Aligned Carbon Nanotubes Implementation in Aerospace Fiber Polymer Composites for Multi-functional Property Enhancement

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TECHNOLOGY LABORATORY FOR ADVANCED MATERIALS AND STRUCTURES
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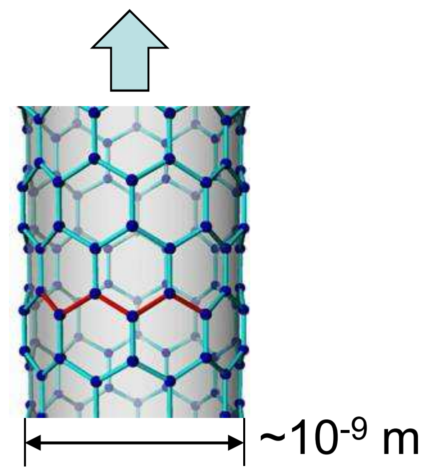
Summary: Nano-engineered Hybrid Advanced Composites

- Advanced fiber-matrix composites hybridized with ***aligned*** carbon nanotubes (CNTs) as the 3rd phase
  - **Multi-functional** (mechanical, ***electrical, thermal***, etc.) property enhancement
  - Possible weight reduction
- Scaling challenges

Aerospace Structures [Meters]



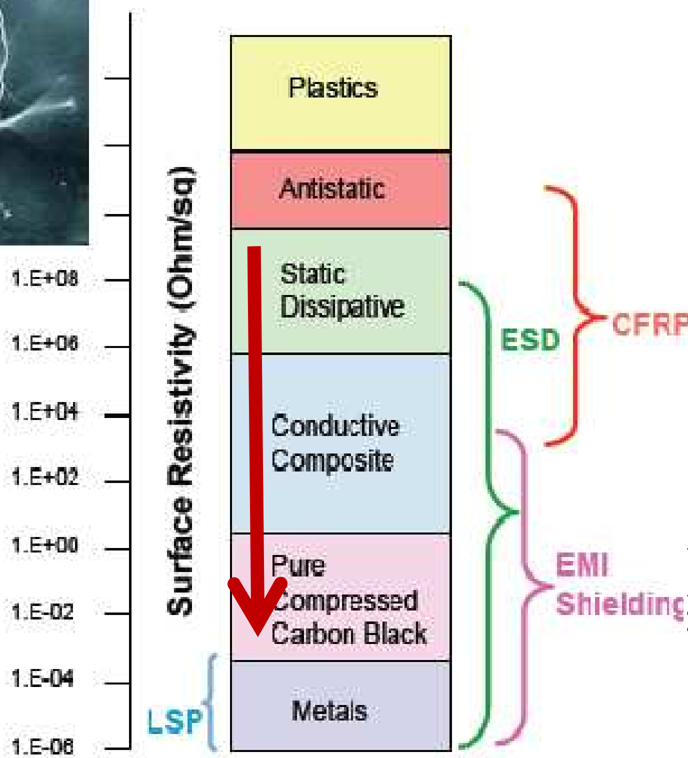
CNTs [Nanometers]

Effective use of nano-scale CNTs, but in macro-scale structures

Applications of Nano-engineered Composites

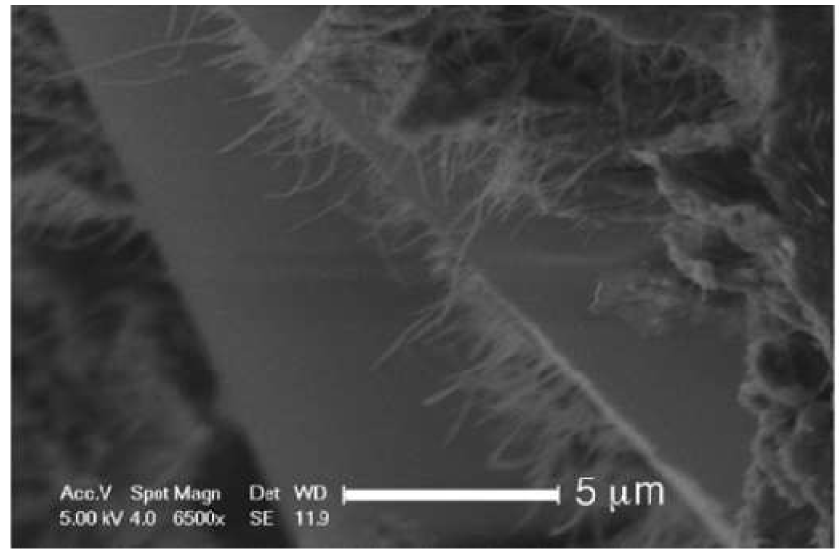
Lightning strike protection
EMI shielding

[NASA]



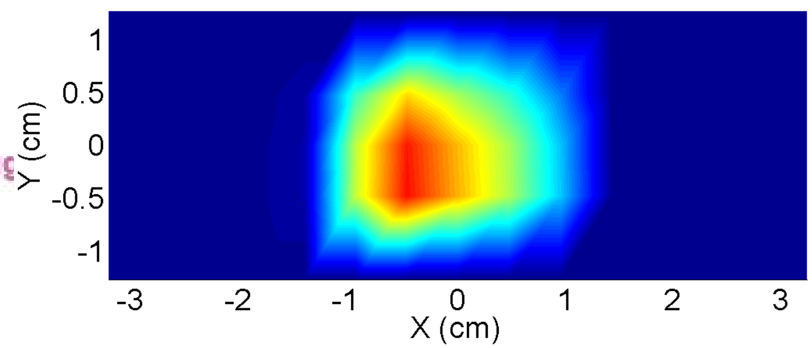
[Farmer, Nano Materials, 2007]

Mechanical interface enhancement



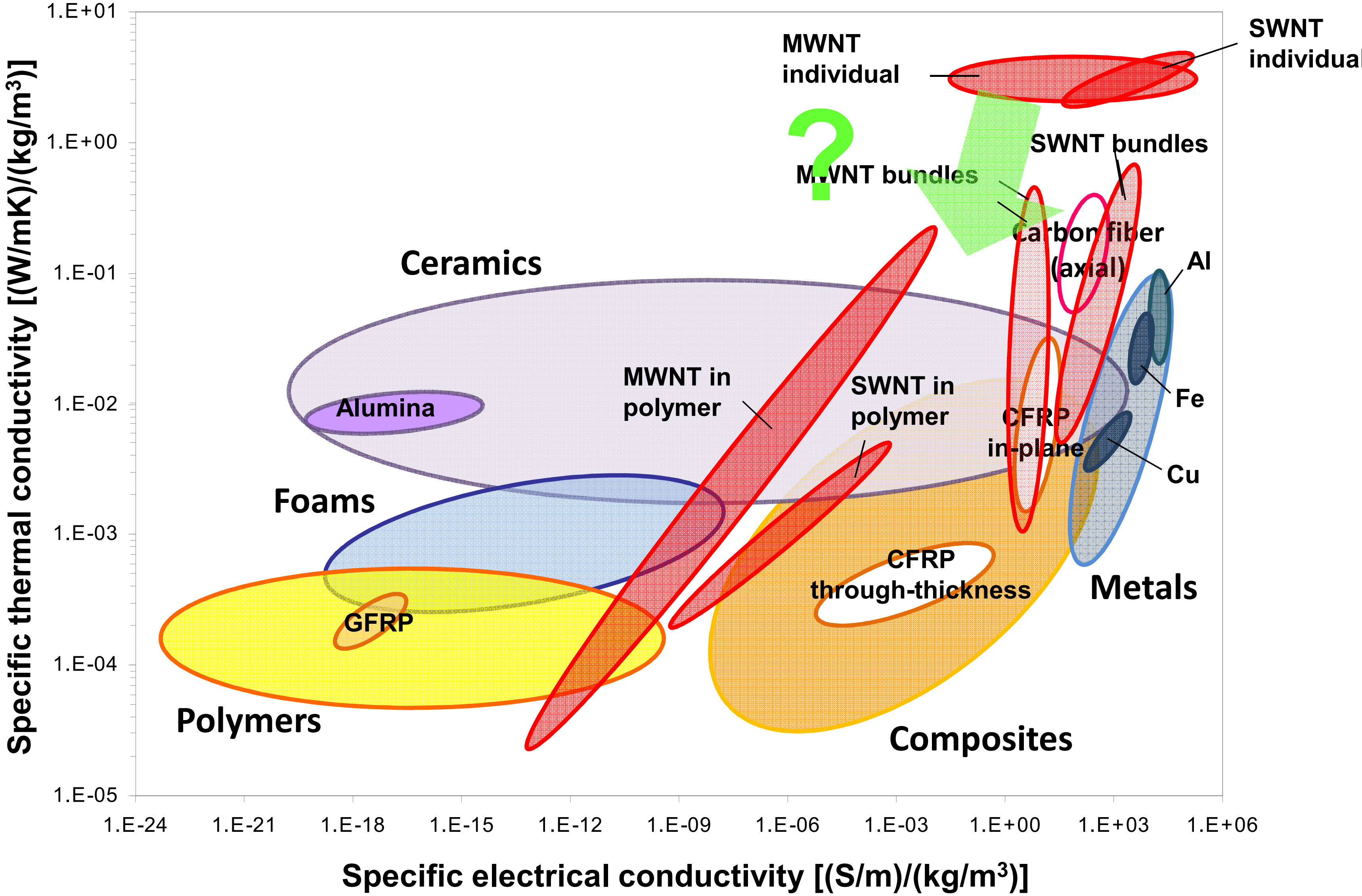
[Wicks et al., Comp. Sci. Tech., 2010]

Damage detection



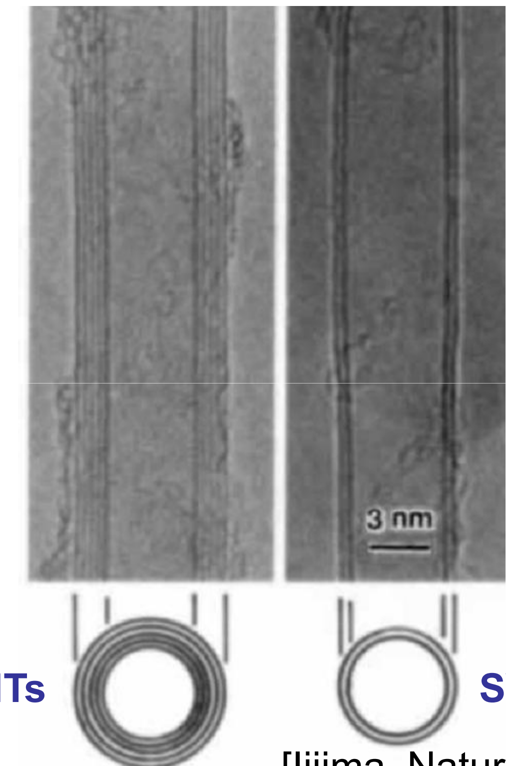
[Wicks et al., AIAA, 2010]

CNT Scaling and Compositing Effects



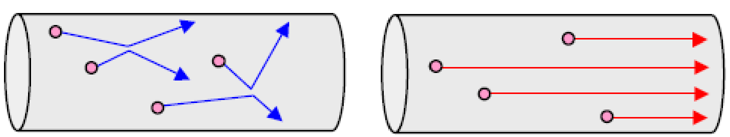
Limiting Factors of Electrical/Thermal Transport in CNT-Composites

CNT itself



MWNTs **SWNTs**

[Iijima, Nature, 1991]

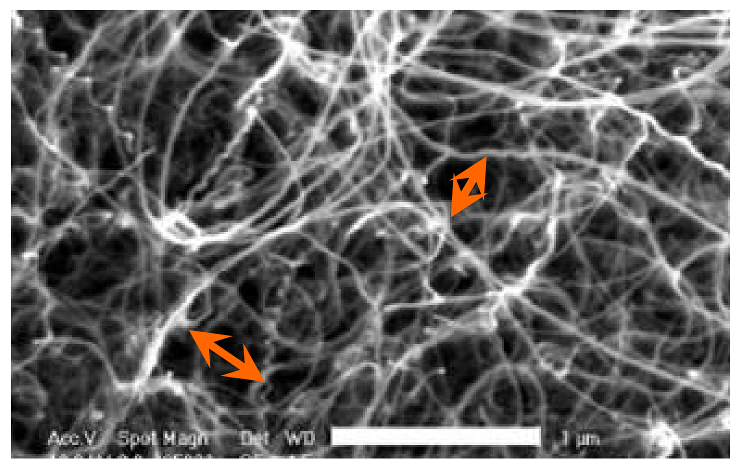


Diffusive vs. Ballistic

[Yamamoto, 6th US-Japan Joint Seminar on Nanoscale Transport Phenomena, 2008]

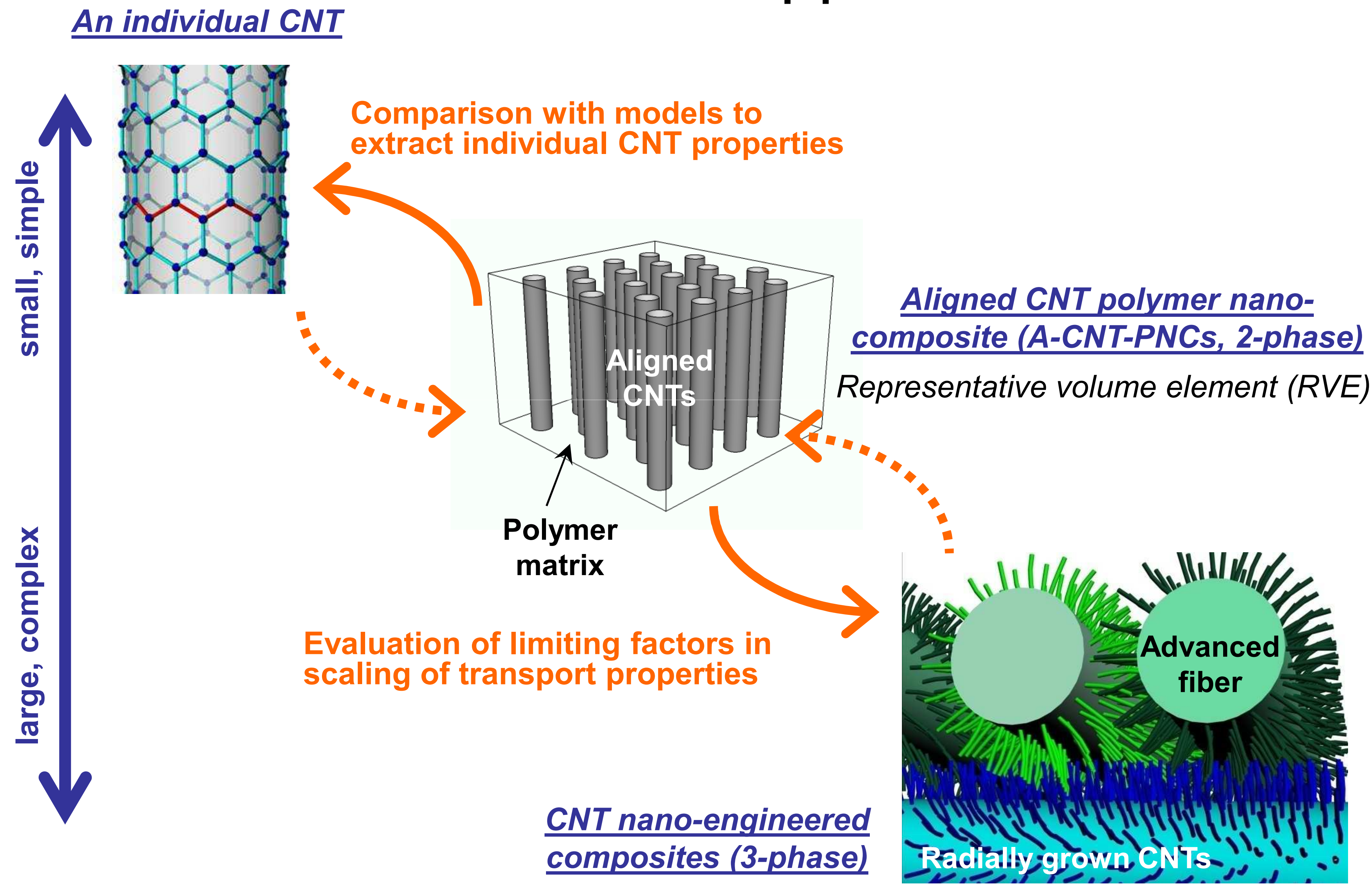
- CNT properties
- CNT composite fabrication
- CNT composite testing
- Transport model of CNT composites

CNT Morphologies



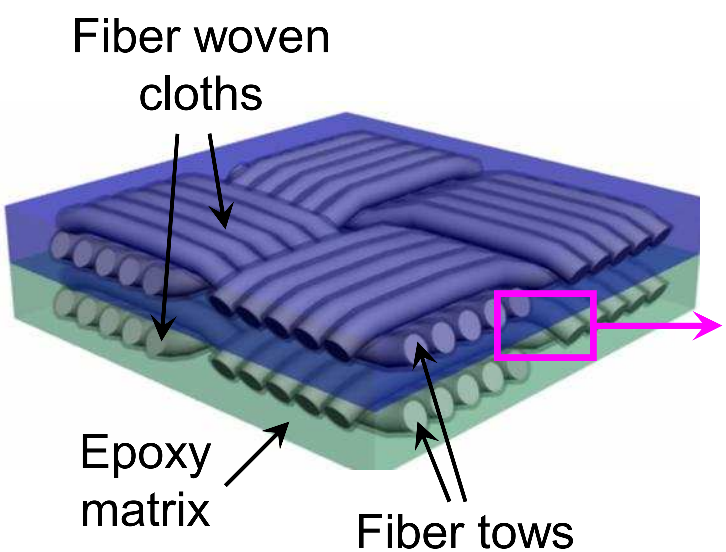
[Hart et al., J. Phys. Chem. B,2006]

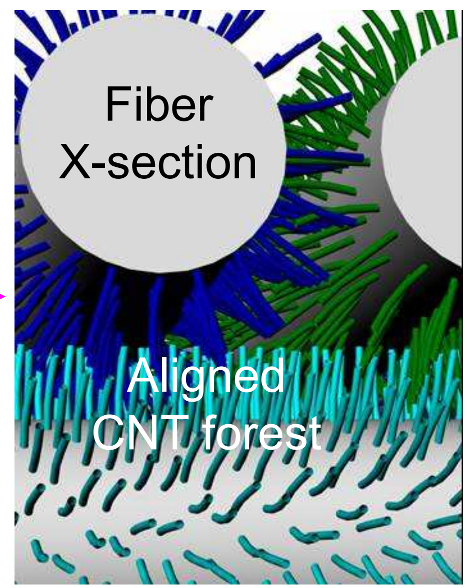
Multi-Scale Approach



CNT Nano-engineered Composites:
Fuzzy Fiber Reinforced Plastic (FFRP)

- ***Radially aligned*** CNTs grown on fiber surfaces (as the 3rd phase)
- ***Mechanical bridging and thermal/electrical conductive pathways*** made of CNTs throughout the structure
- Good CNT dispersion in matrix

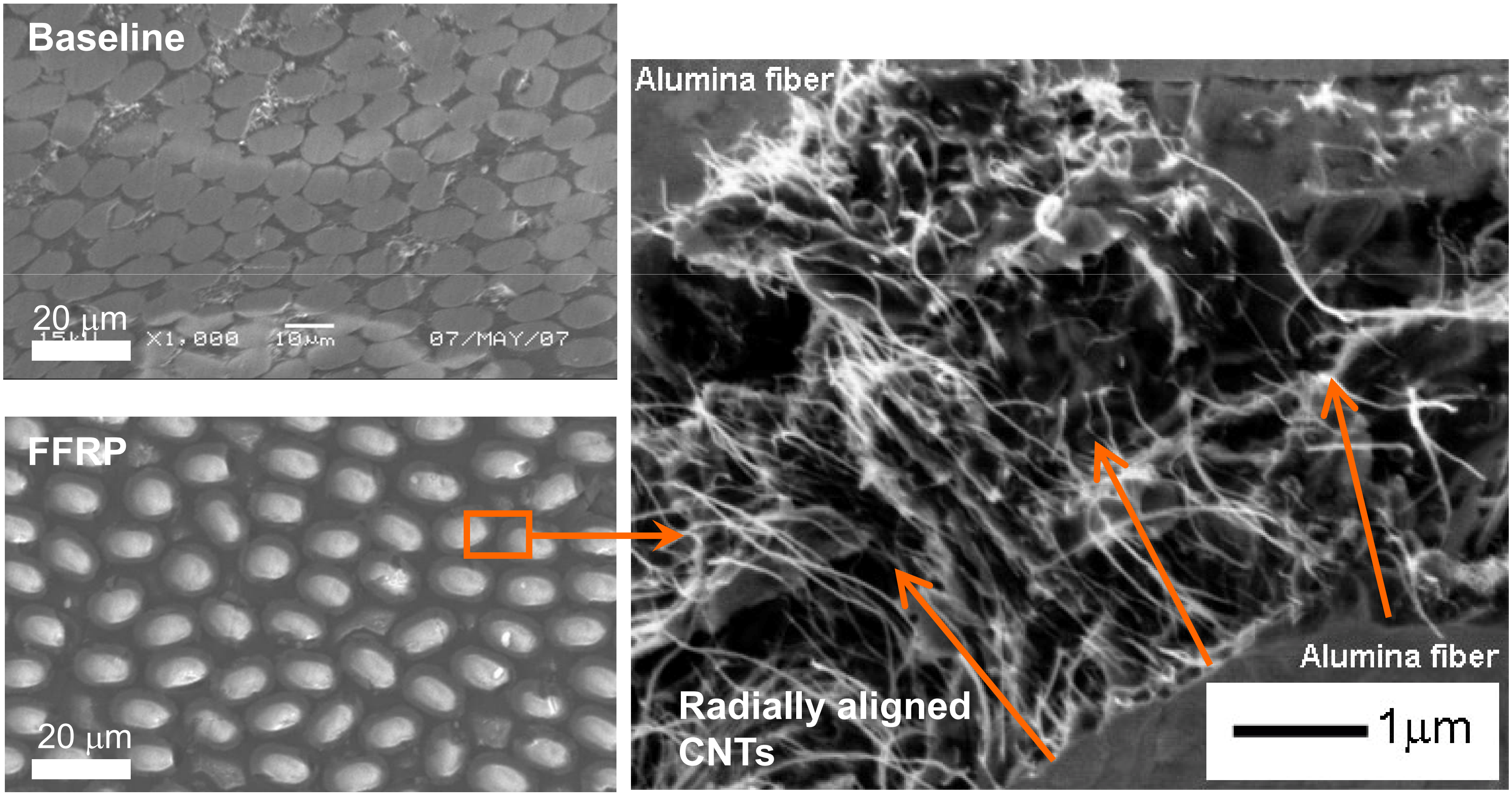




1 cm

FFRP Fabrication

Capillary-driven epoxy infiltration: retained CNT alignment and dispersion

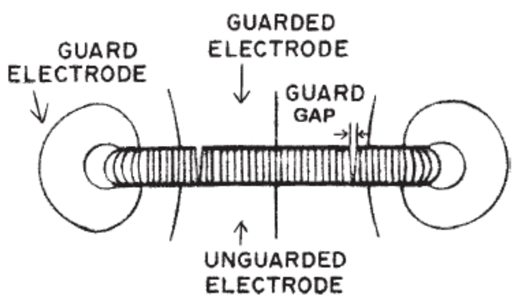


[Yamamoto et al., ICCM, 2007]

FFRP Electrical Testing

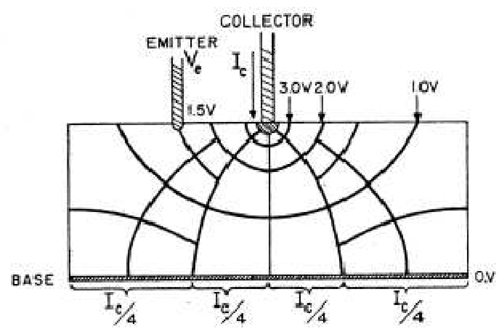
$X10^6$-10^8 conduction enhancement with ~1-3% V_f of CNTs

2 probe, bulk (DC/AC)



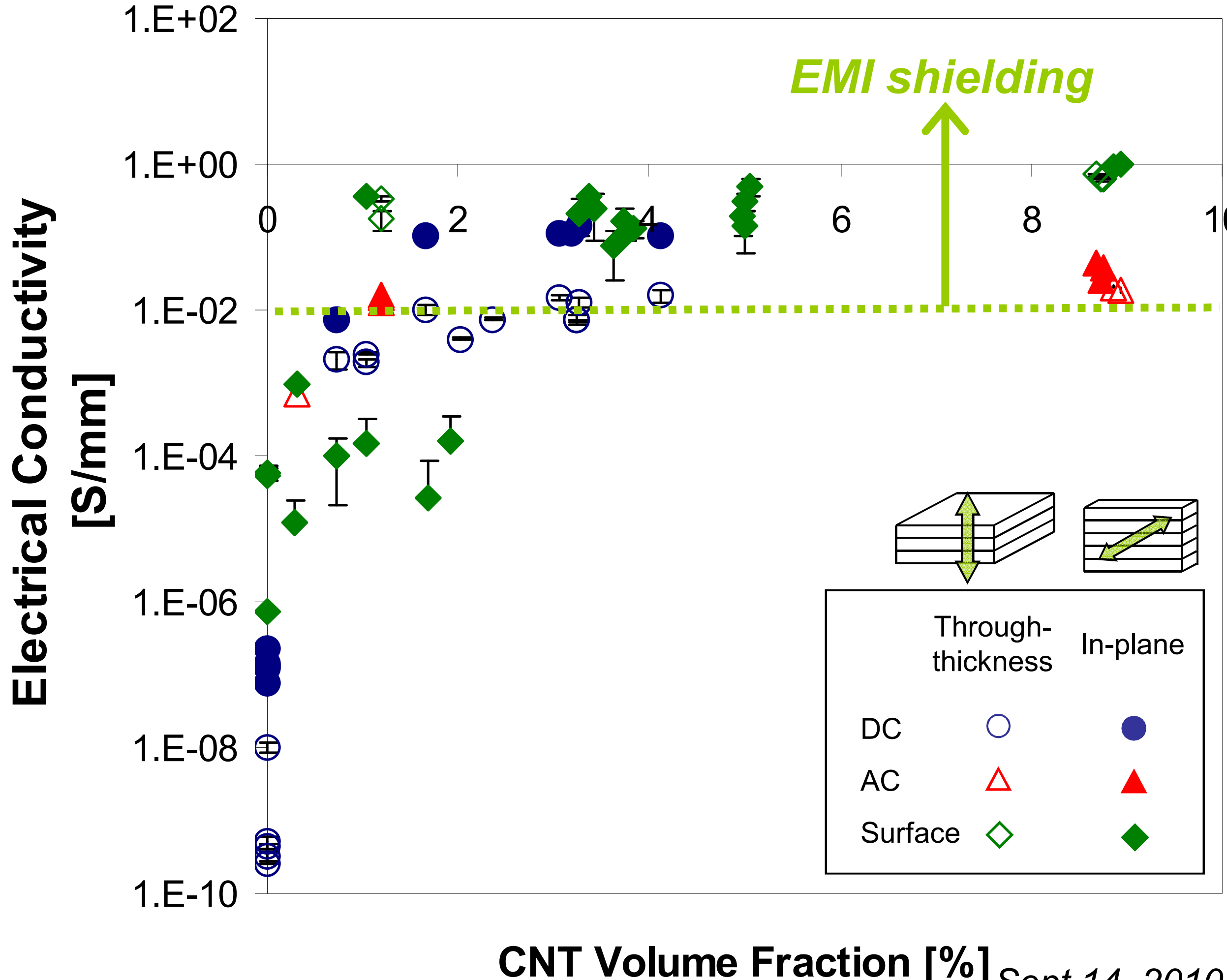
[ASTM D150]

4 probe, surface



[Valdes, Proceedings of the IRE,1952]

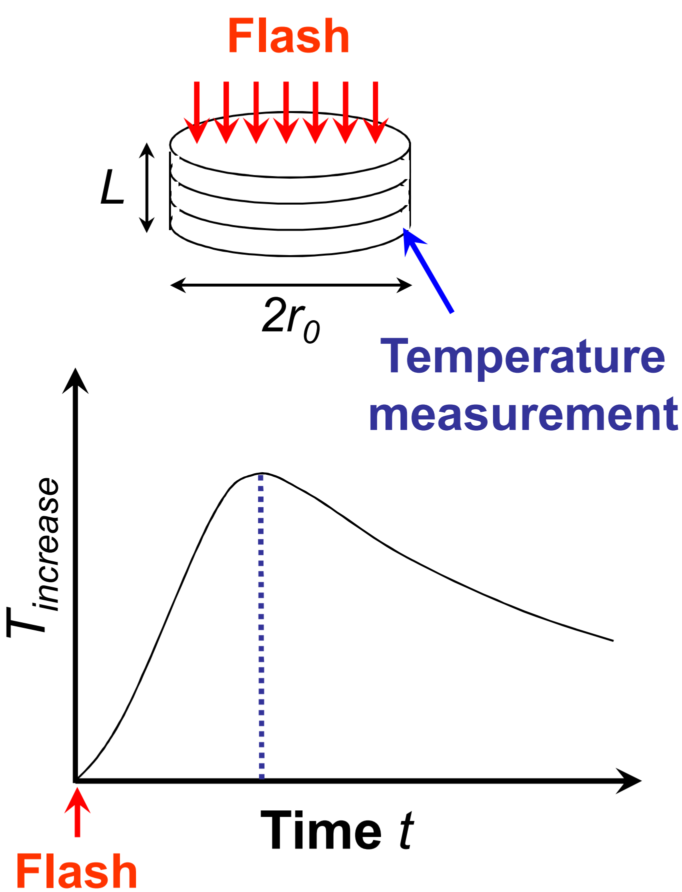
[Yamamoto et al., AIAA, 2010]



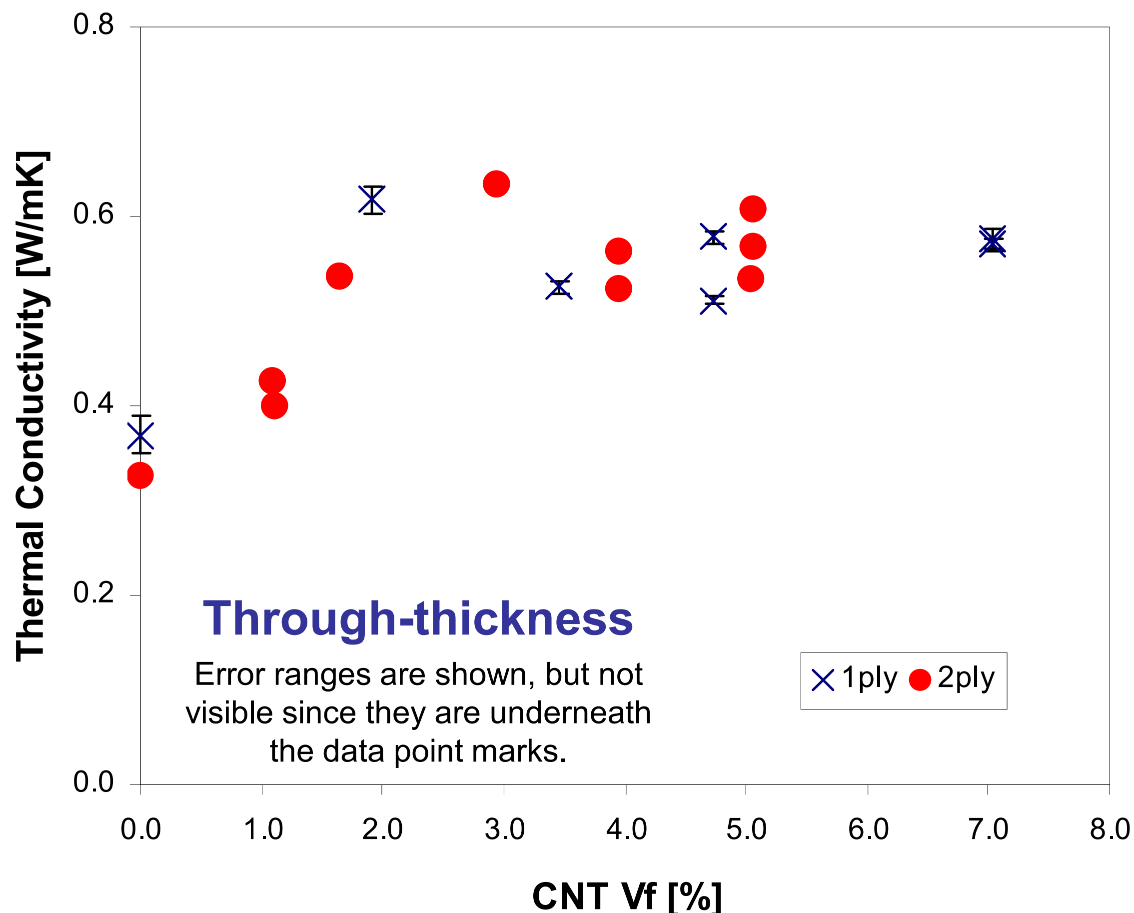
FFRP Thermal Testing

x1.9 conduction enhancement with ~3% V_f of CNTs
suggests larger inter-CNT resistance effects in thermal conduction

Laser-flash

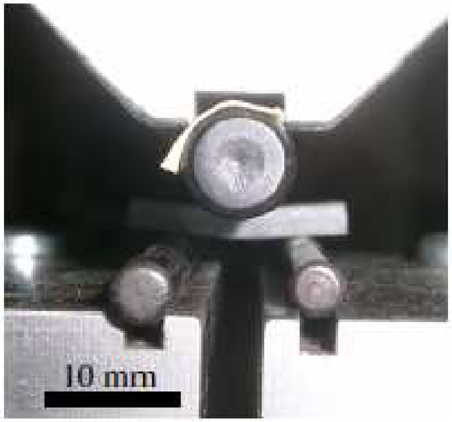


[Yamamoto et al., AIAA, 2010]



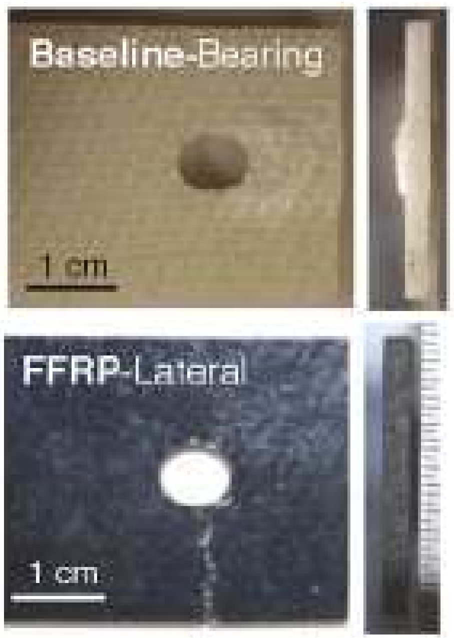
FFRP Mechanical Testing

Short beam shear strength



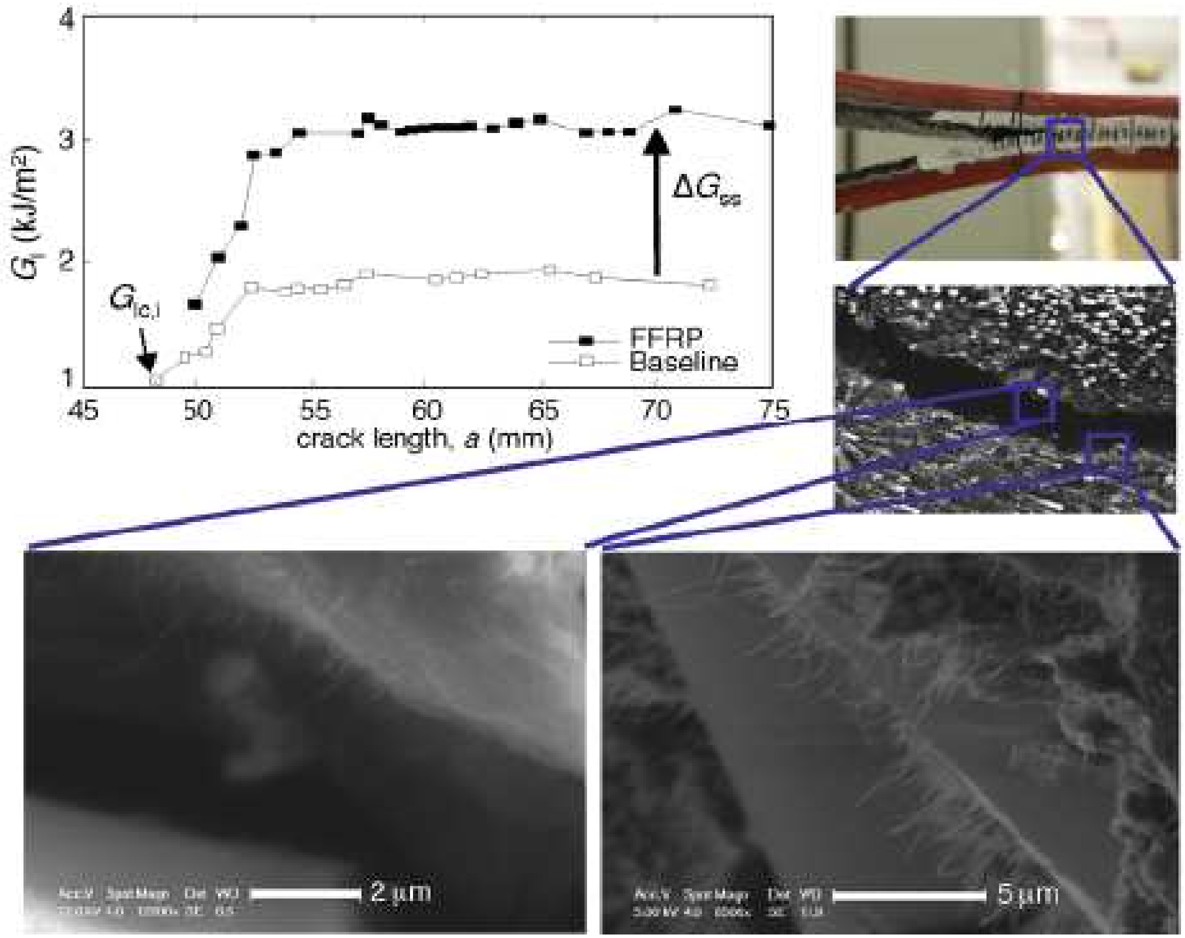
[Garcia et al., Comp.Sci.Tech., 2008]

Tension bearing



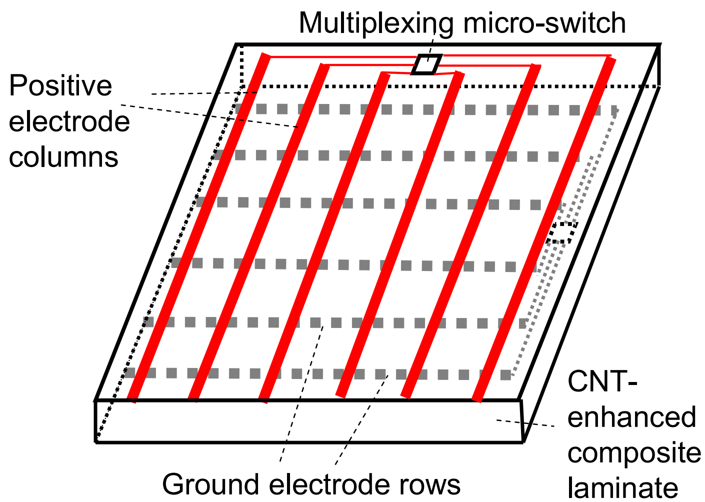
[Wicks et al., Comp.Sci.Tech., 2010]

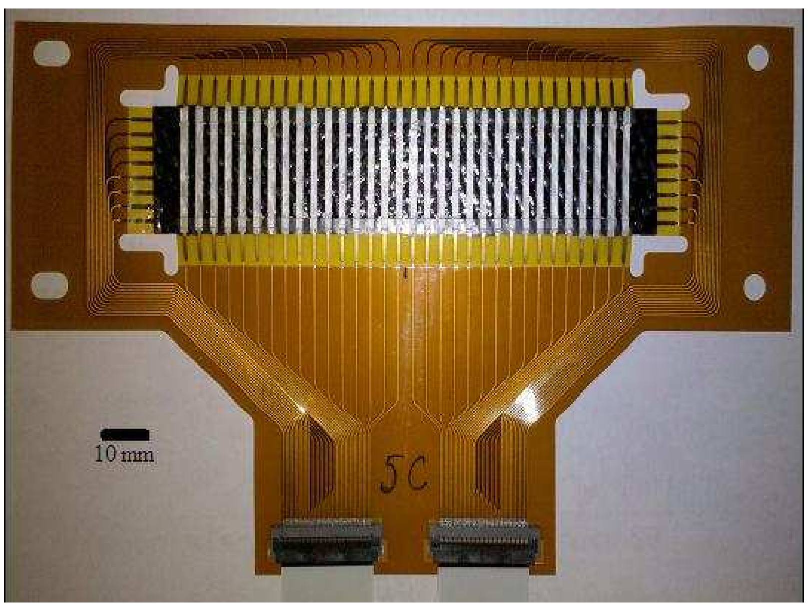
Mode I fracture toughness



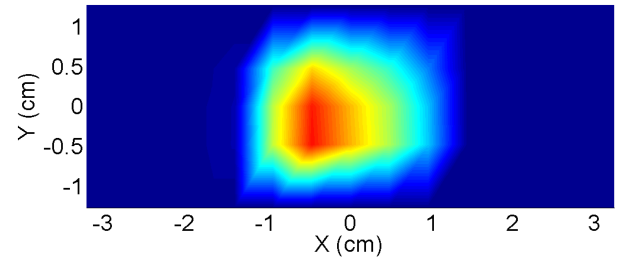
[Wicks et al., Comp.Sci.Tech., 2010]

FFRP System Health Monitoring

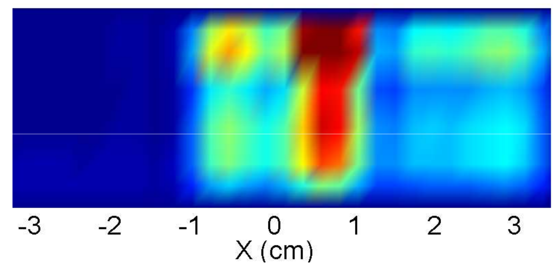




In-plane



Through-thickness



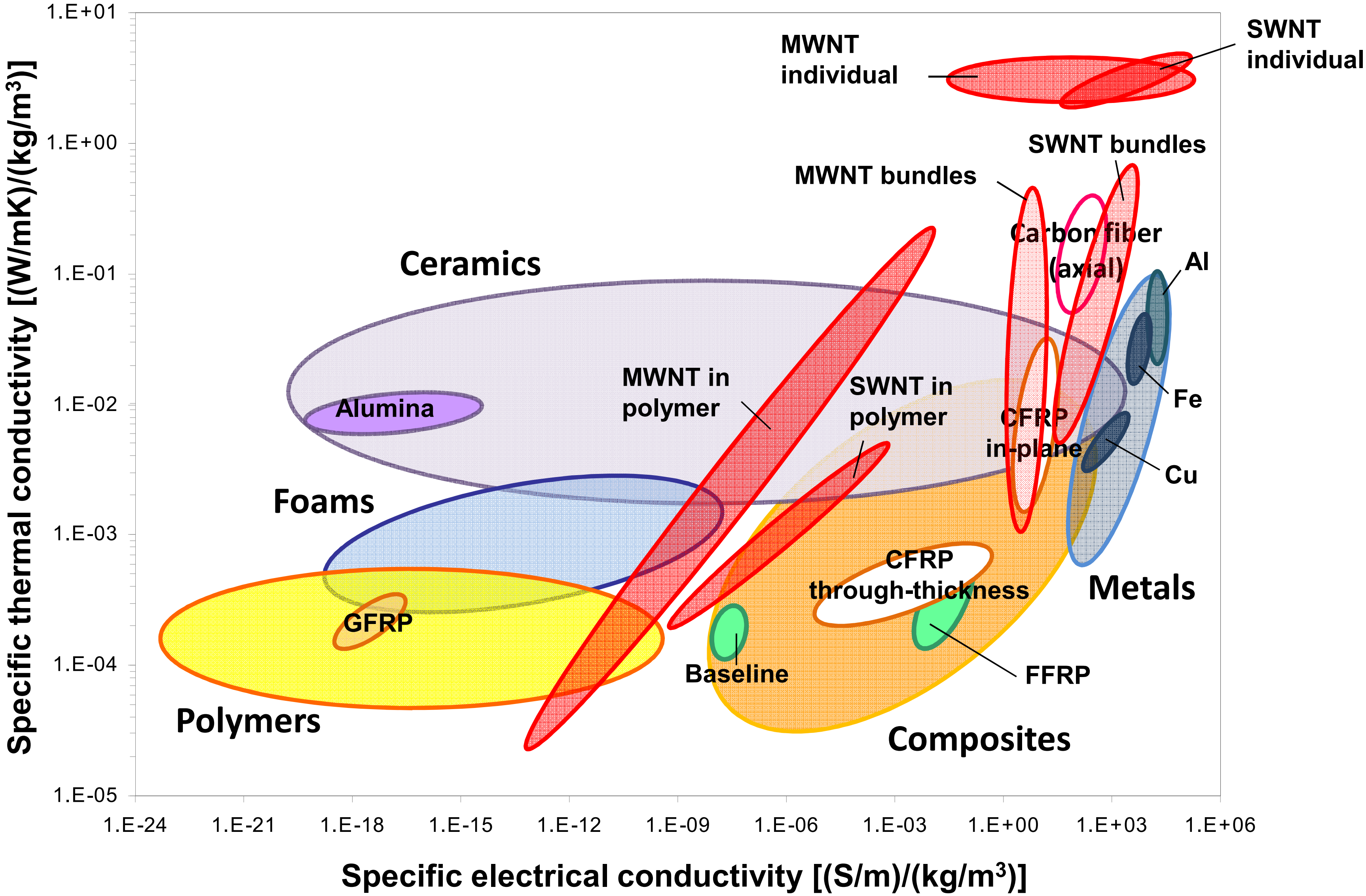
- Patterned with Ag paint electrode grids
- Applied on impact damage
- Significant electrical resistance changes to represent the damage locations

[Wicks et al., AIAA, 2010]

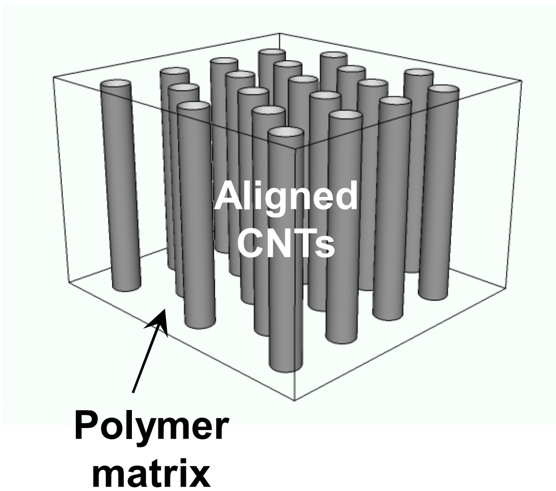
Measured Multi-functional Properties of FFRP

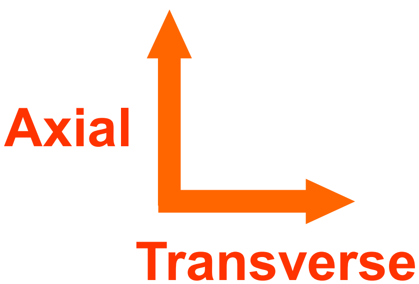
Property		Baseline	FFRP	Enhancement by CNT	CNT V_f [%]
Short beam shear strength [MPa]		20.1	33.8	x1.7	~1-3
Mode I fracture toughness [kJ/m^2]	Non-linear initiation	1.21	2.02	x1.7	~1-2
	Steady-state	2.12	3.74	x1.8	
Tension bearing [MPa]	Chord stiffness	226	246	x1.2	~2.5
	Ultimate bearing stress	236	248	x1.1	
DC electrical conductivity [S/mm]	In-plane	~10^{-7}	~ 10^{-1}	x10^6	~2.7
	Through-thickness	~10^{-10}	~10^{-2}	x10^8	
Thermal conductivity [W/mK]	In-plane	0.42	0.75	x1.8	~5
	Through-thickness	0.58	0.94	x1.6	

CNT Scaling and Compositing Effects



Scaling Down to A-CNT-PNCs





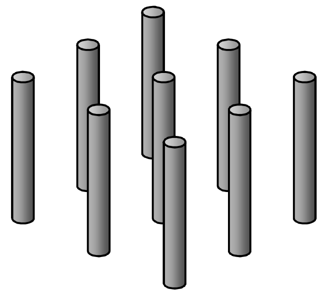
Likely with larger influence by inter-CNT transfers

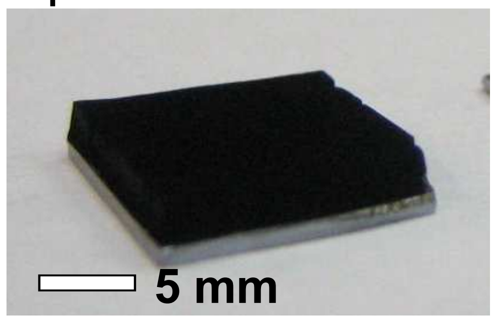
- Unknowns of transport in FFRPs
  - Limiting factors in scaling: even with good CNT dispersion
  - Difference between electrical and thermal transport behavior
  - Keys to further improvement: alignment, morphology?
- A-CNT-PNCs as RVE
  - Simple: easy to model, fewer parameters/unknowns
  - Controlled morphology: variable aligned CNT V_f and length
  - Anisotropic: amplify inter-CNT effects

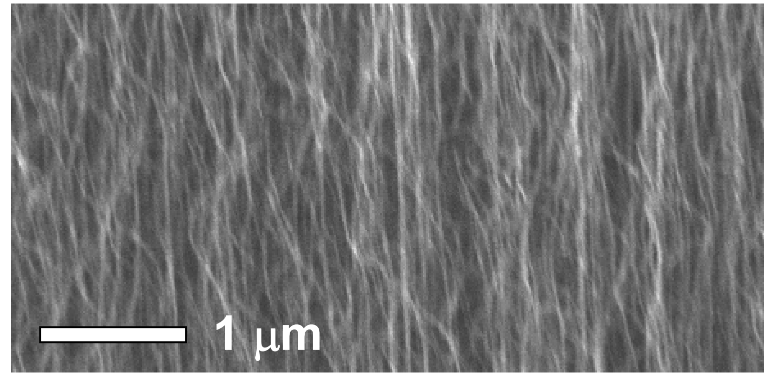
<u>Consistent data on samples with morphology control</u>

Fabrication of A-CNT-PNCs

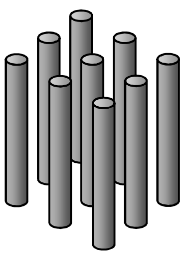
As grown on Si, ~1%V_f

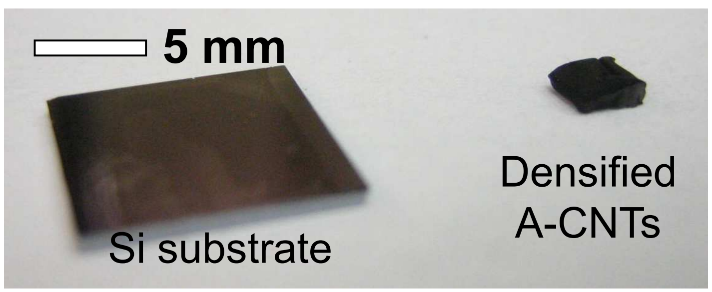


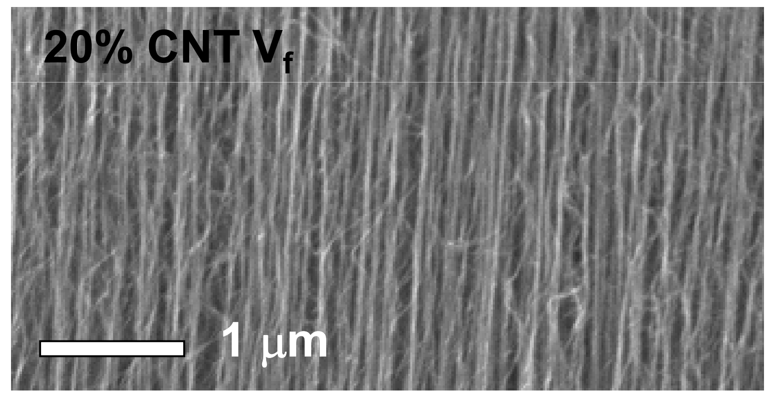




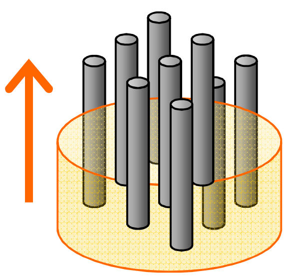
As densified, up to ~20%V_f

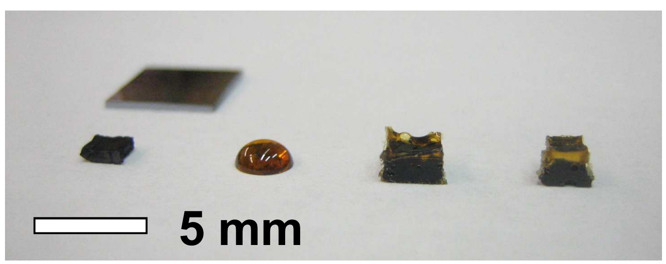


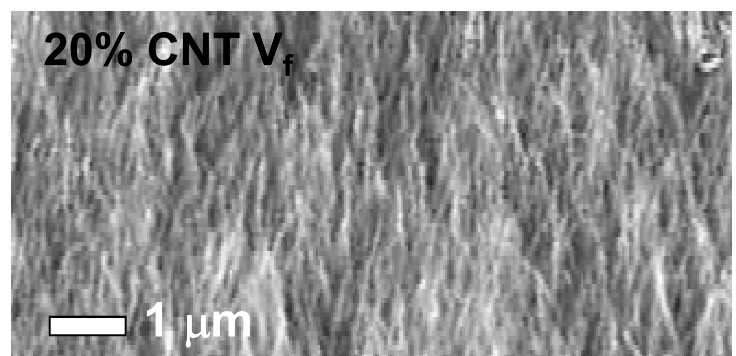




As epoxy-infiltrated/cured, up to ~20%V_f







Contributions and Future Work

- Conclusions
  - Aligned CNTs as 3rd phase (2nd fiber) provides concomitant mechanical, thermal, and electrical enhancement
  - Limiting factors in thermal and electrical transport were identified and quantified through characterization of A-CNT-PNCs.
- Future Work
  - Composite processing: CNT growth on carbon fibers, infusion with aero-grade epoxy
  - Further FFRP characterization: mechanical and thermoelectrical properties, focusing on anisotropy due to aligned-CNTs

Thank you!

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