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Electrical Conductivity Modeling and Validation in Unidirectional Carbon Fiber Reinforced Polymer Composites

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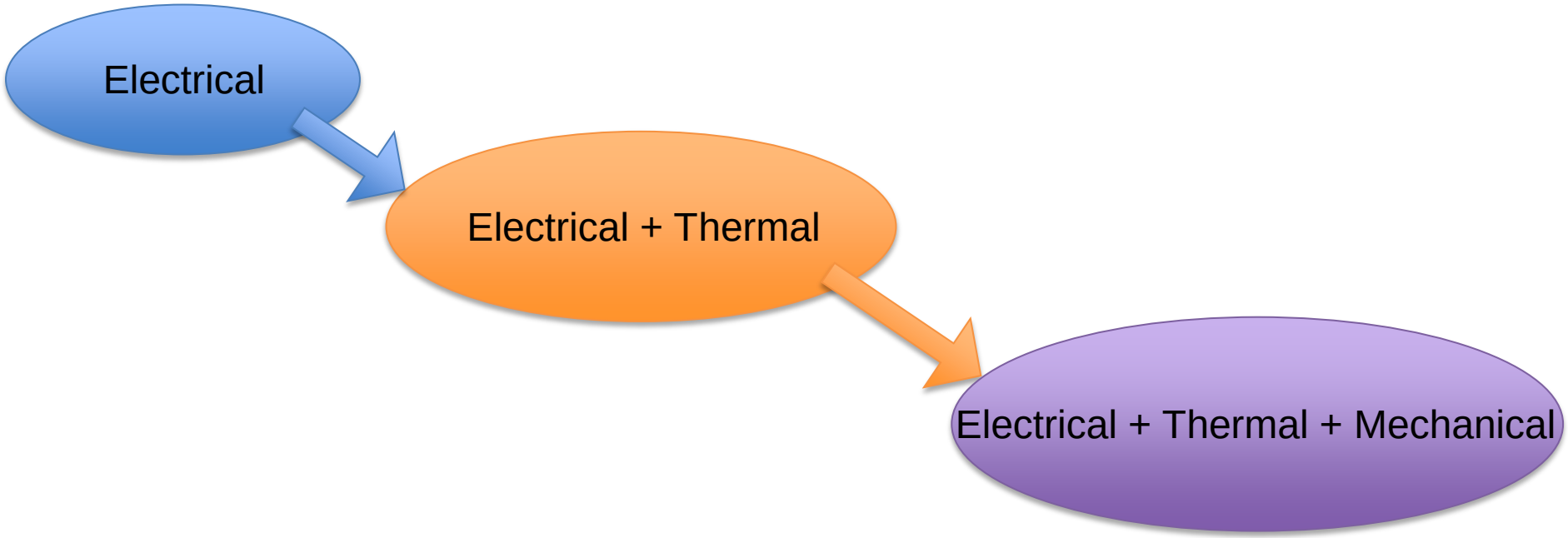
Background

- Why *electrical conductivity* modeling of carbon fiber reinforced polymer composites?
  - Lightning strike protection of aircraft
  - Electrostatic discharge/electromagnetic interference

Paur, Wired.com (2009)

Why COMSOL?

- COMSOL is useful in this study because:
  - Modeling saves resources
  - It provides a nearly complete suite of software to model:
    - the current system in three dimensions
    - multiple physics interactions

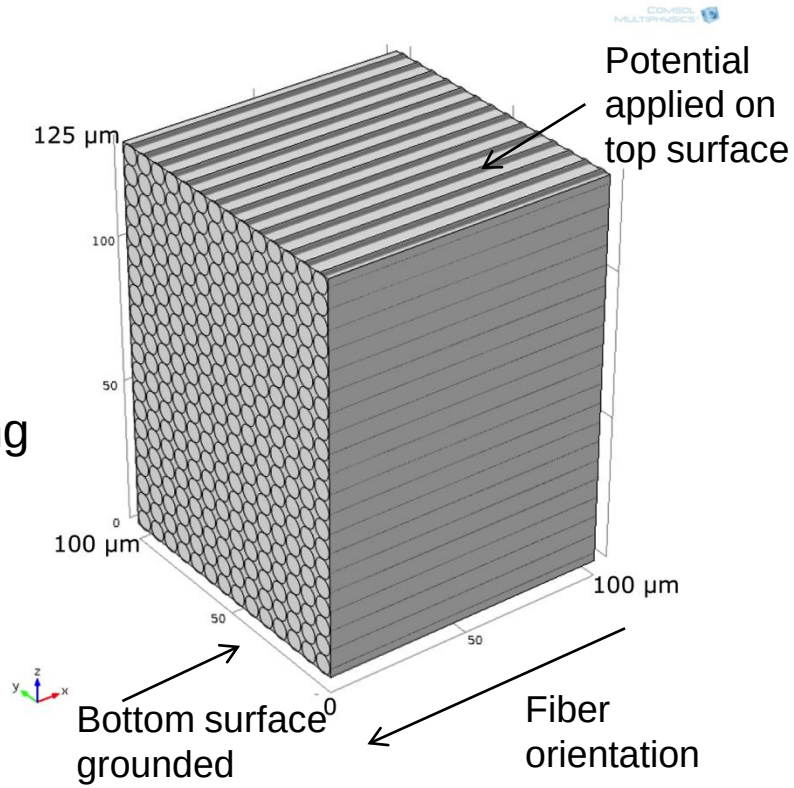


MODEL SETUP

Basic Model Setup

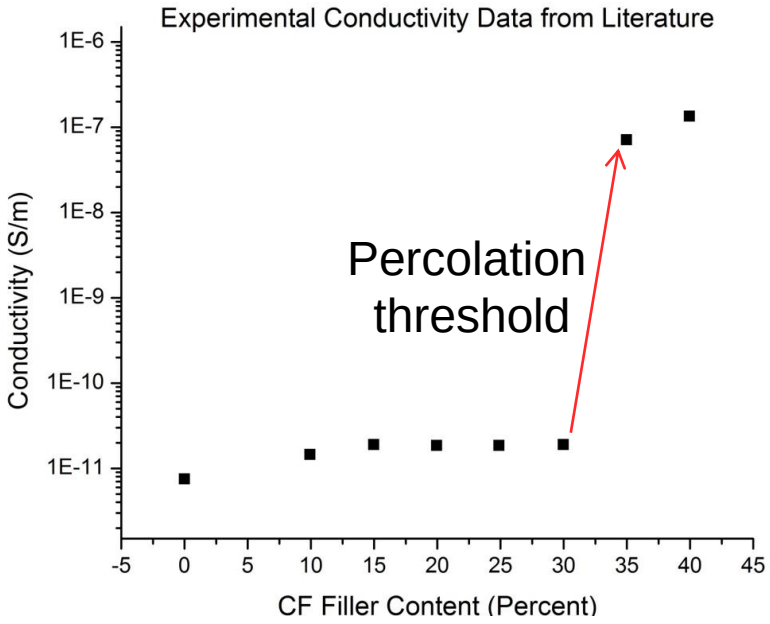
- Electric Currents Node within AC/DC Module of COMSOL Multiphysics (base package)

  - 1 “ply”
  - 78% fiber loading



Percolation in Composites

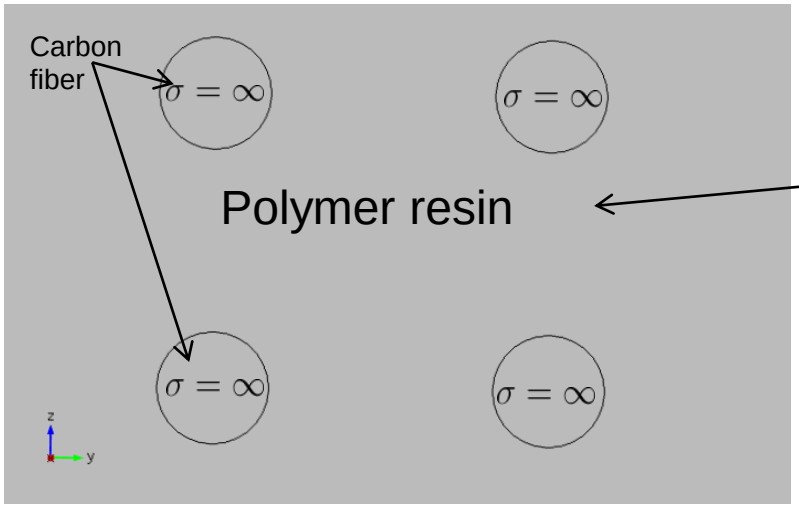
- A percolation state in porous material occurs when most of the current flows through the conductive portion of a composite.



Adapted from: A. Saleem, L. Frormann, A. Iqbal, *Polymer Composites* (2007)

Modeling the Non-Percolation State

- Both carbon fiber <u>and</u> polymer are conductive.
- Carbon fibers contribute very little to the resistance
  - therefore $\sigma_{CF} = \infty$



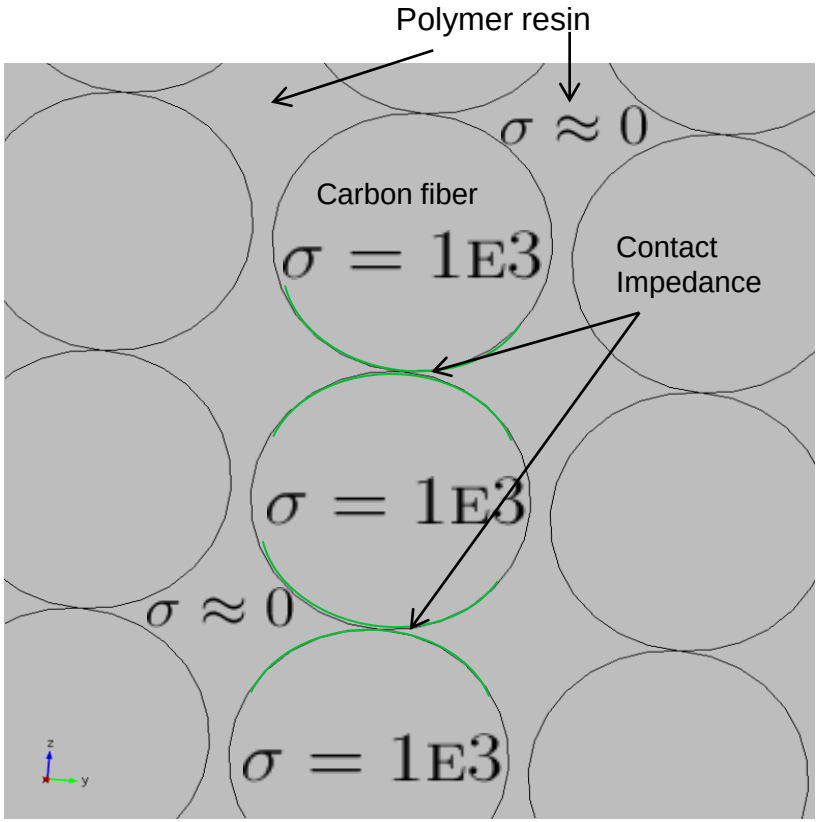
Boggs, *et al.*, IEEE Trans. Power Del. (2001)

$$\sigma(E,T) = Aexp\left(\frac{-\varphi \cdot q}{k_b T}\right)\frac{\sinh(B\,|E|)}{|E|}$$

A and B	Constants
φ	Thermal activation energy
q	Elementary charge
T	Temperature
E	Electric field

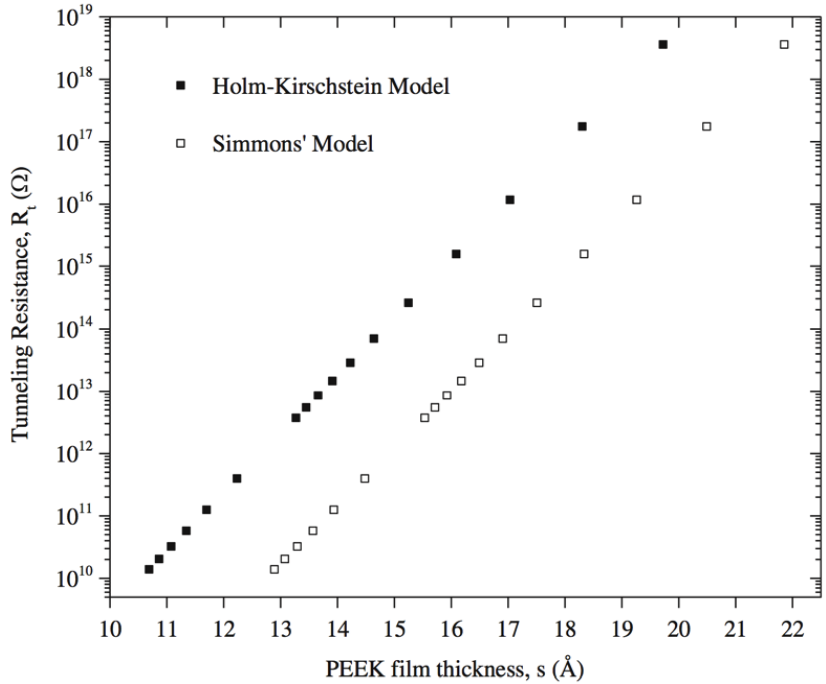
Modeling the Percolation State

- Carbon fiber is the only conductor.
- The carbon fiber was considered conductive, and the polymer was considered virtually non-conductive.

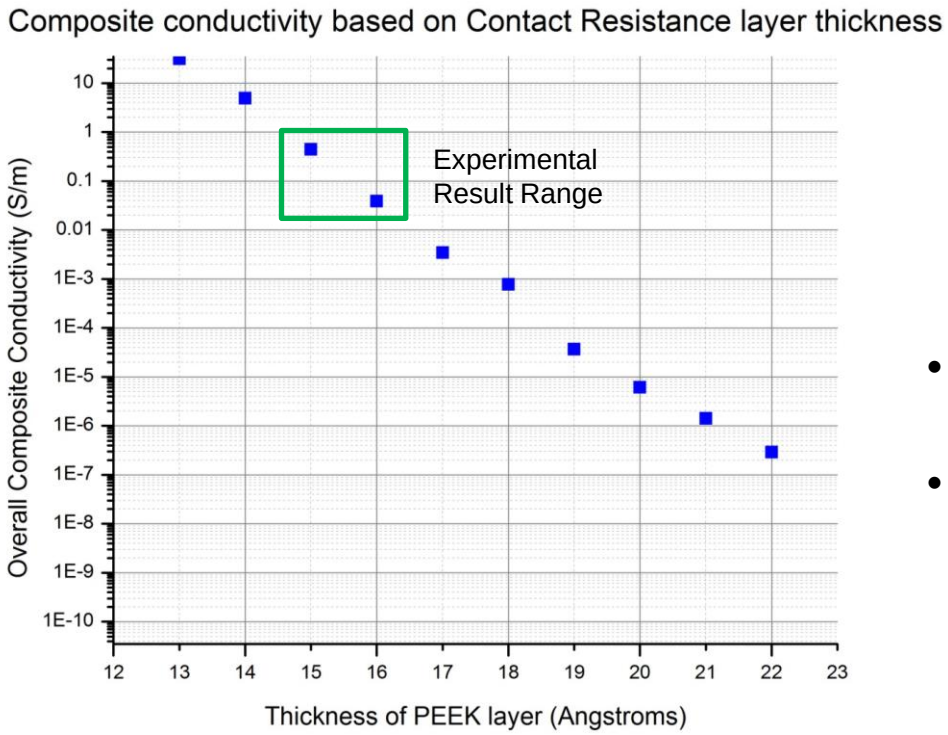


Contact Impedance and Validation

- The resistivity of each node was applied from Mohiuddin and Hoa.



M. Mohiuddin, S. Hoa, *Composites Science and Technology* (February 2013)

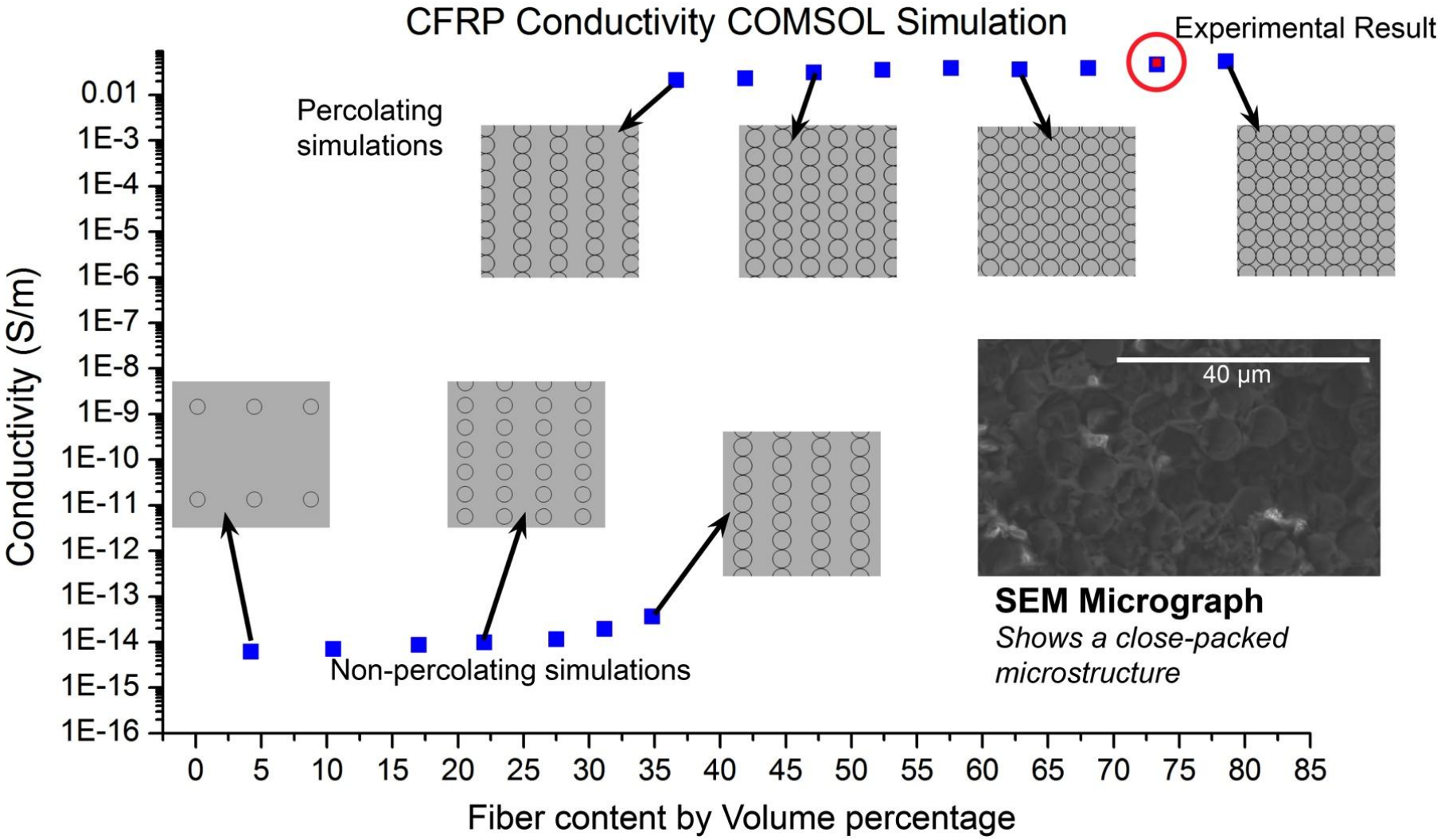


- Experimentally, a ply conductivity value of ~0.04 S/m was found.
- Phenomenologically, this indicates a contact resistance exists which is equal to the tunneling distance of 16 Å of PEEK.

MODELING RESULTS

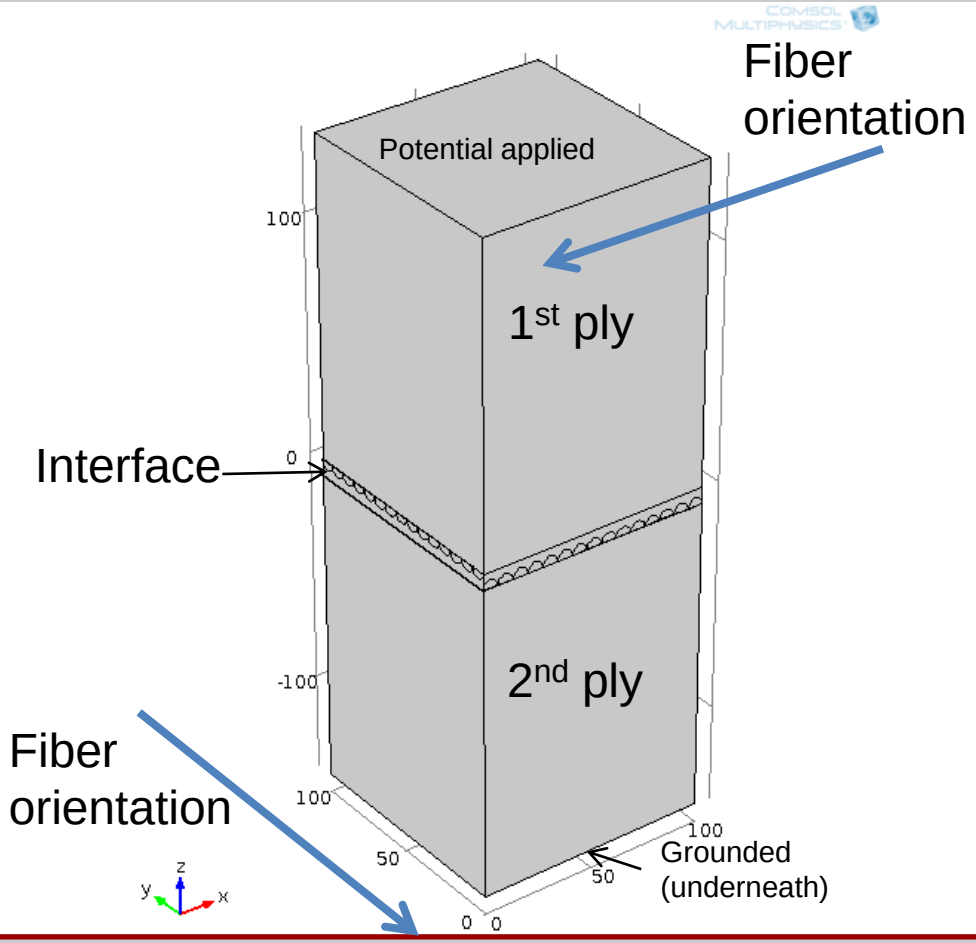
The effect of fiber content and verification

- A wide range of fiber content was modeled.



Scaling beyond one ply

- These verified results can be used to build and analyze larger more complicated objects
- The number of contacts between two plys was taken into account



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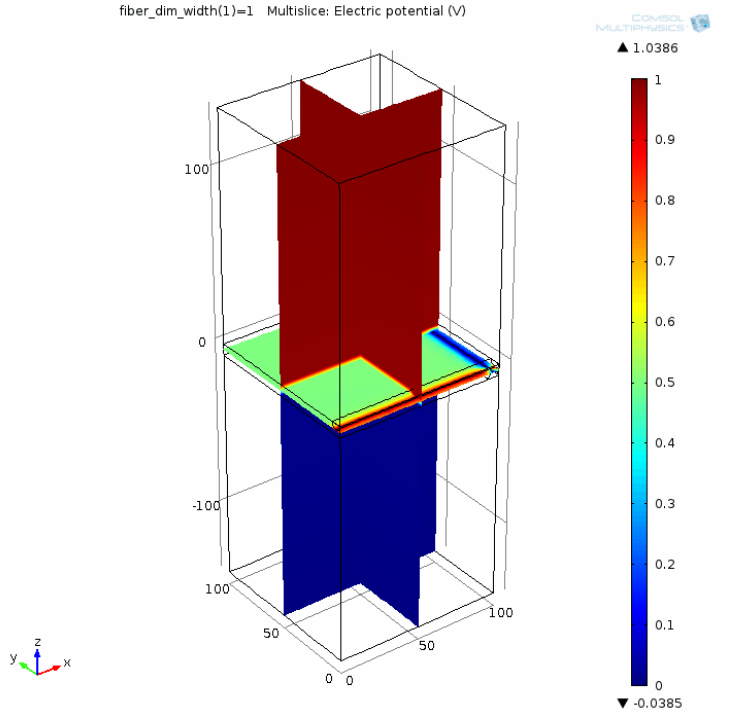

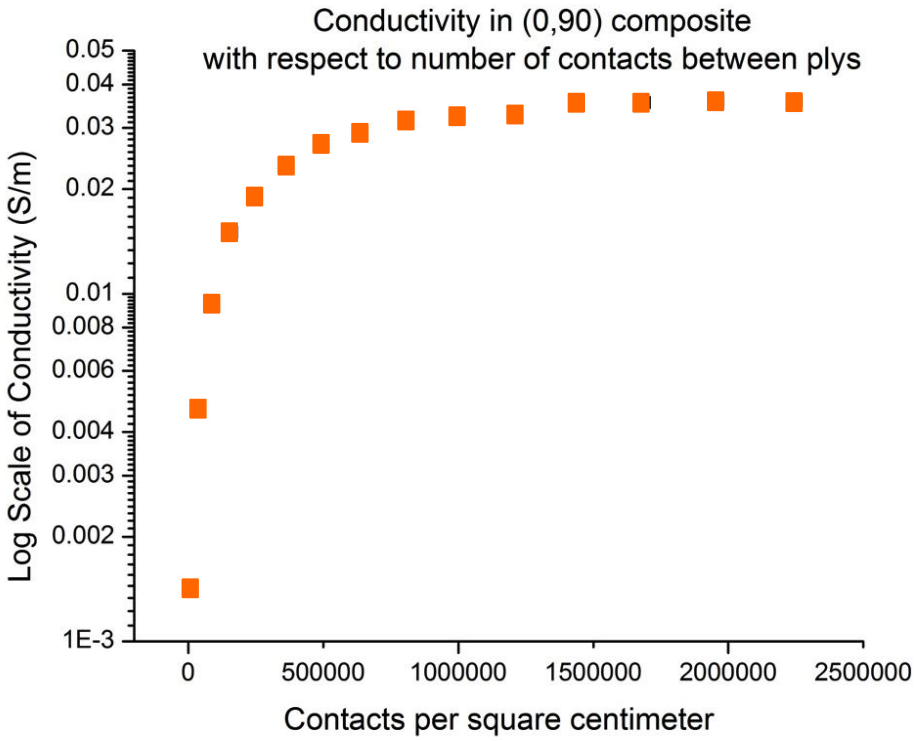

This image loops from 1 to 15x15 contacts

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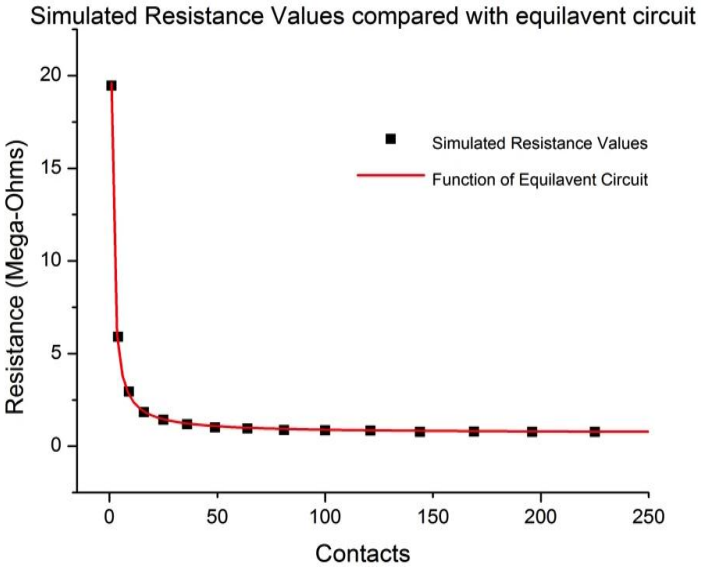
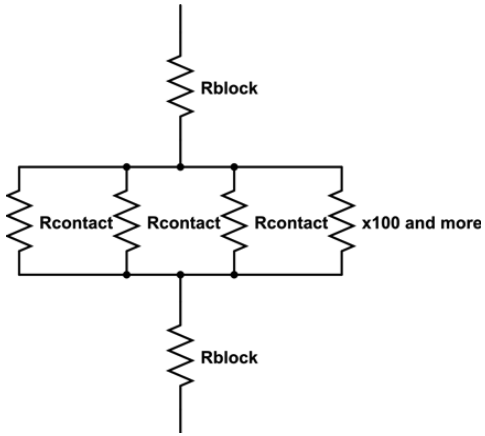
Fitting to an equivalent circuit:

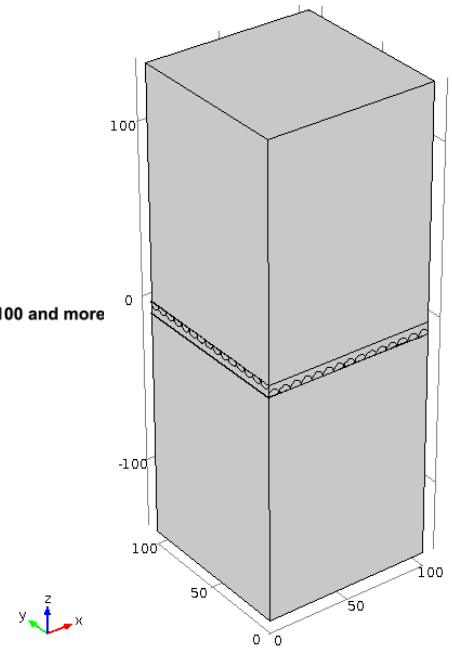
$$\mathrm{R} = 2 \cdot R_{\mathrm{block}} + \frac{R_{contact}}{\mathrm{Contacts}}$$

Coefficients (R^2 = 0.9991):
$R_{contact}$= 1.889e+07 Ohms
R_{block} = 3.534e+05 Ohms
Analytical R_{block} = 3.37e5 Ohms

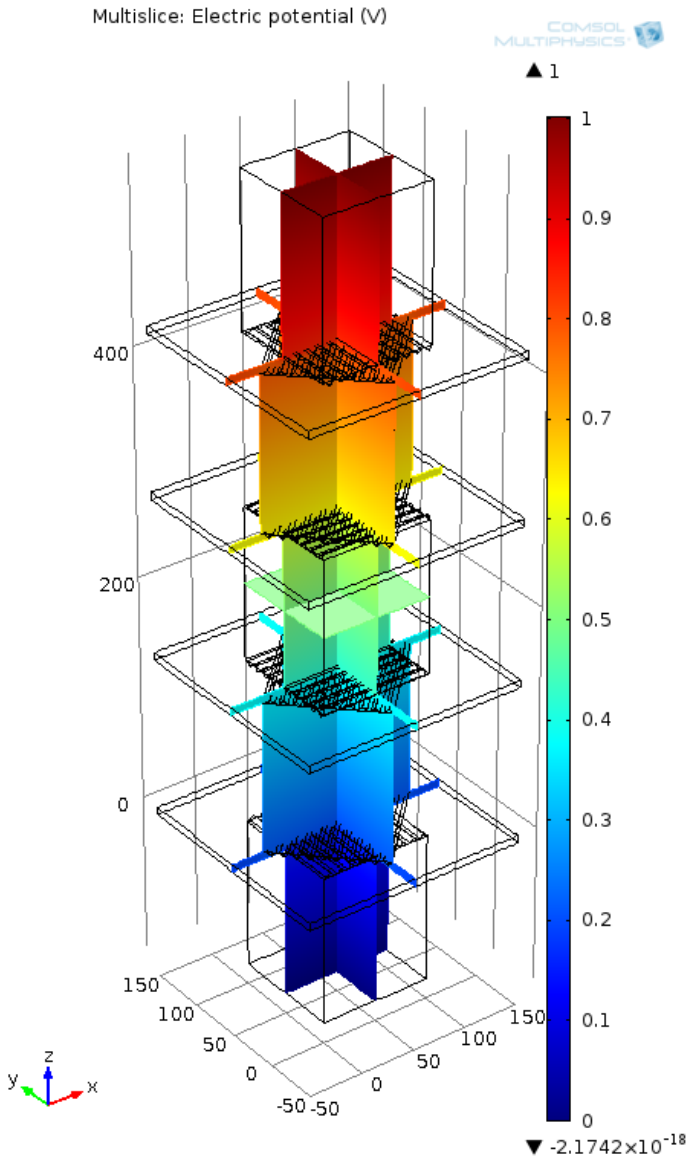


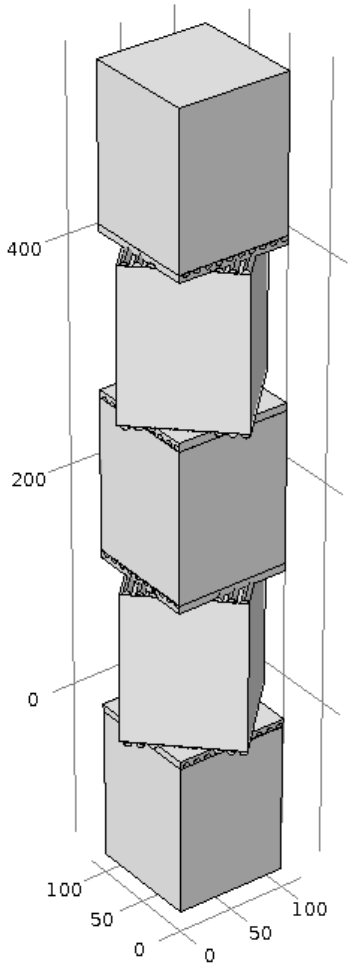
Equivalent Circuit





(0°, 45°, 90°, 45°, 0°) Composite Example





This kind of composite is very frequently used industrially.

Overall conductivity of composite:
0.0323 S/m with ~10x10 contacts at each interface.

Conclusions

- COMSOL Multiphysics can be used to model the electrical conductivity of carbon fiber reinforced polymer composites.
- **Conductivity models were produced for above and below the percolation threshold.**
- **The percolation model was validated through agreement with experimentally determined contact resistance** between two fibers.
- Electrical conductivity was modeled across the entire CF loading range.
- **These basic models were scaled to a more typical industrial composite** consisting of multiple plies with different contact configurations.

Acknowledgements

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