Process Models for Fibrous Composite Materials

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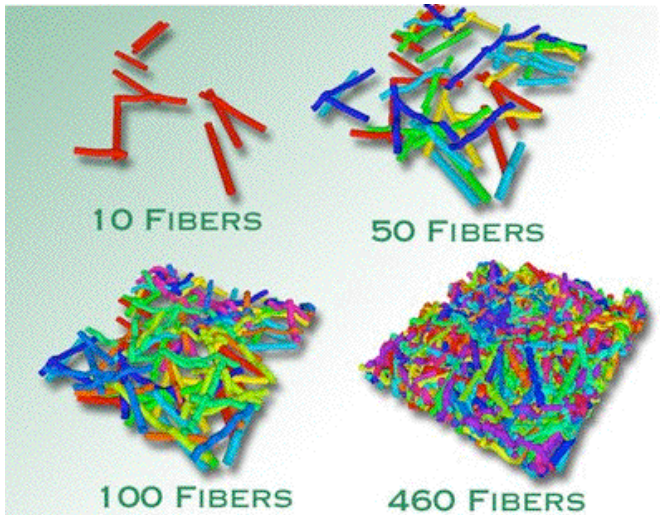
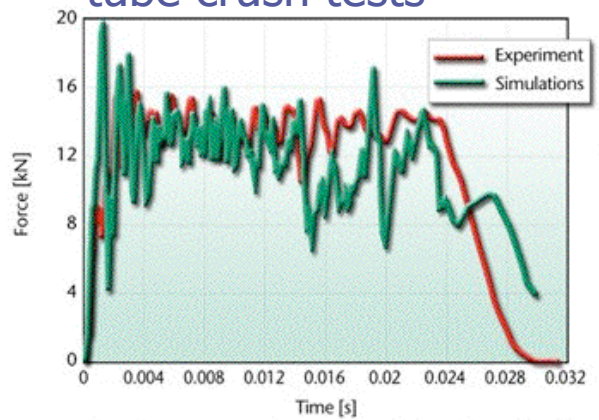
Material Models for Composites



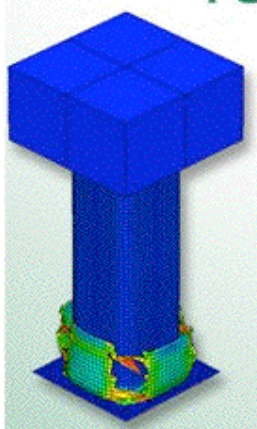
- Constitutive model for random fiber composite has been developed and implemented into FEM crash codes
- The model has been verified against tube crush tests



Impact Force Comparison with Experiments

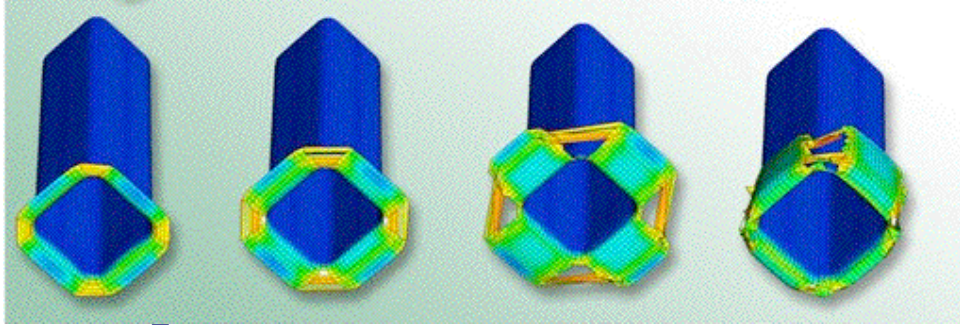
Area under the curves is proportional to dissipated crash energy

Tube Crush Simulation



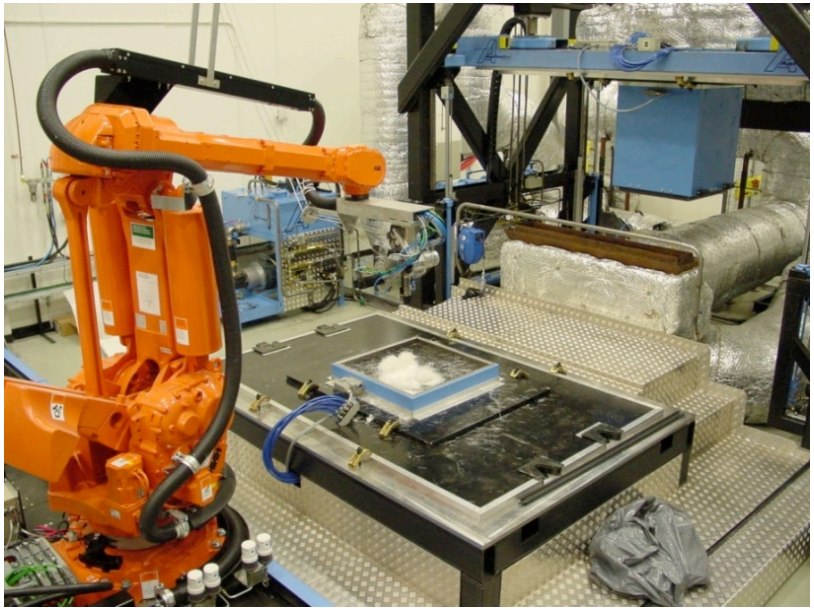
Simulation of progressive crush of a random fiber composite tube in drop tower experiment.

Below are images of tube crush for increasing time.

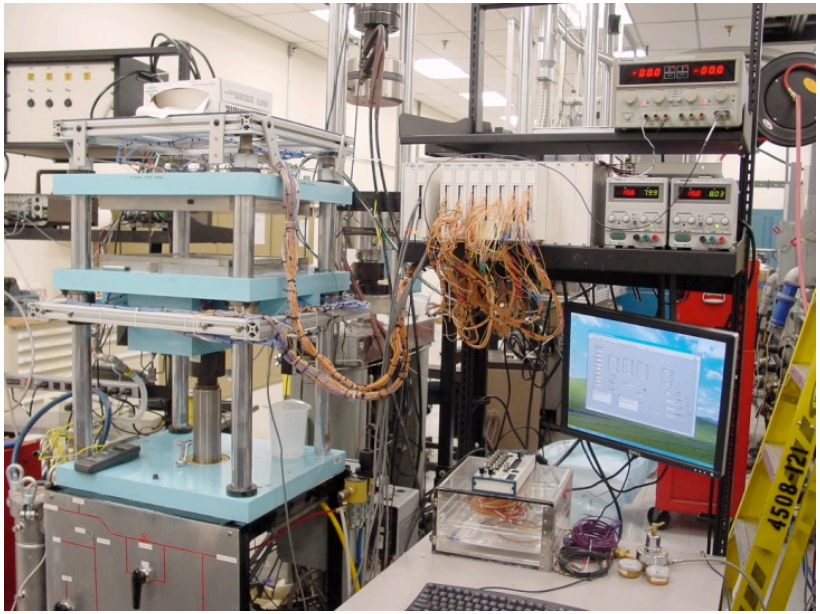


- Composite material models are used for design of vehicle prototypes

Composite Preforming



Robot preforming



Permeability testing

- Objective was to develop process models for new composite manufacturing processes and preforming
- Process model can then be used to determine feasible forms and process parameters
  - Fiber types, orientation distributions, nozzle traversal, layering, resin infusion, etc.
- Linking manufacturing to performance

Open Problems

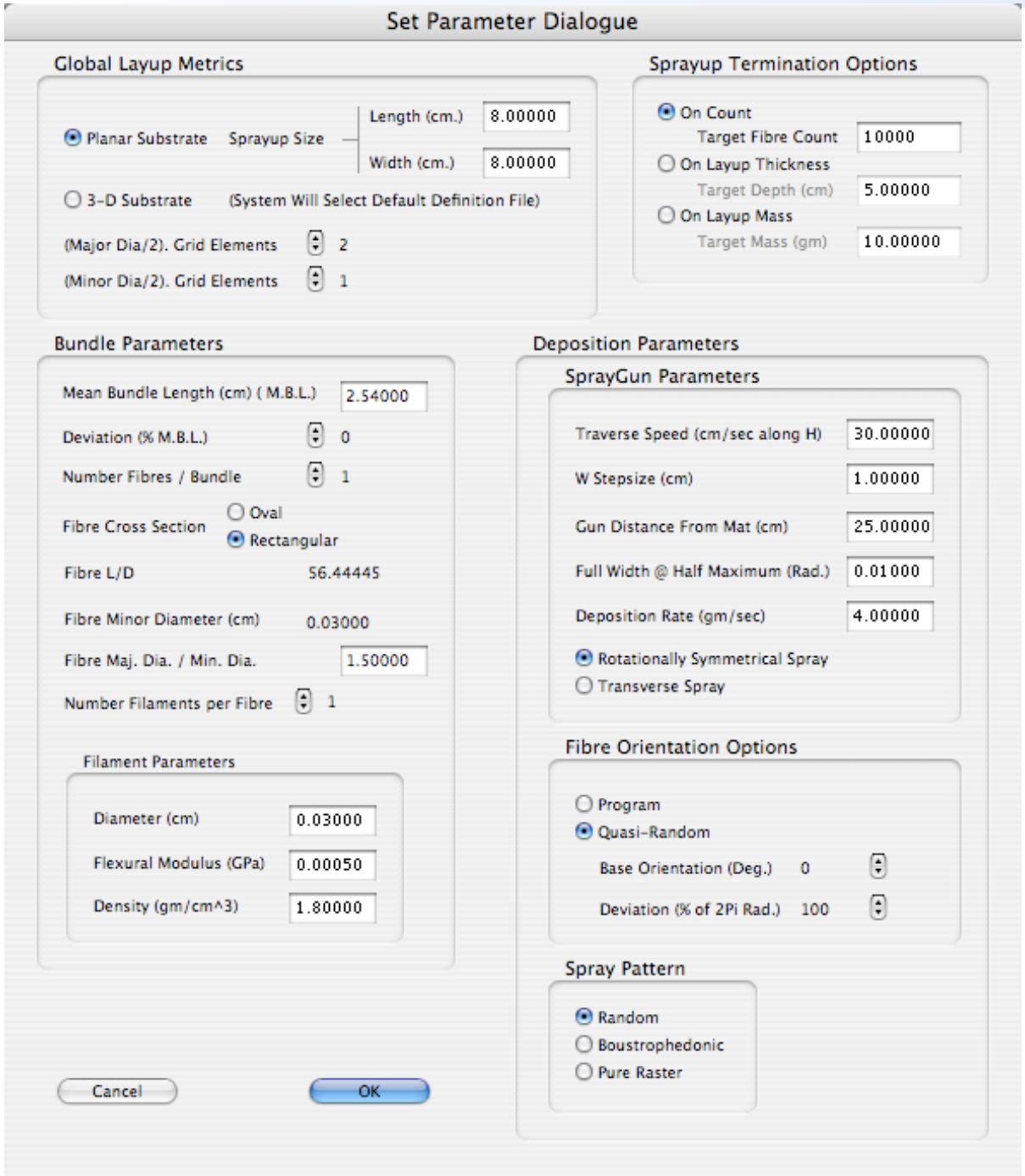
- Process- and math-related
- What are the appropriate parameters and measures for fiber network characterization?
- How to optimize competing effects, e.g. structural integrity and permeability?
- Measures for permeability, tortuosity, caging volumes, caging constraints, resin infusion (saturated, unsaturated), flow restriction due to fiber obstacles and curing, clogging by capillary tension by the small pores, changes of fiber network during compression, force transfer, compression induced flow, etc.
- We had to look into paper physics, textiles, non-wovens, filters, diapers, etc.

Planned Project Activities

- Process model for fiber network formation by explicit modeling of fiber and powder placement on a substrate
- Deposition on complex substrate shapes
- Analysis tools for fiber and void spaces
- Models for placement and transport in fiber networks
  - Particles (binder, resin, layering, blending)
  - Dissolvable fibers (resin)
  - Caging volumes
  - Liquid transport (variations on curing, saturation, adhesion)
- Models for mechanical response during preforming, compression and resin infusion with compression
- Support for multi-process optimization by linking mechanical performance to manufacturing processes

Current 3-D Fiber Modeling Capability

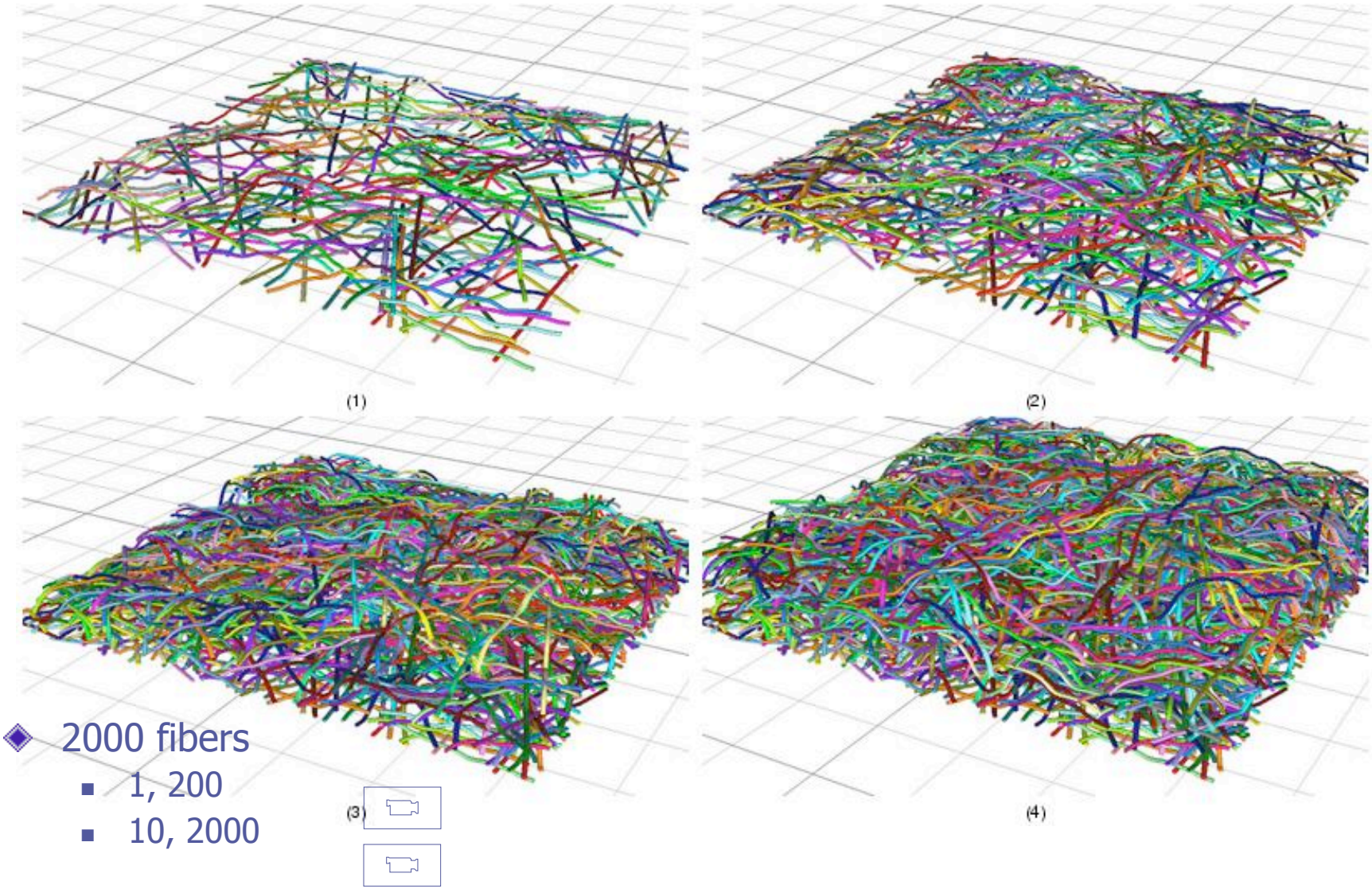
- FNSim: Computer program for:
  - Modeling of deposition process of fibers onto substrates
  - Analysis of the structure of resulting fiber networks
- The program can simulate a variety of fiber deposition patterns, orientations, fiber types, layers, network densities, and thicknesses.
- The goal is to create virtual process model of composite material and tailor it to its end use
- Variations have been implemented for electro-spinning and commingling fibers
- The model can be used for simulation of other phenomena such as super-absorbing polymers in fibrous networks, filtration, paper physics, etc.



Program Controls

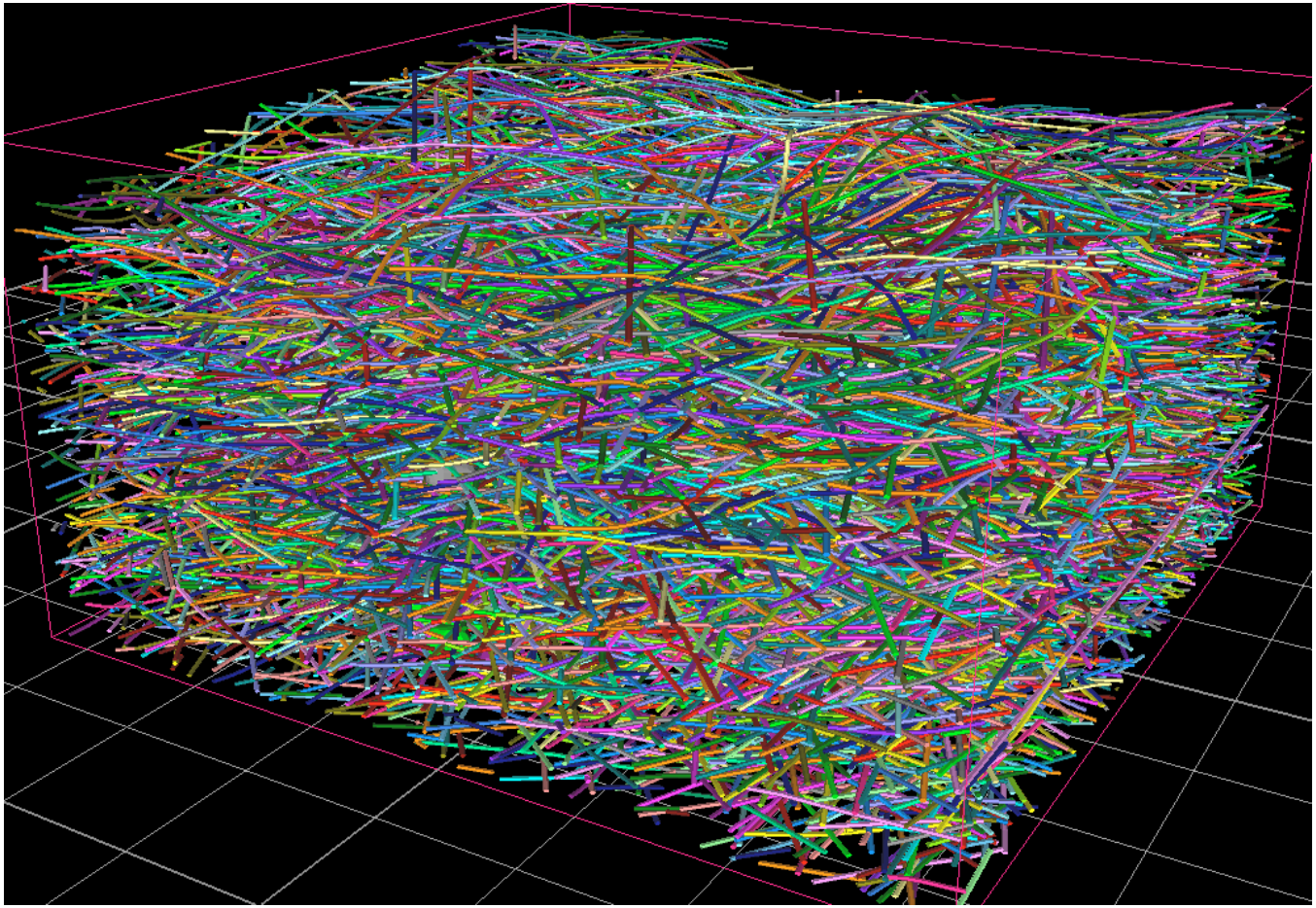
- Used to generate 3-D structure of fiber network
- Models statistical material properties such as distribution of contacts, voids, segment lengths, fiber undulation, layers, etc.
- Controlling parameters are selected based on P4 process, but can be modified as the process changes

P4 Fiber Deposition Process Model



- 2000 fibers
  - 1, 200
  - 10, 2000

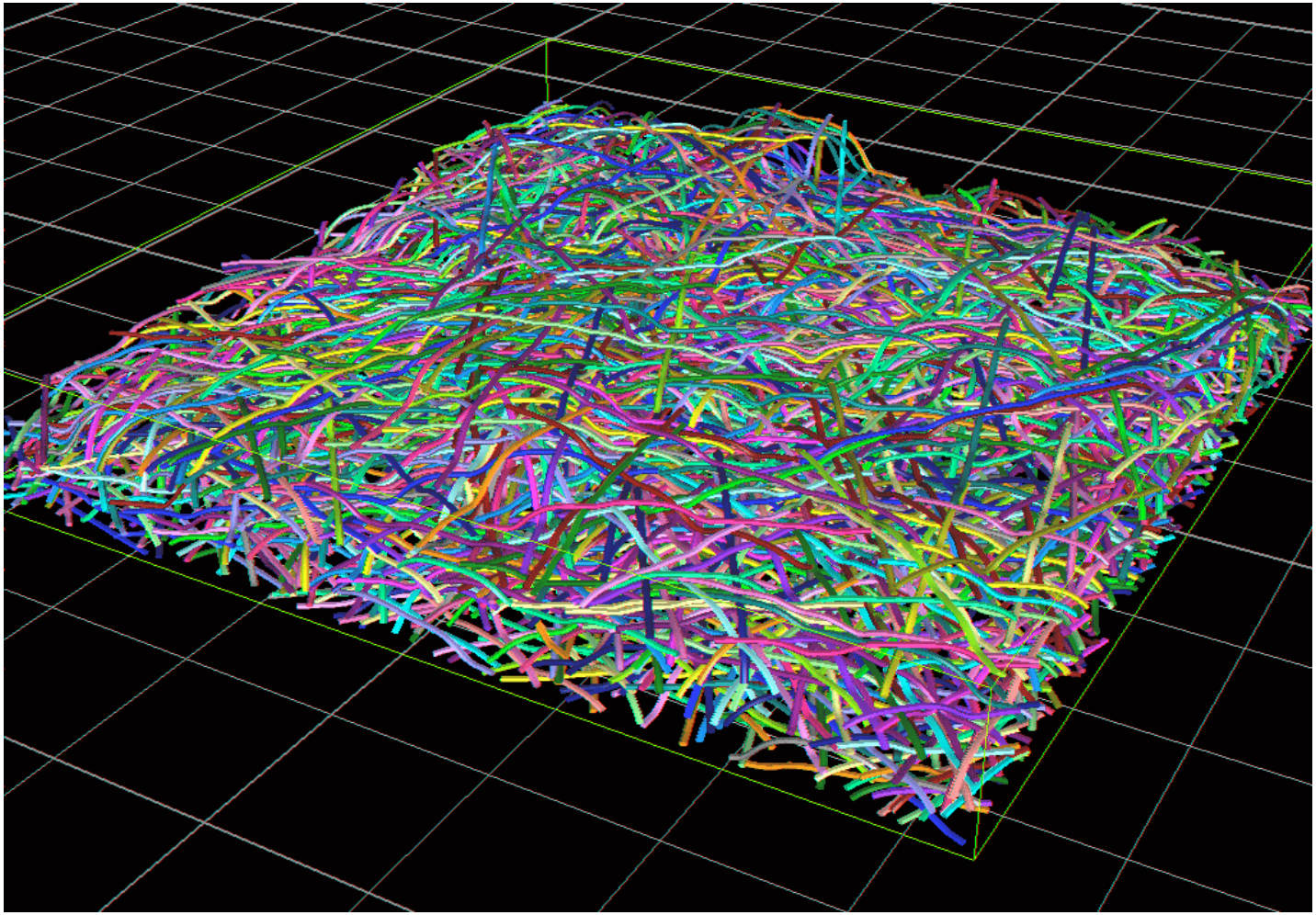
Fiber Commingling Process



- Different types of fibers commingled on- or off-line

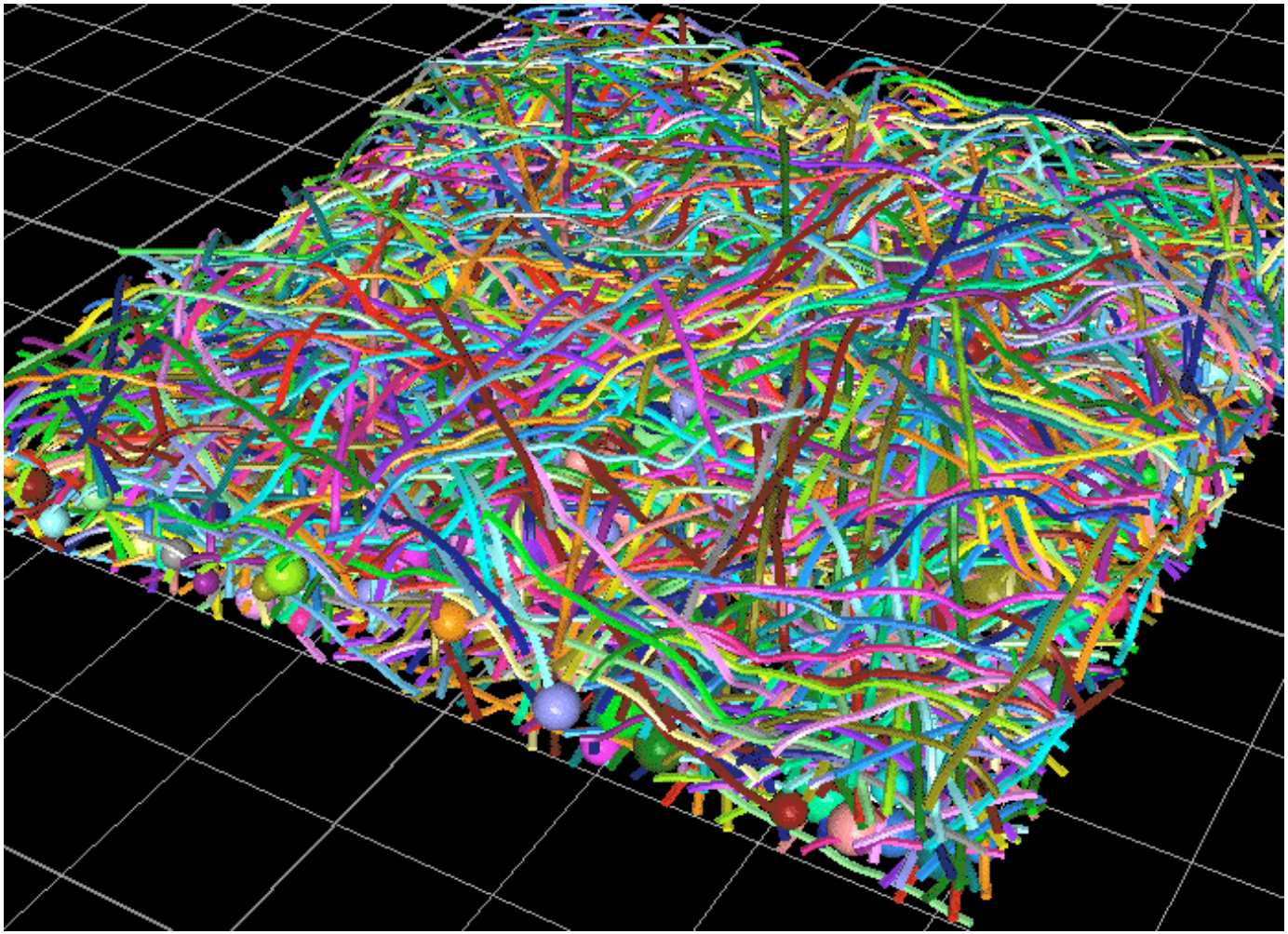
- Objective is to tailor the material with different layers to promote flow, increase bending stiffness, mechanical performance, investigate possible process controls, etc

Flexible Deposited Fibers



- Fibers deform due to contacts with other fibers and vacuum suction from the substrate base

Void Space within the Fiber Network

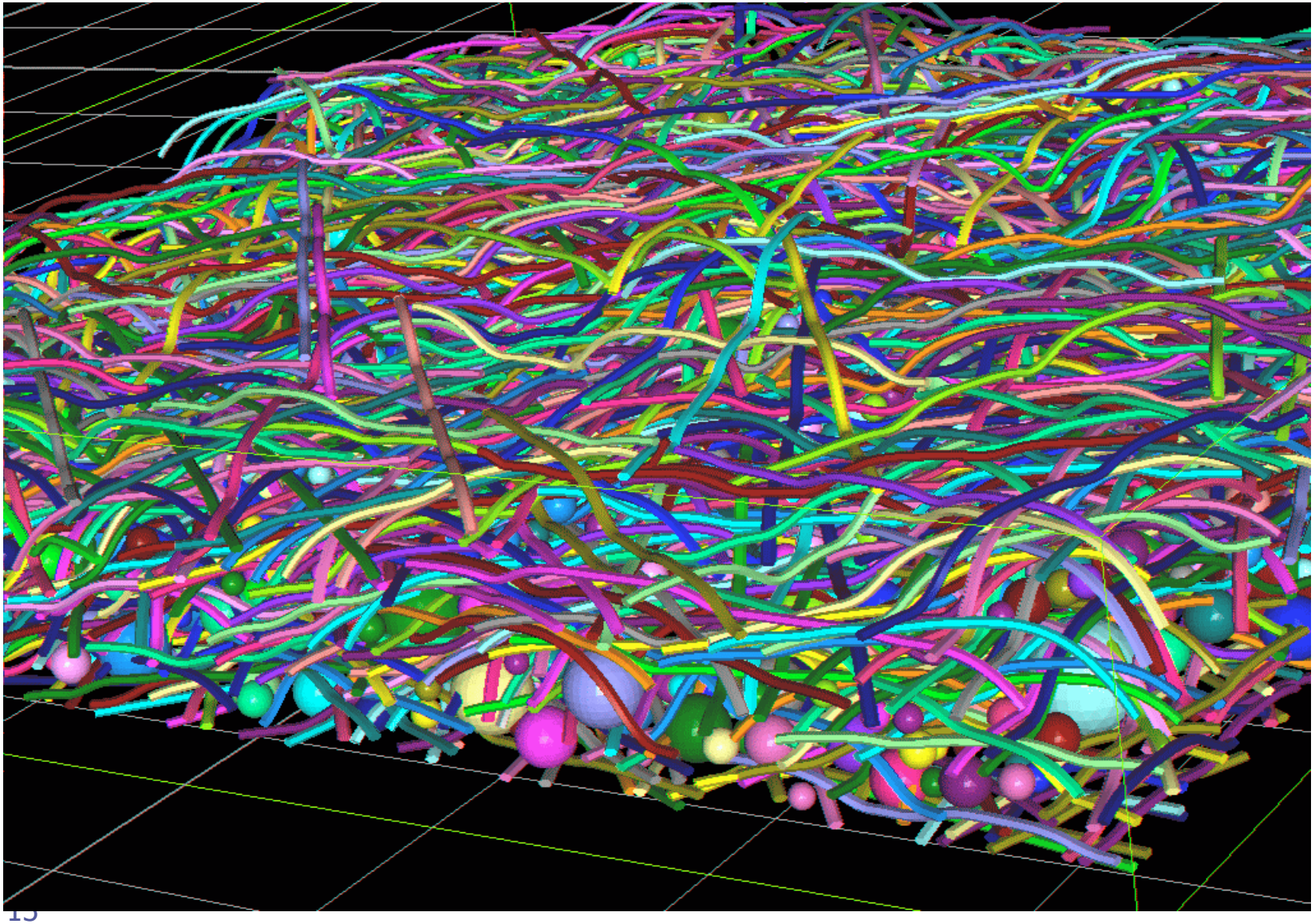


- Voids are defined as spaces where probing object is caged

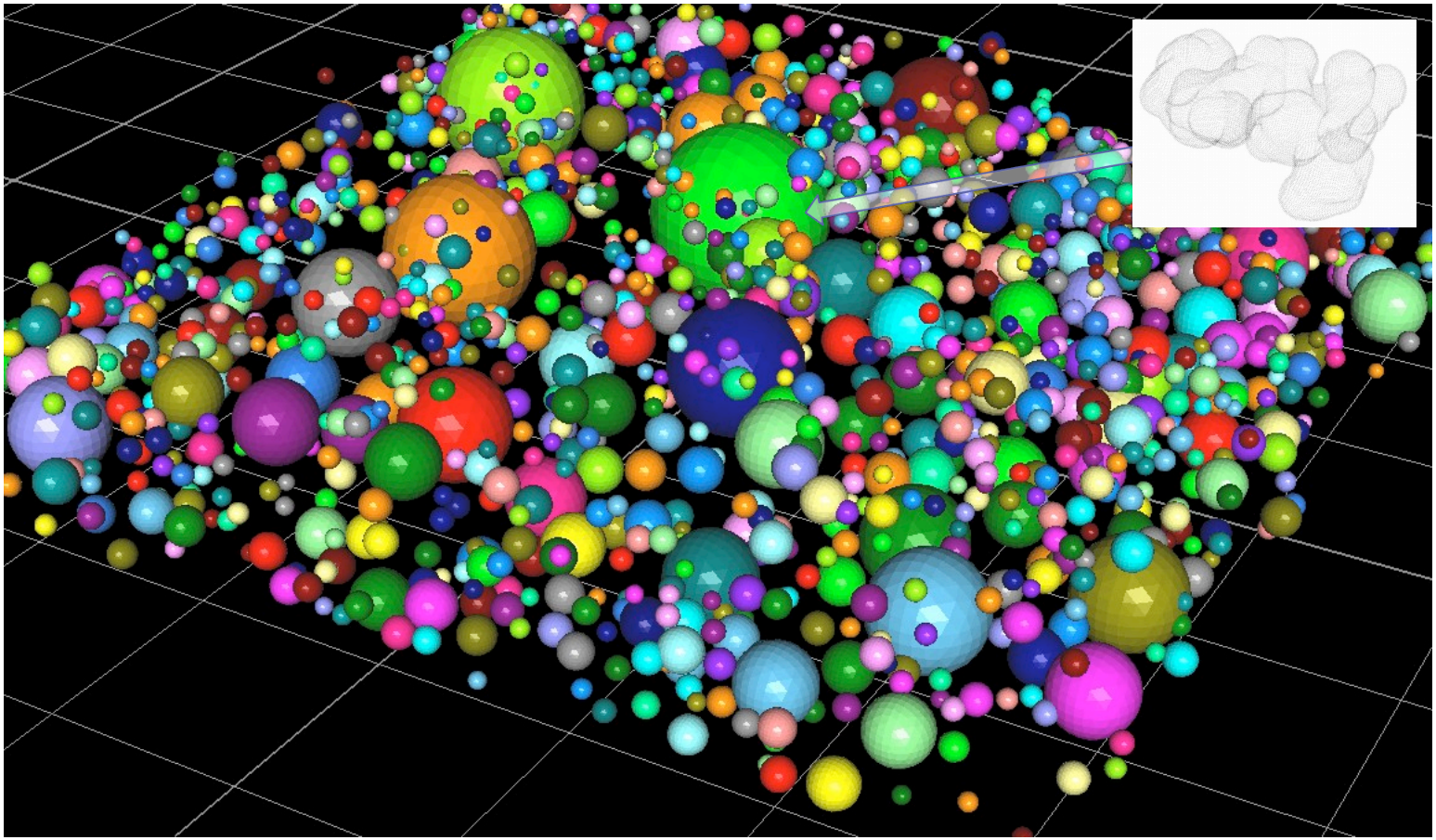
Resulting Model Discretization

- Actual deposition computations are performed on much finer grid

Fibers and Equivalent Spheres

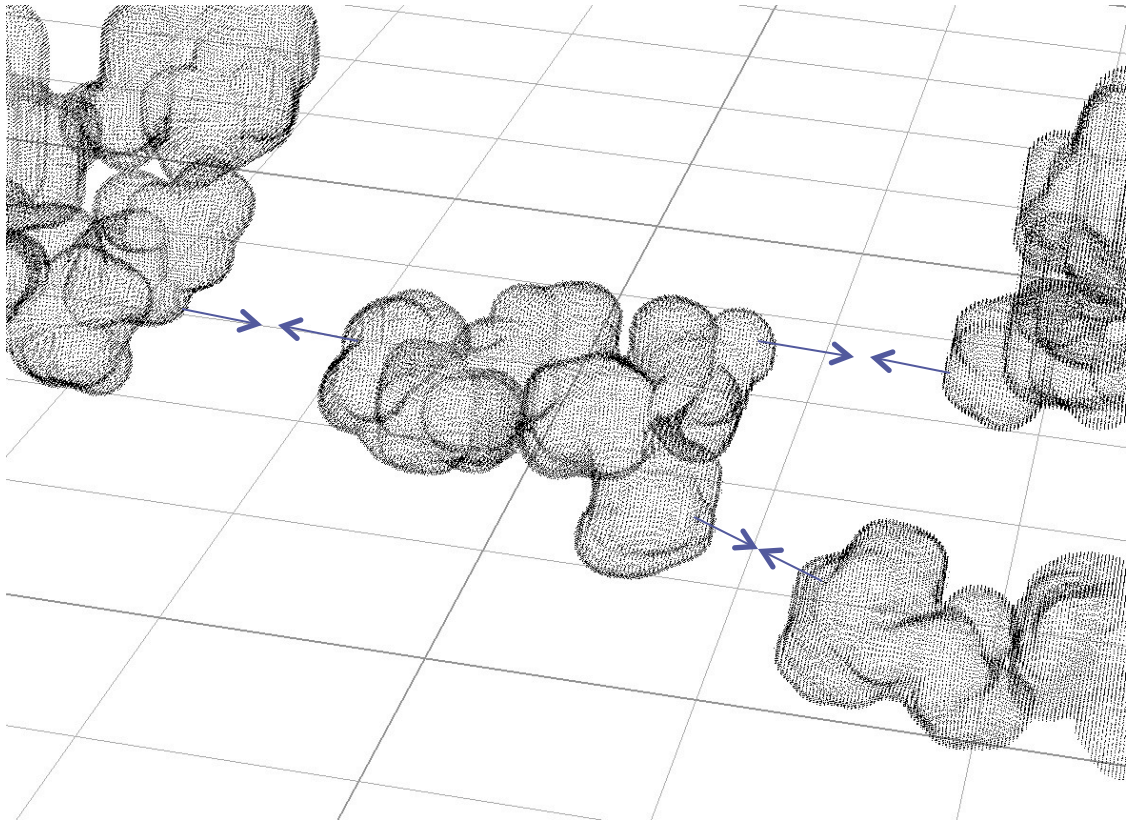


Void (Caging) Space



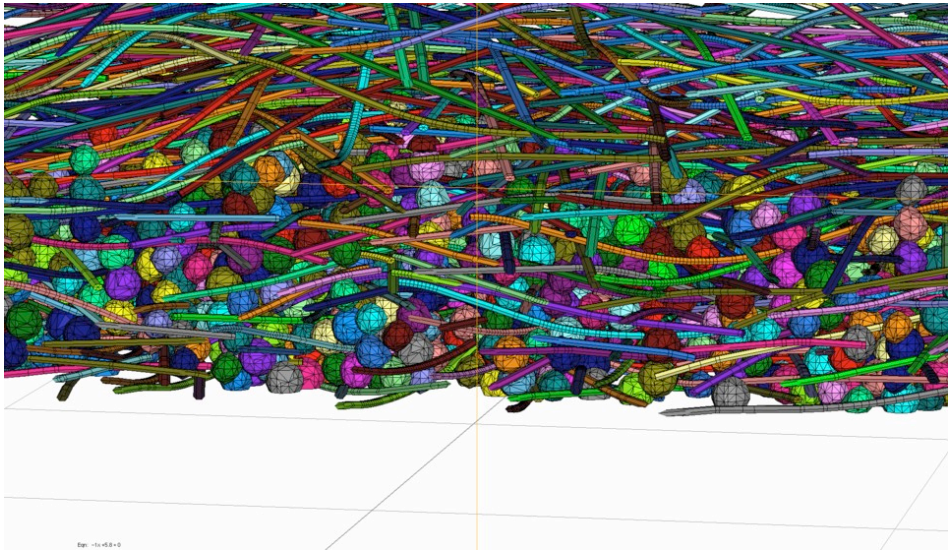
- Equivalent sphere representation of the voids
- Actual voids have irregular shapes

Caging Volume Transition



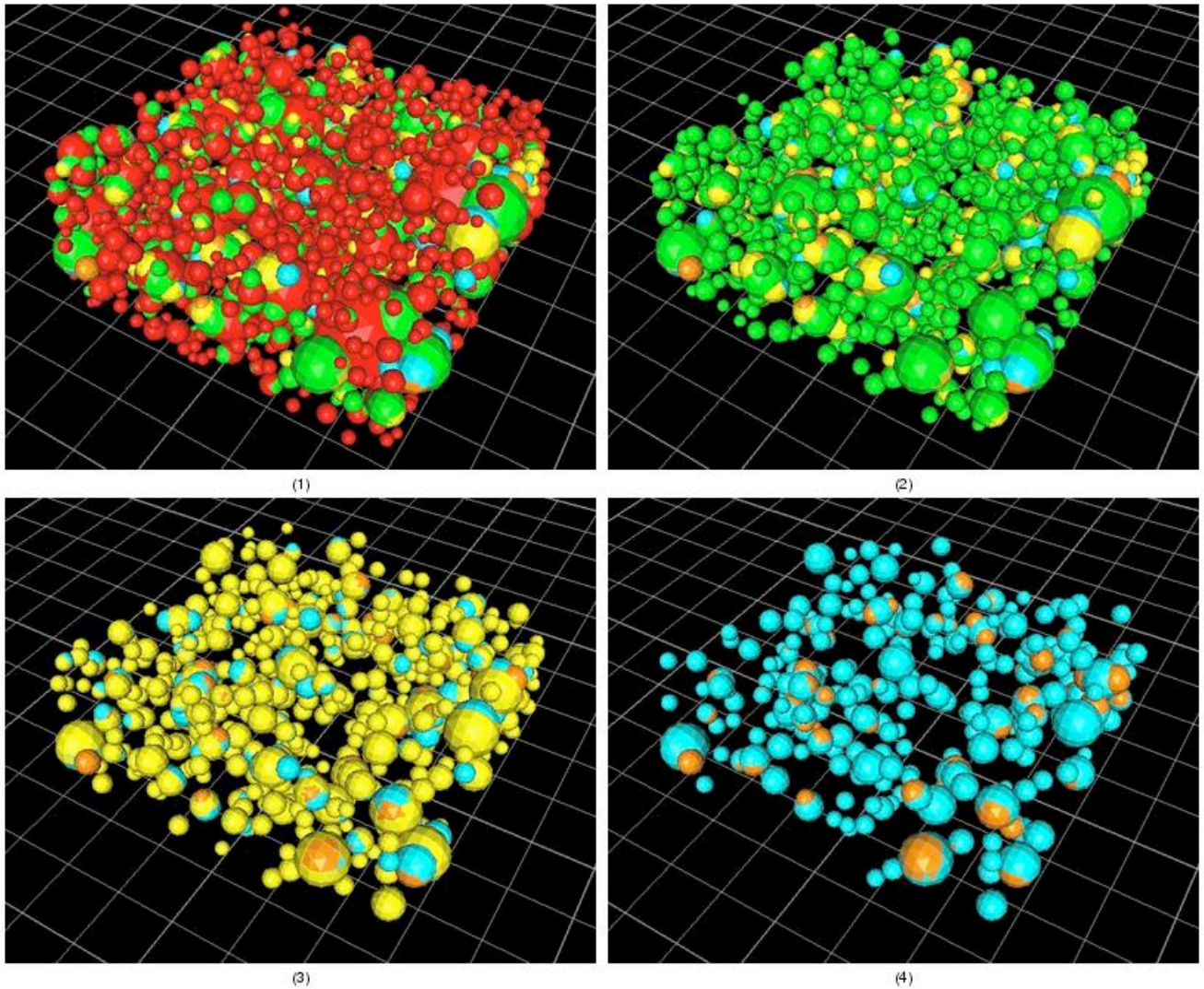
- As we reduce the probing sphere size, the resulting caging volumes approach each other
- Size of probing sphere that percolates the system may be used as a permeability indicator

Multiple Particle Storage



- When maximum occupation volume is set, then multiple caging spaces can be found in a larger caging volume

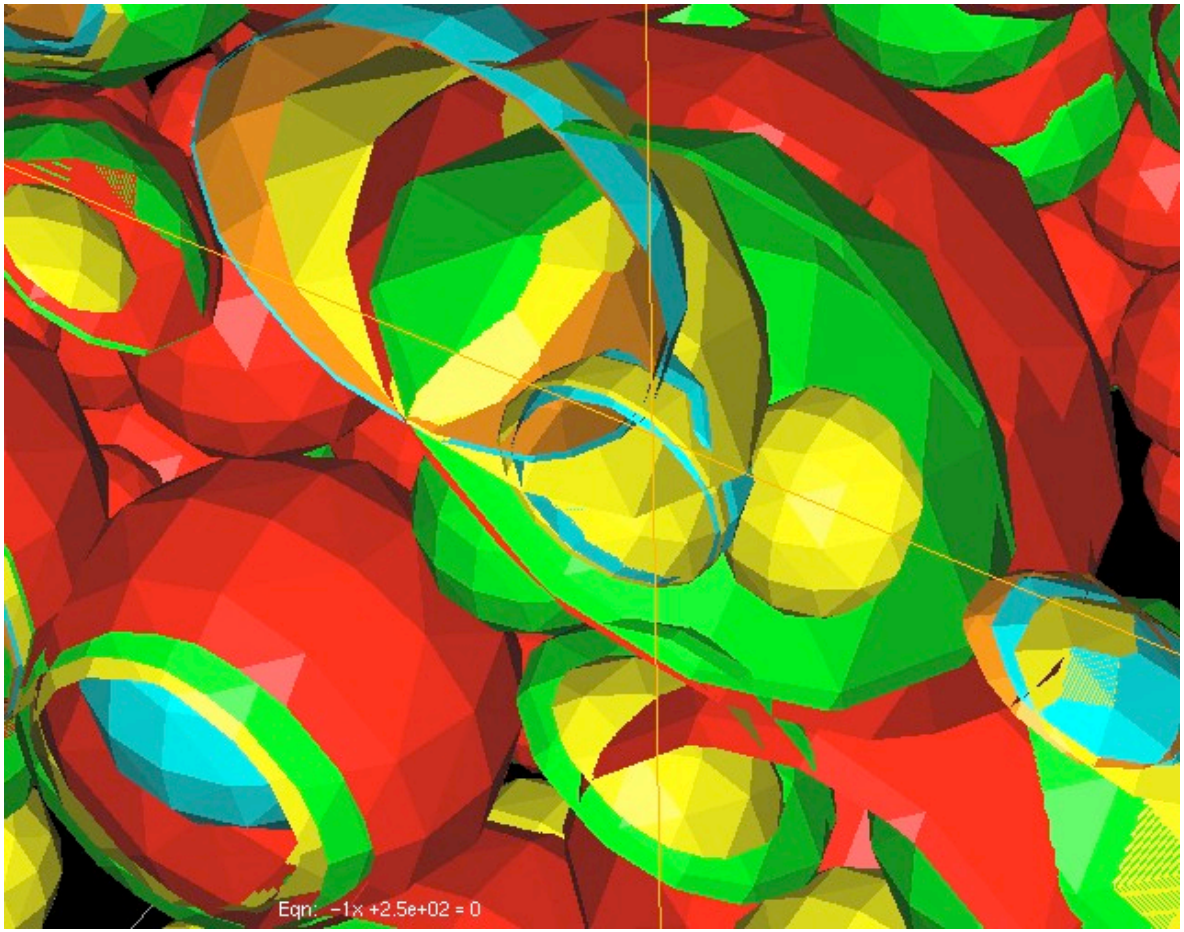
Void Space Transitions



Colors denote voids found using probing spheres of increasing (1-4) radii

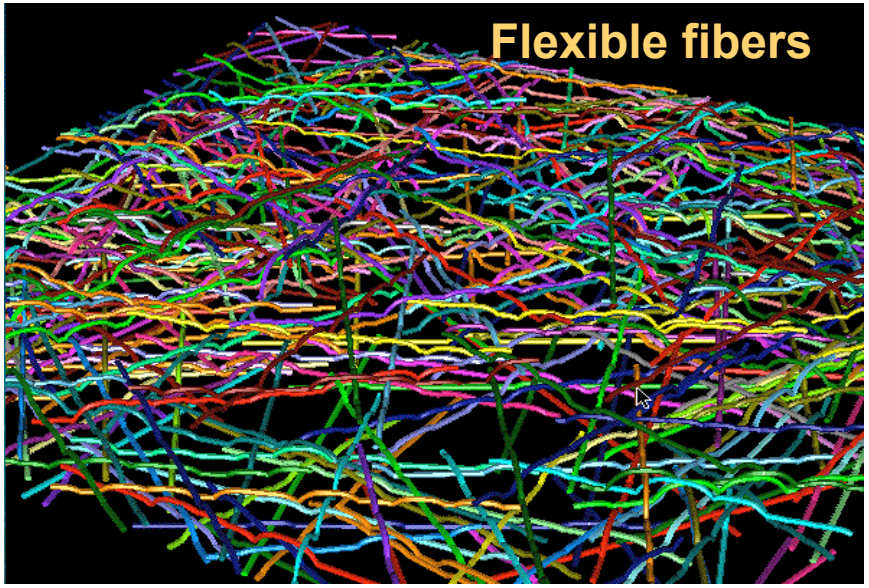
- Depending on the size of probing object, voids change volume, convexity, and connectivity
- Connectivity of the voids strongly influences permeability
- Distribution of throat sizes was shown to correlate better to permeability than porosity

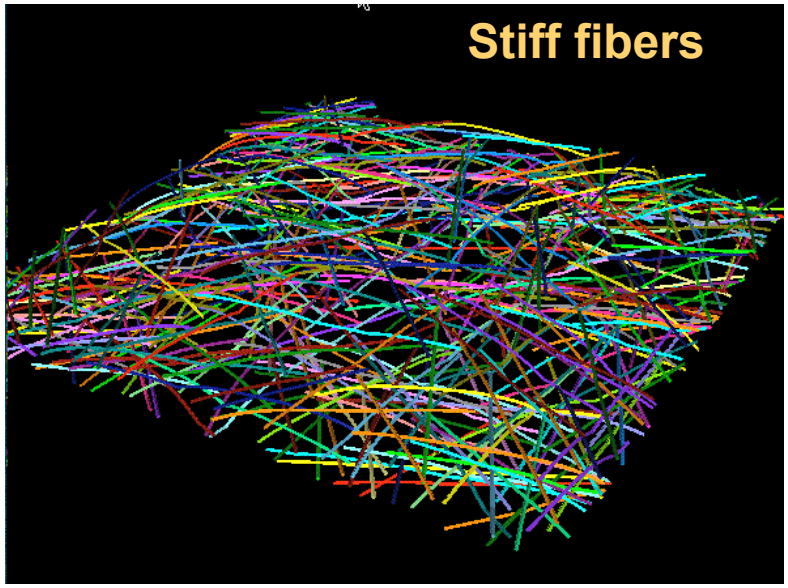
Probe Size Effect



- Change in the probe size leads to splitting of the voids, changing of their connectivity, throat sizes, etc.
- Probe size may correlate to liquids of different viscosities and fiber surface energies
- Percolation of void network will depend on the probe size

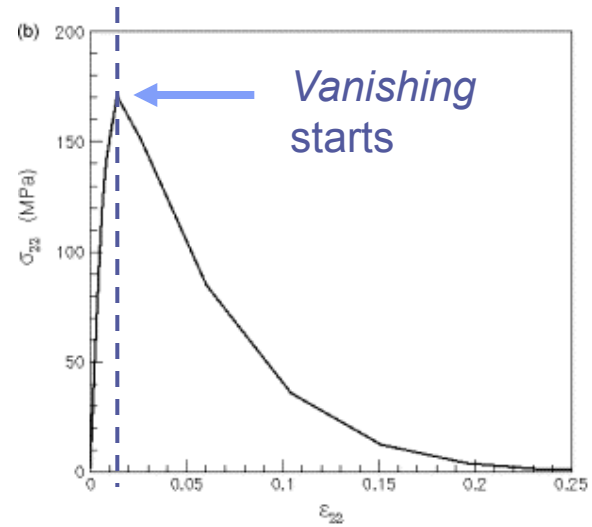
Example Application: Mechanical Models





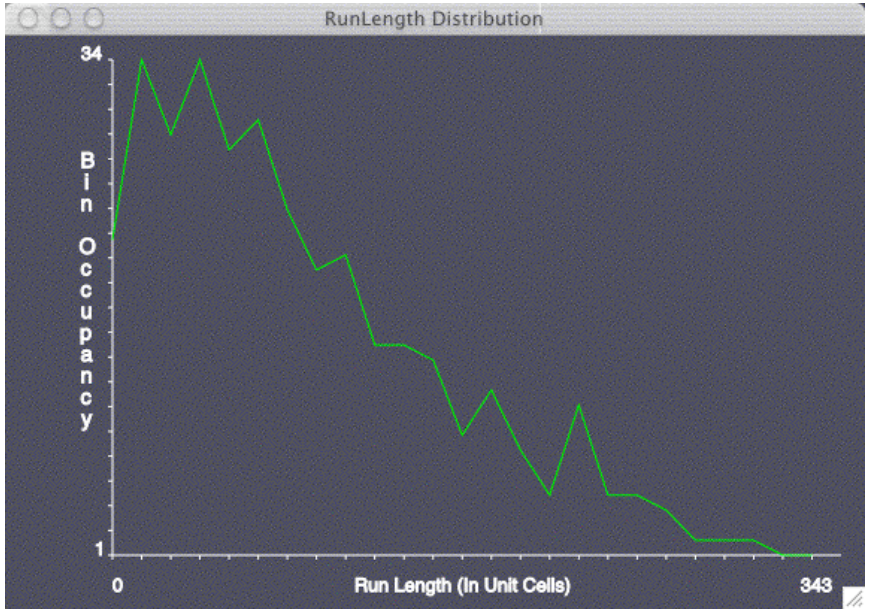
- Experiments and short fiber network simulations show that damage localizes into 1-D zone with uncorrelated fiber breaks
- Failure in fibers (tows) occur in the segments between fiber's connection with the network
- **Fiber break segment determines internal cohesive length necessary for failure model**

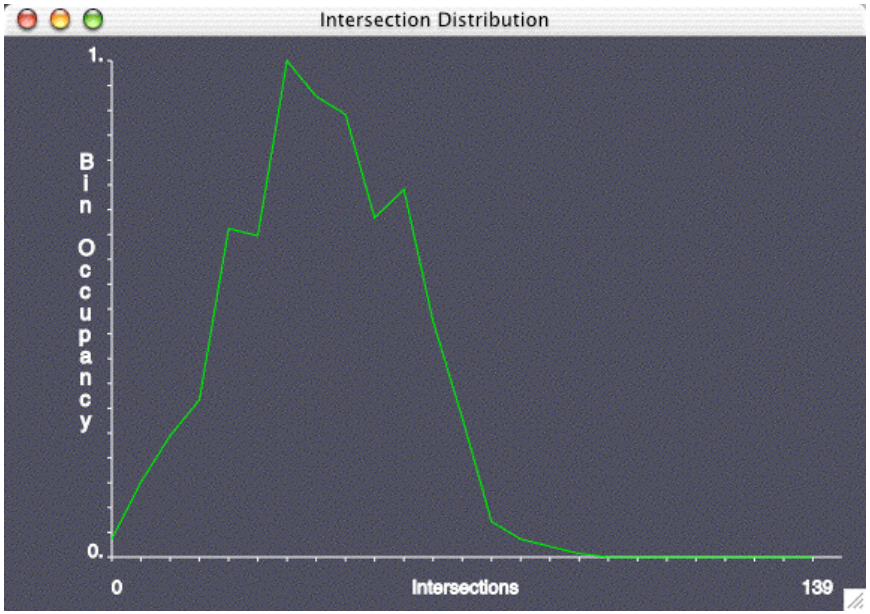
Shortcuts in the Current FEM Models



- Tricks abound to avoid tough problems
- e.g. from recent literature (2000+):
  - *Total failure can be modeled using a vanishing element technique that consists of reducing the local stiffness and stress field to zero in a certain number of steps in order to avoid numerical instability.*
- The problem is that model formulation is accurate only until vanishing starts
- Afterwards, the model is not based on the underlying physics, however it dissipates 90% of energy in that region
- Such models have severe discretization (FEM mesh) dependency
- **Models for localization and fracture must be based on characteristic lengths, rates and loadings associated with the failure process**

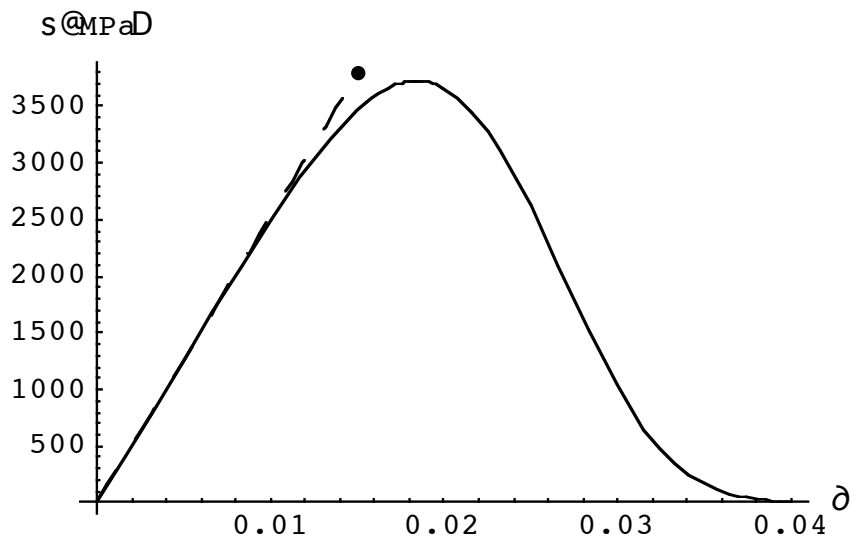
Fiber Layup Structure Distributions





- Distribution of segments has characteristics of exponential distribution
- Number of fiber intersections has Gaussian character
- **The above statistical distributions are used in the constitutive model to define characteristic length distributions for fiber failure segments (cohesive zone parameters)**

Carbon Fiber (Tow) Model



- Based on experiments by fiber manufacturer
- Strength is a function of tow length and filament count
- It is the basic failure mechanism in the composite
- The energy to of a tow's segment is used to estimate failure energy and scaling of energy dissipation with the domain (finite element) size

Fiber Distribution Along Failure Lines

Experiments

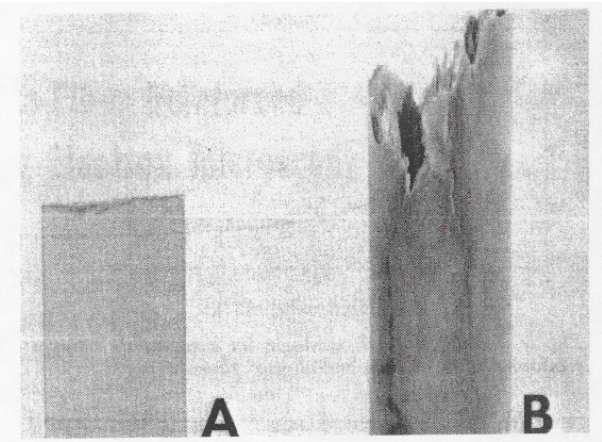
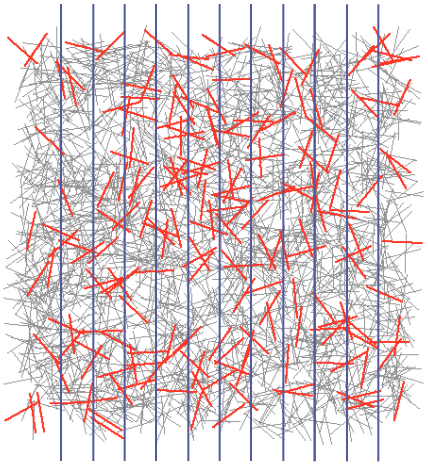


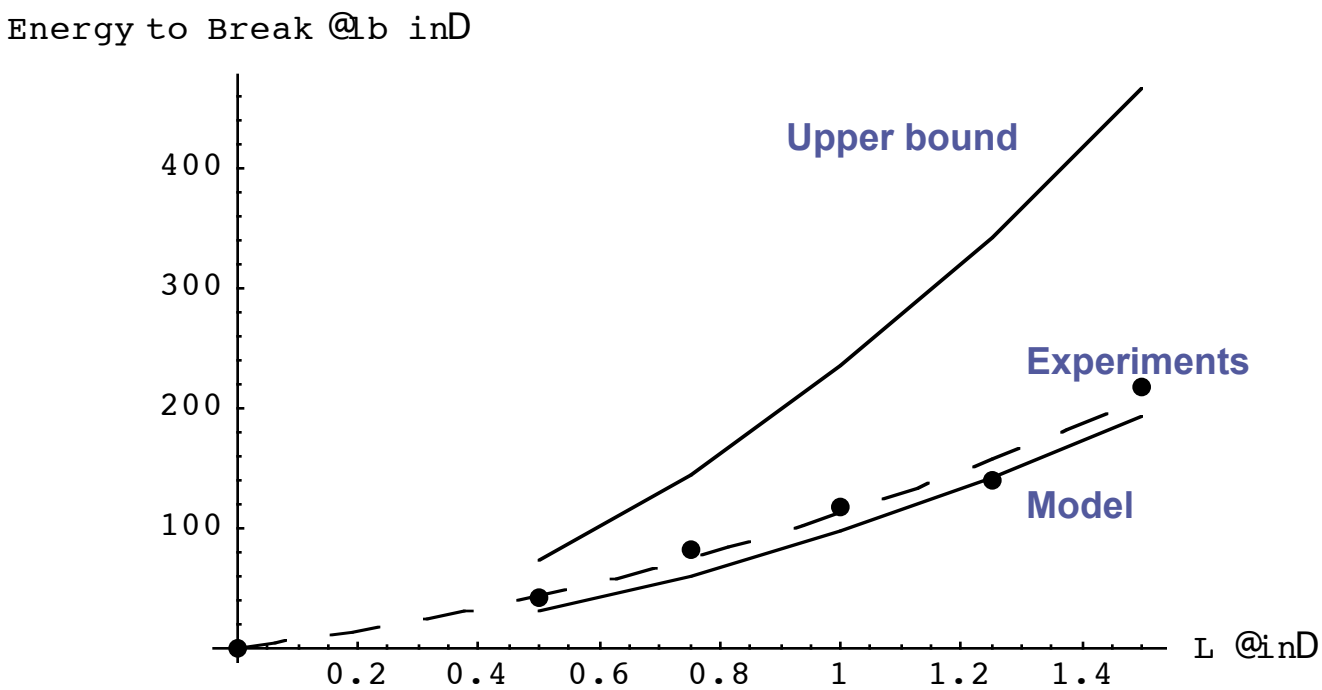
Fig. 7. Typical fracture patterns for (a) randomly oriented and (b) aligned fiber composites.

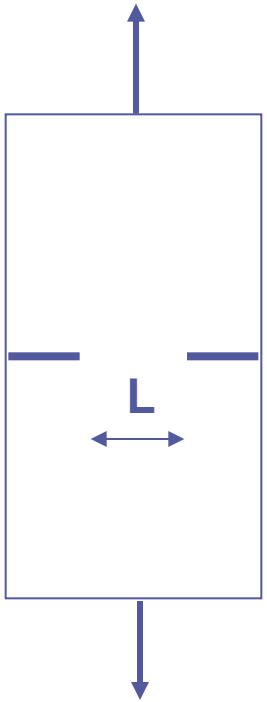
Distribution of fibers crossing scan lines



- Failure occurs in 1-D zone orthogonal to the direction of principal tensile stress as an uncorrelated event
- Fiber network simulations are used to determine the average number of fibers that crosses the failure line
- Energy to break is then determined by the number of fibers breaking and the fiber segment energy to break

DENT Specimen - Energy to Break





- Experiments are performed on P4 composite
- Fiber failure segment length was based on composite structure
- Lower and upper solid lines (model) provide good bounds for the energy to break
- **The results confirm model assumptions and the scaling law**
- **Physics based model for fracture and cohesive zone models**

Current Status

- Project is not funded due to the shift of DOE EERE priorities to low-cost fiber manufacturing
- Many possibilities for the extension of current capability
  - Filtration
  - Fuel cells
  - Paper products
  - Non-wovens
  - Nano-fibrous assemblies

Summary

- We are developing new algorithms and simulations technologies for virtual manufacturing and performance modeling of fibrous composites
- The current capabilities of the simulator can be extended to similar problems in fibrous networks
- HPC resources can enable looking into much bigger substrates and more complex problems