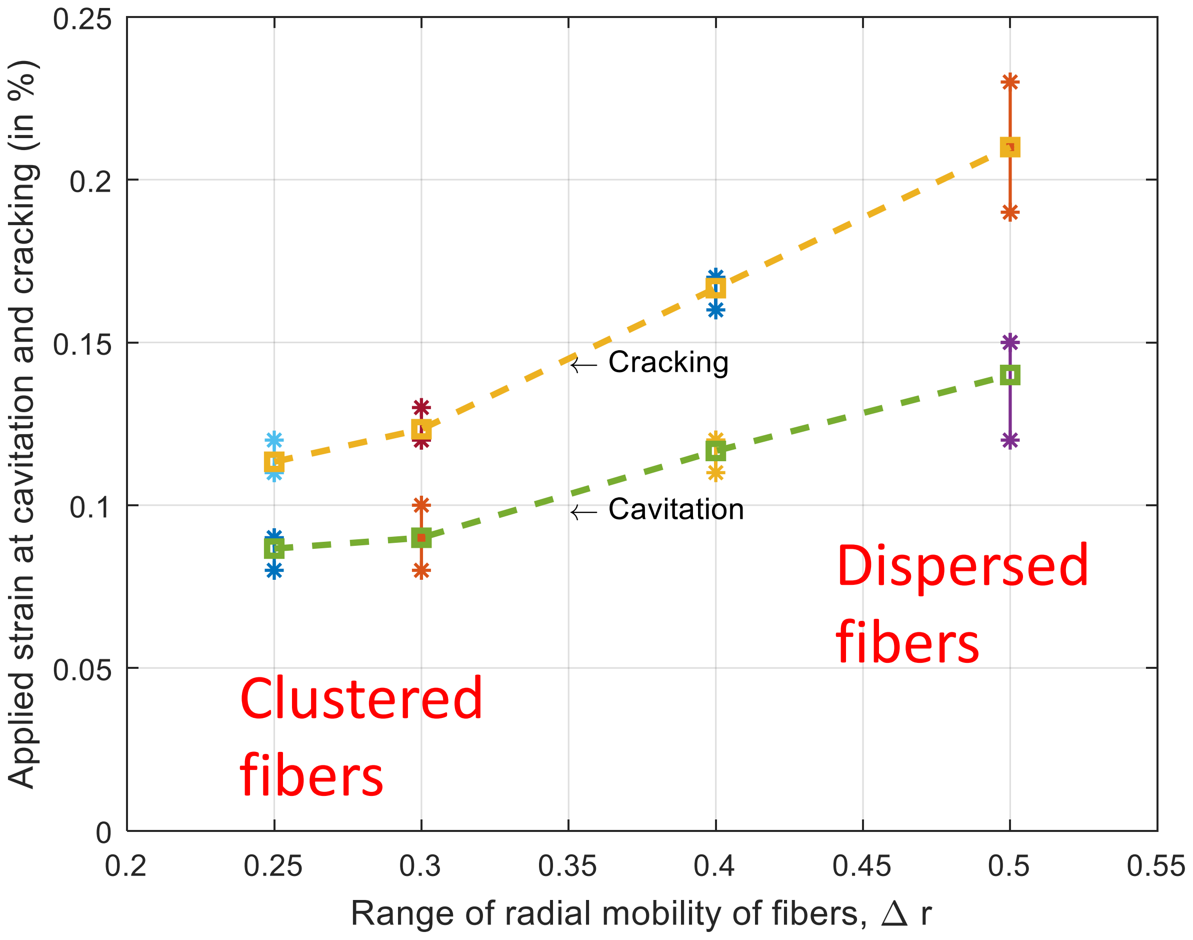
Crack Formation by Debond Coalescence

$$dr = \pm 0.25r$$
$$d\theta = \pm 15°$$



Increasing load

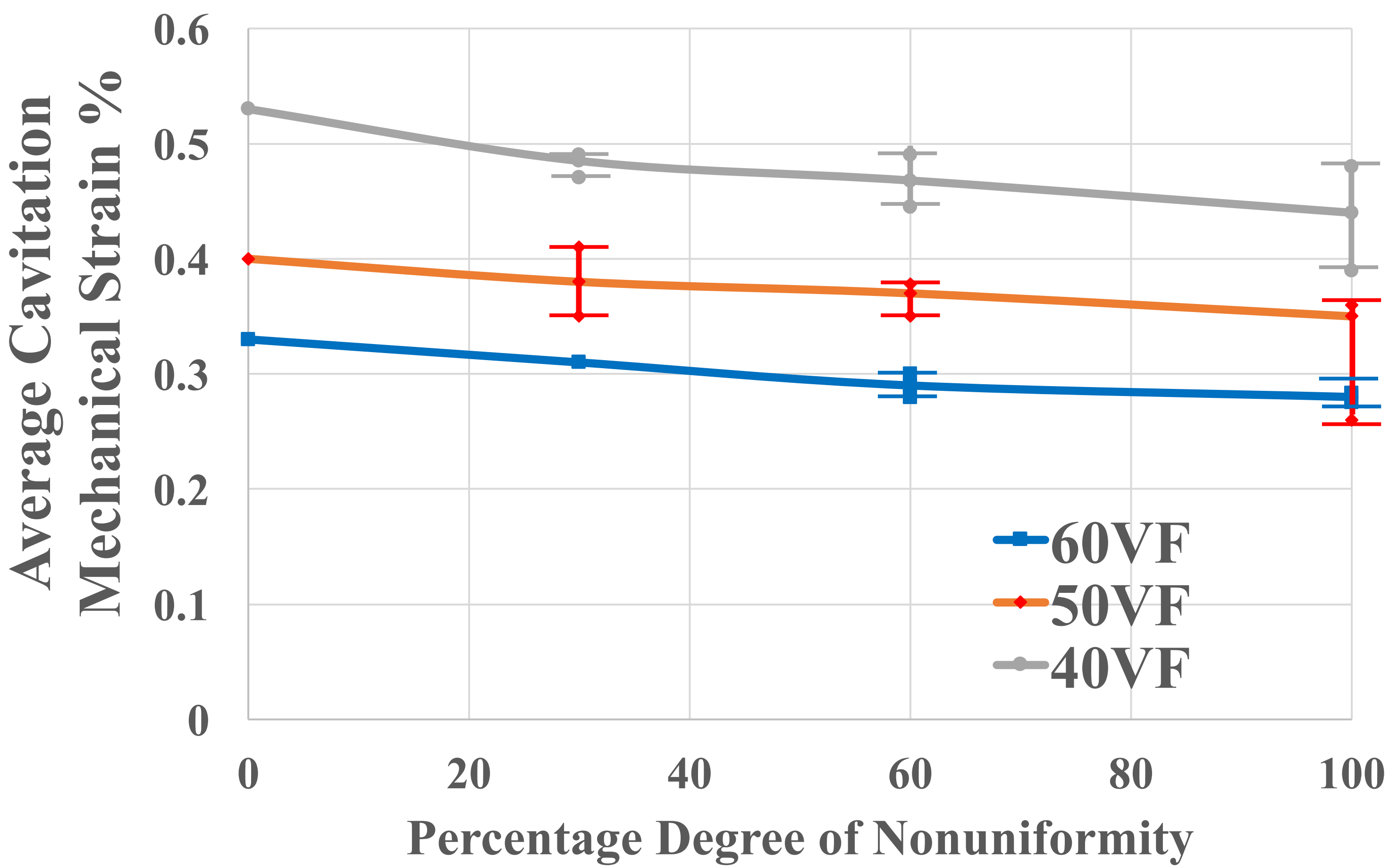
Applied strain to transverse cracking



Note: These results cannot be obtained by homogenizing composites, or by considering uniform fiber distributions

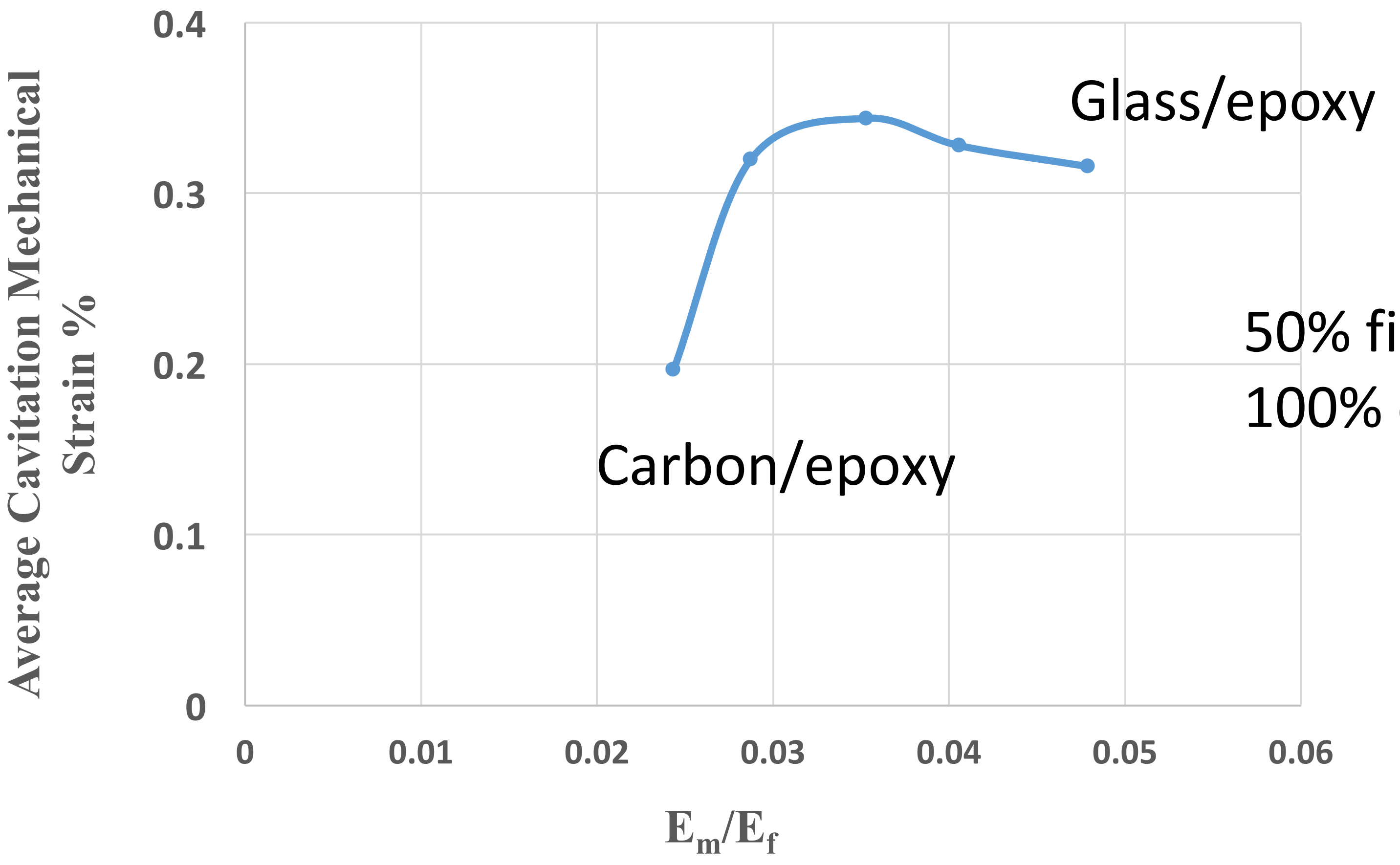
Sudhir and Talreja, ASC, 2018

Transverse strain to initiation of debonding



Effect of fiber volume fraction and degree of nonuniformity

Debond initiation depends on fiber stiffness



50% fiber volume fraction
100% degree of nonuniformity

Elnekhaily & Talreja, CST, 2017

Summarizing remarks

- Manufacturing defects cannot be fully eliminated without making composite structures prohibitively expensive
- Stress and failure analysis of early failure events must include defects
- Defect severity depends on the failure mode, e.g., for transverse crack formation, it is the degree of nonuniformity of fiber distribution (degree of fiber clusters)

Other examples:

- Fiber misalignment for axial compression failure
- Voids for matrix crack initiation
- Fiber surface defects for axial tension failure