UNIVERSITY OF CAMBRIDGE

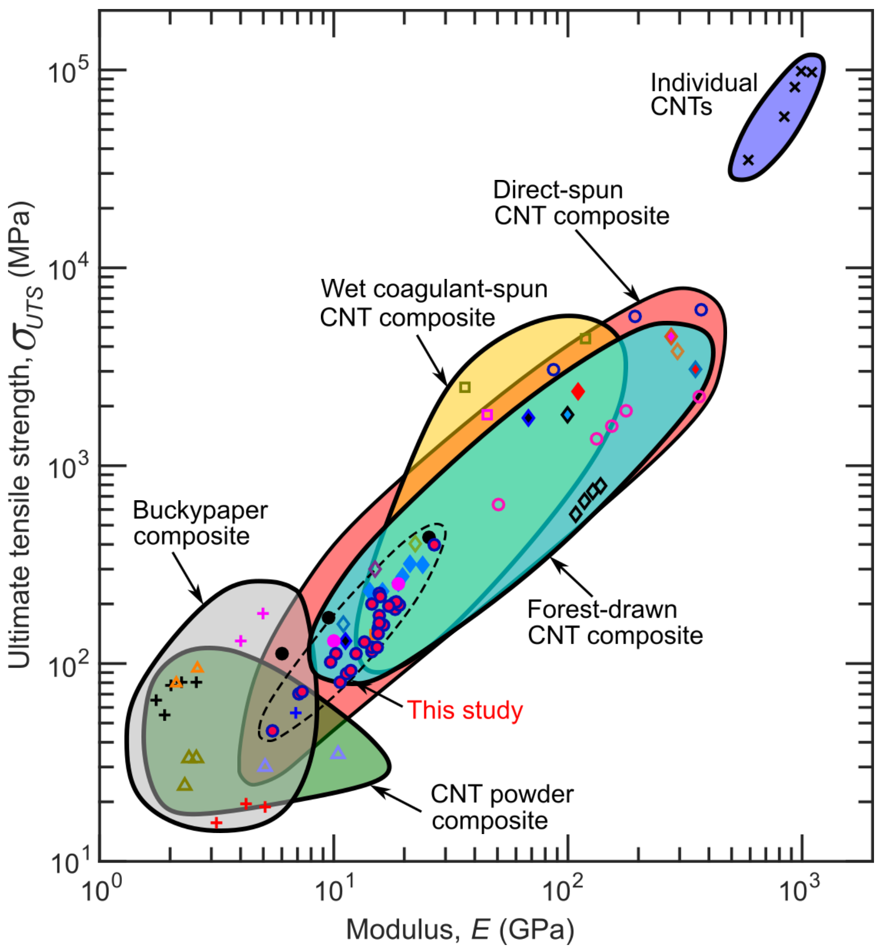
Mechanical and energy-storage properties of carbon nanotube-polymer composites

Dr. Wei Tan

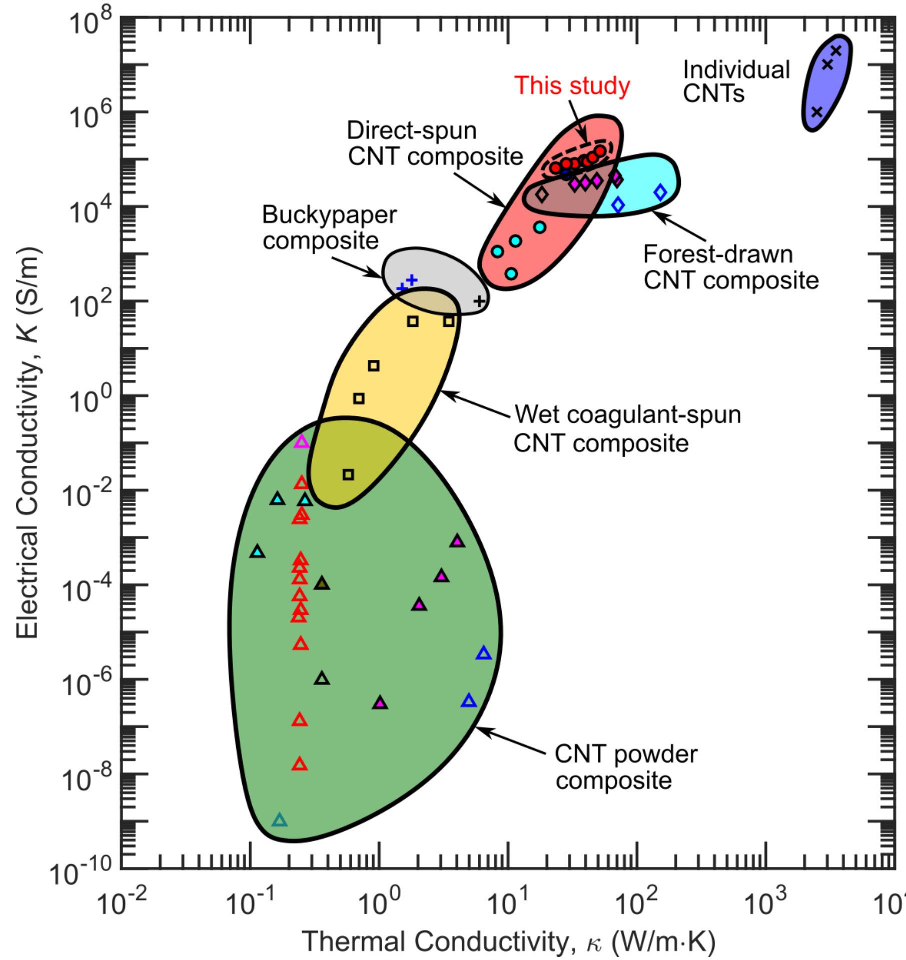
Research Associate, University of Cambridge

Classes of CNT-polymer composites

Strength vs. Modulus



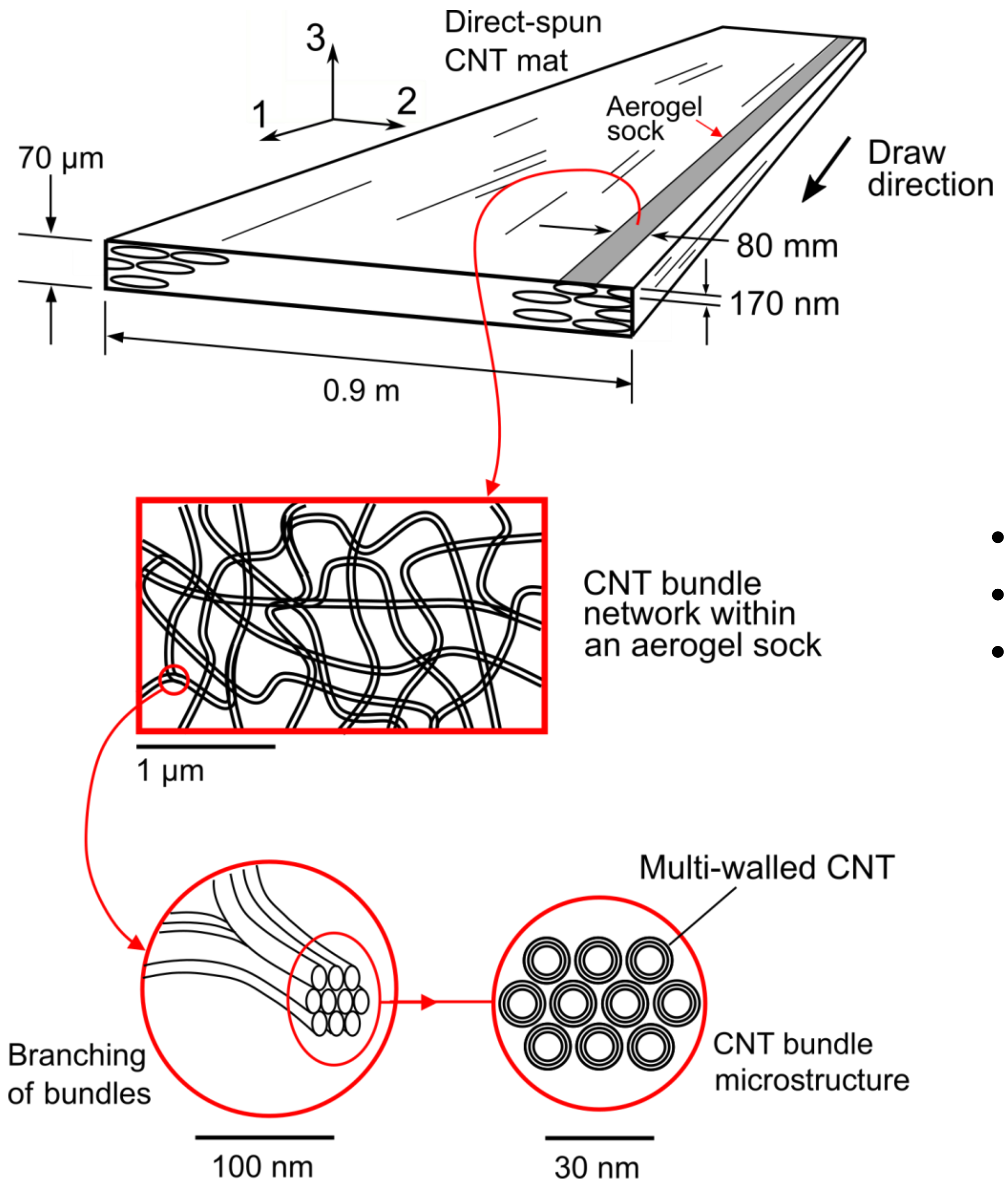
Electrical vs. Thermal



Why? alignment, waviness, composition, etc

UNIVERSITY OF CAMBRIDGE

Hierarchical structure of CNT material

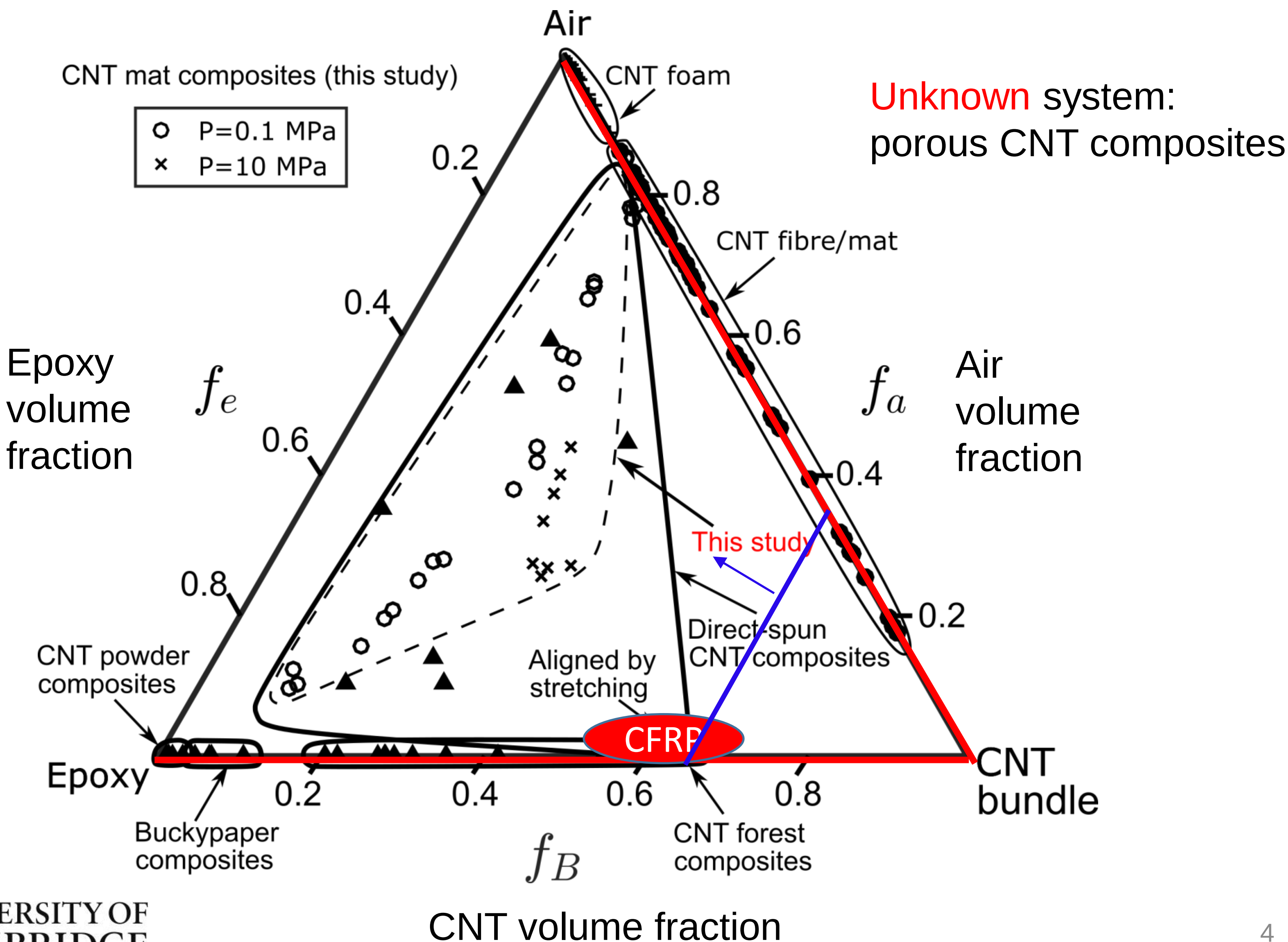


Factors:

- Composition
- Alignment
- waviness, etc

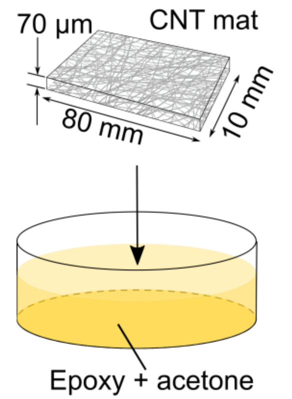
Compositional space

- CNT-epoxy composites consist of a mixture of three phases.



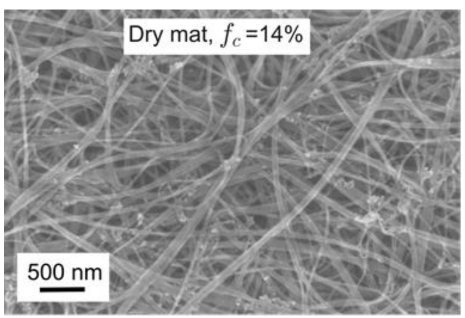
CNT/epoxy composite with various composition

Infiltration | **Remove acetone and condensation** | **Consolidation**

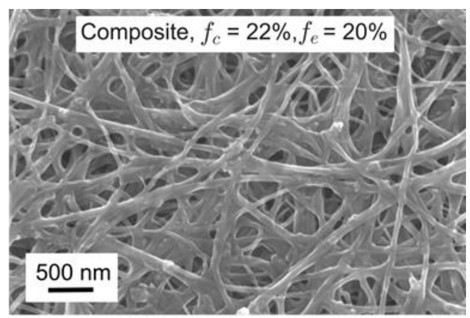


ϕ_e= 0.1% - 100%

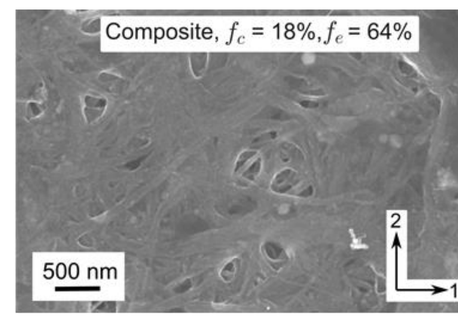
(1)



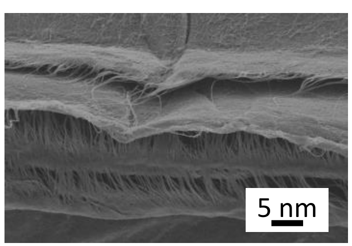
(5)

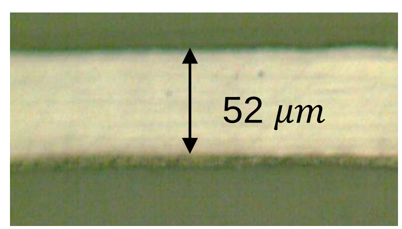


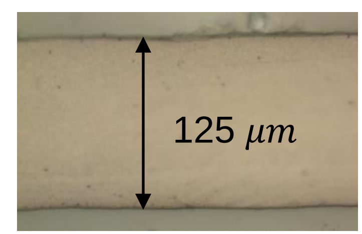
(8)



Thickness (70 μm)

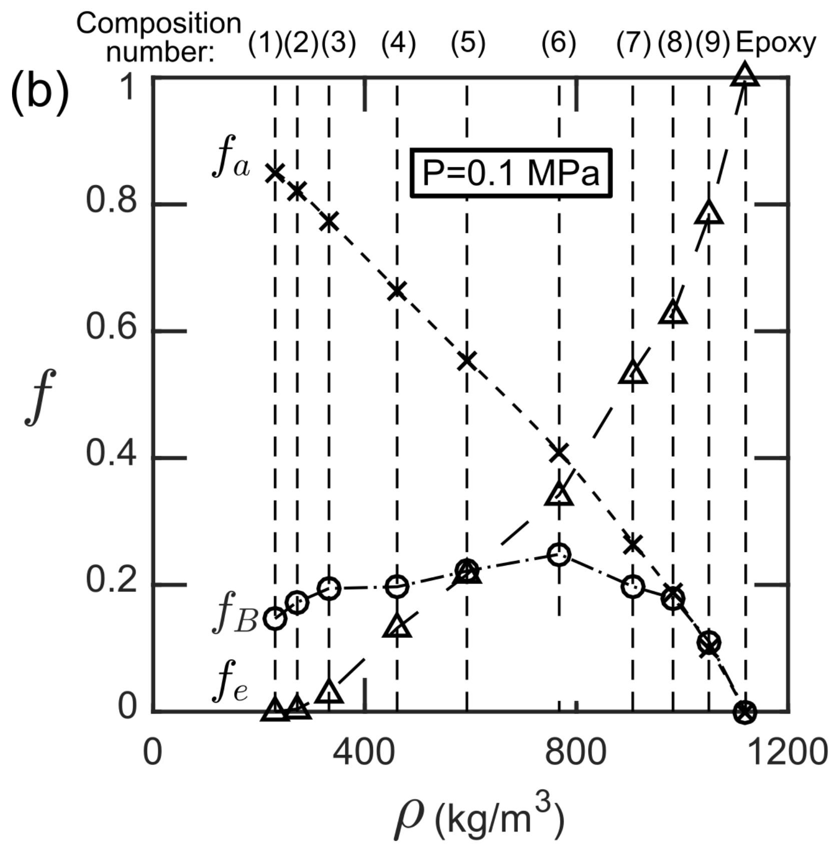




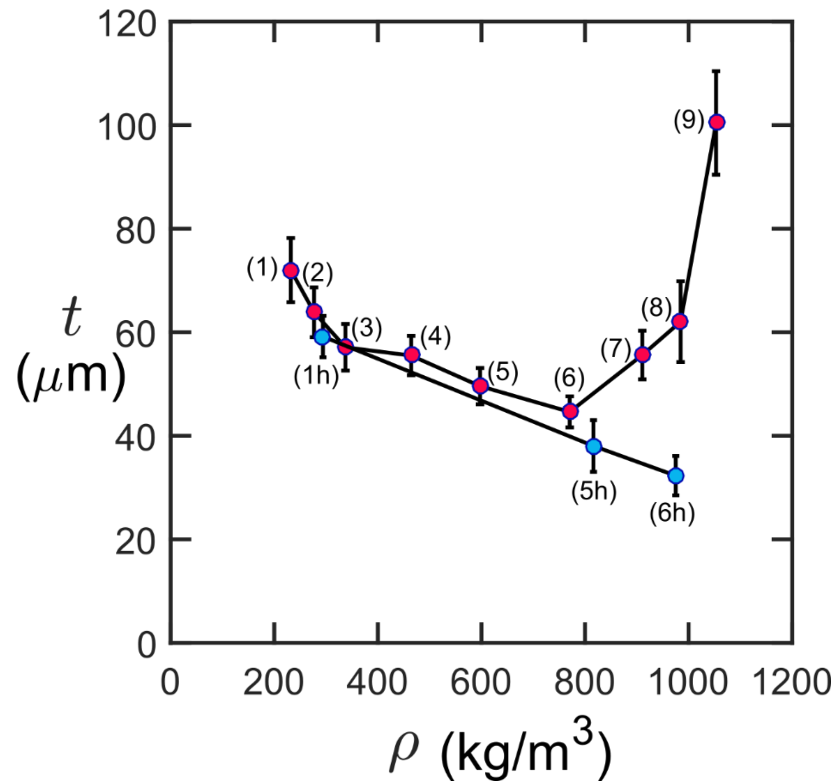


CNT-epoxy composites

Volume fraction of three phases



Thickness of cured composites



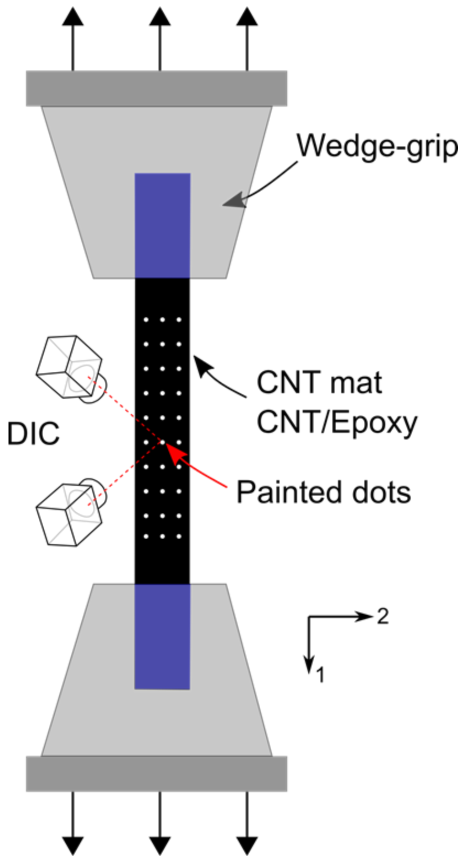
f_B – CNT vol%
f_e – Epoxy vol%
f_a – Air vol%

- CNT volume fraction mainly changes in the out-of-plane direction

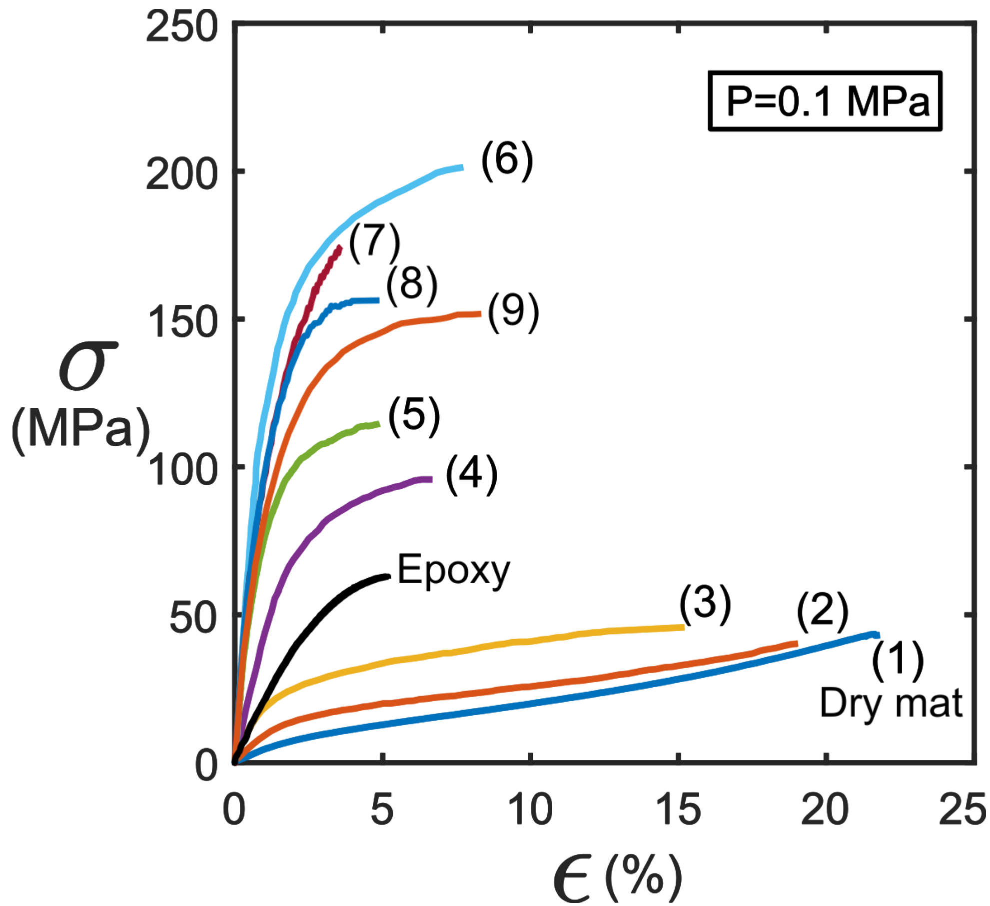
UNIVERSITY OF CAMBRIDGE

Tensile properties of CNT mat and their composites

Tensile tests



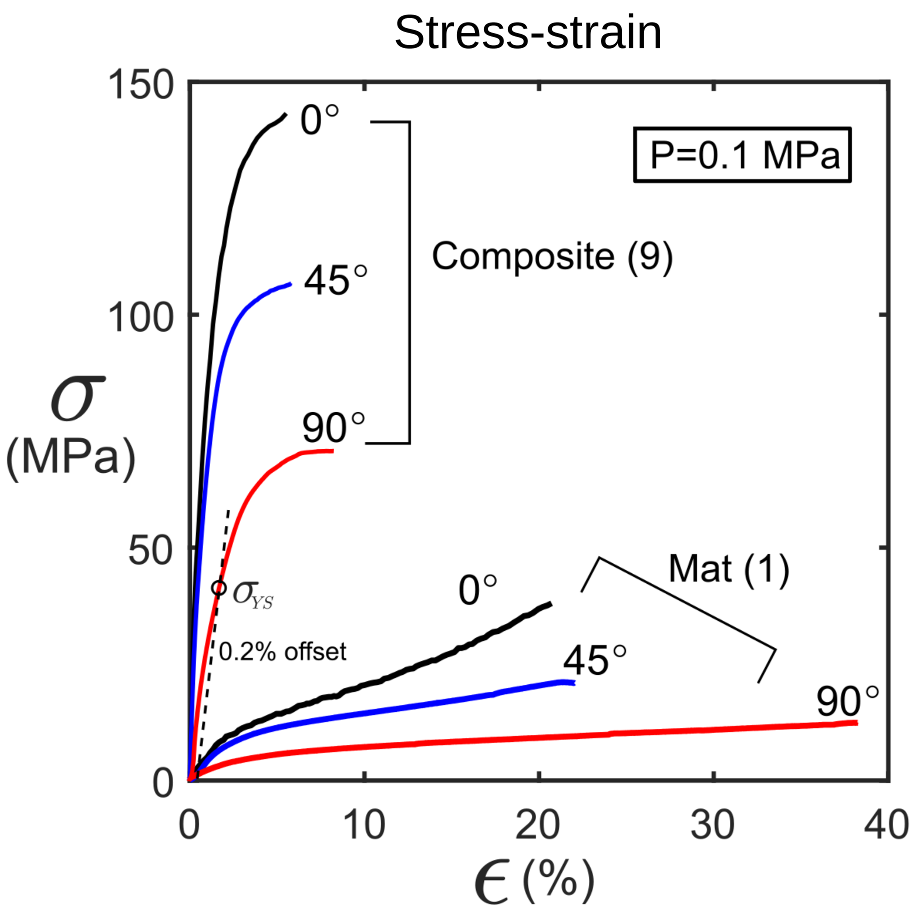
Stress-strain curves

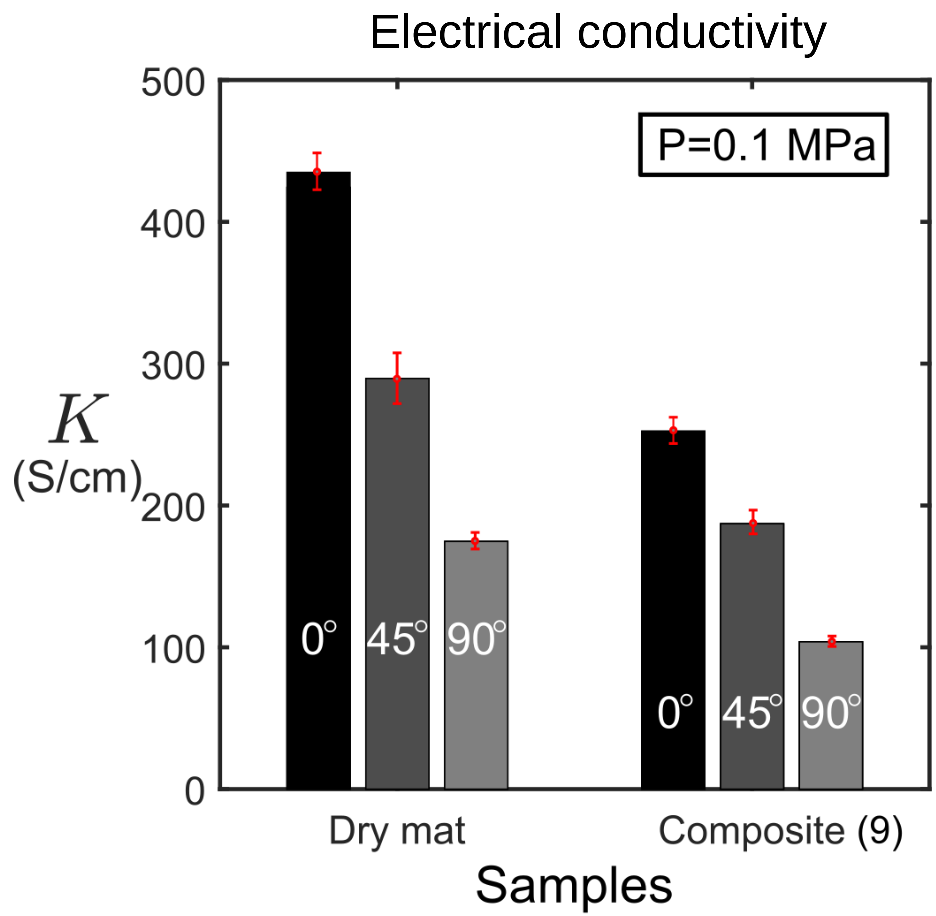


- The mutual effect of **CNT bundles** and **epoxy resin**, together with the intrinsic anisotropy of the network, produce a large variability in its tensile response.

UNIVERSITY OF CAMBRIDGE

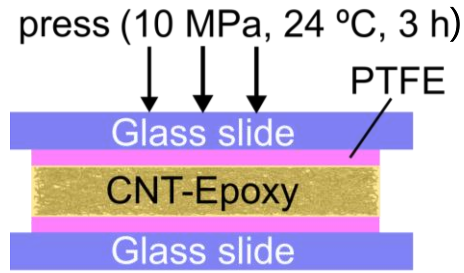
Anisotropy of CNT and CNT-epoxy composite



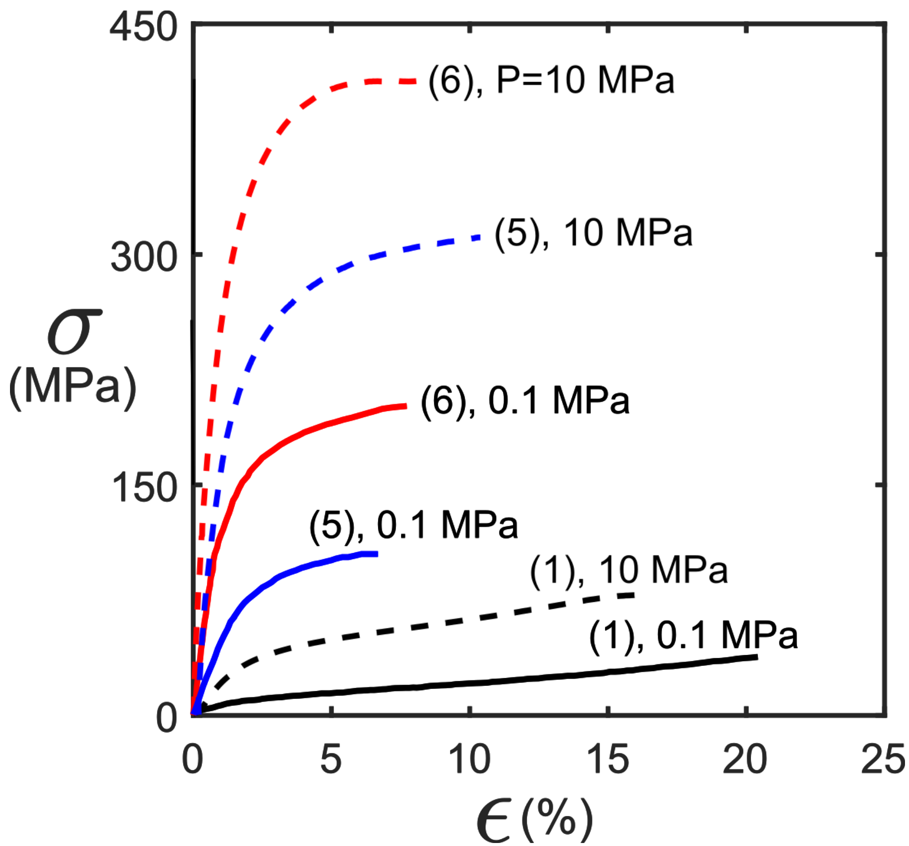


UNIVERSITY OF CAMBRIDGE

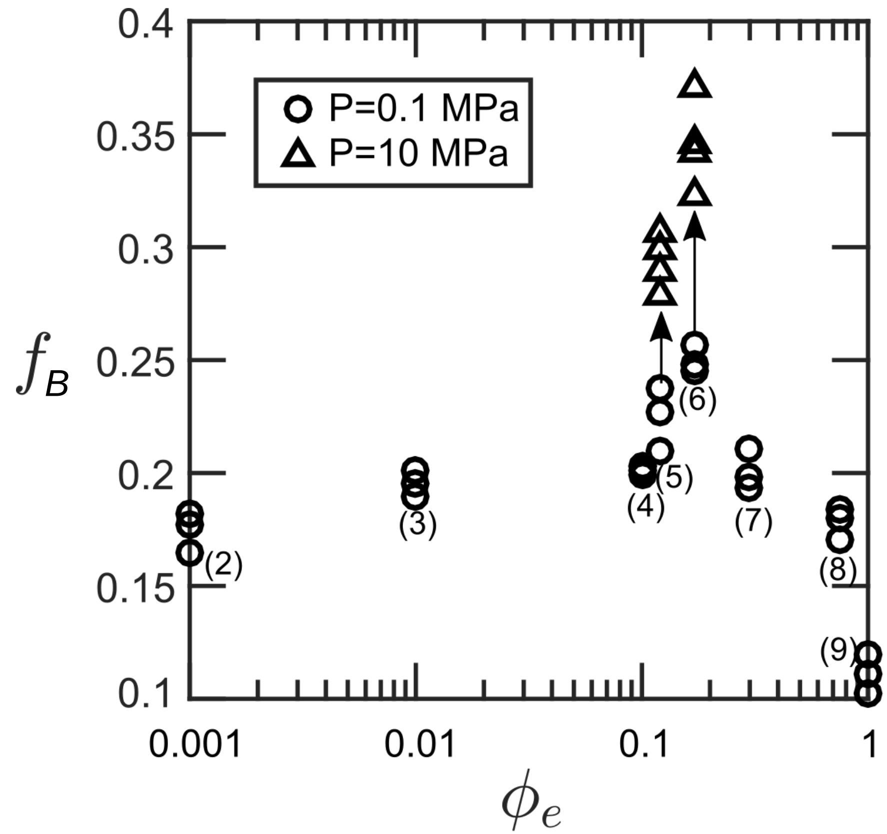
Tensile response of composites



Higher pressure processing



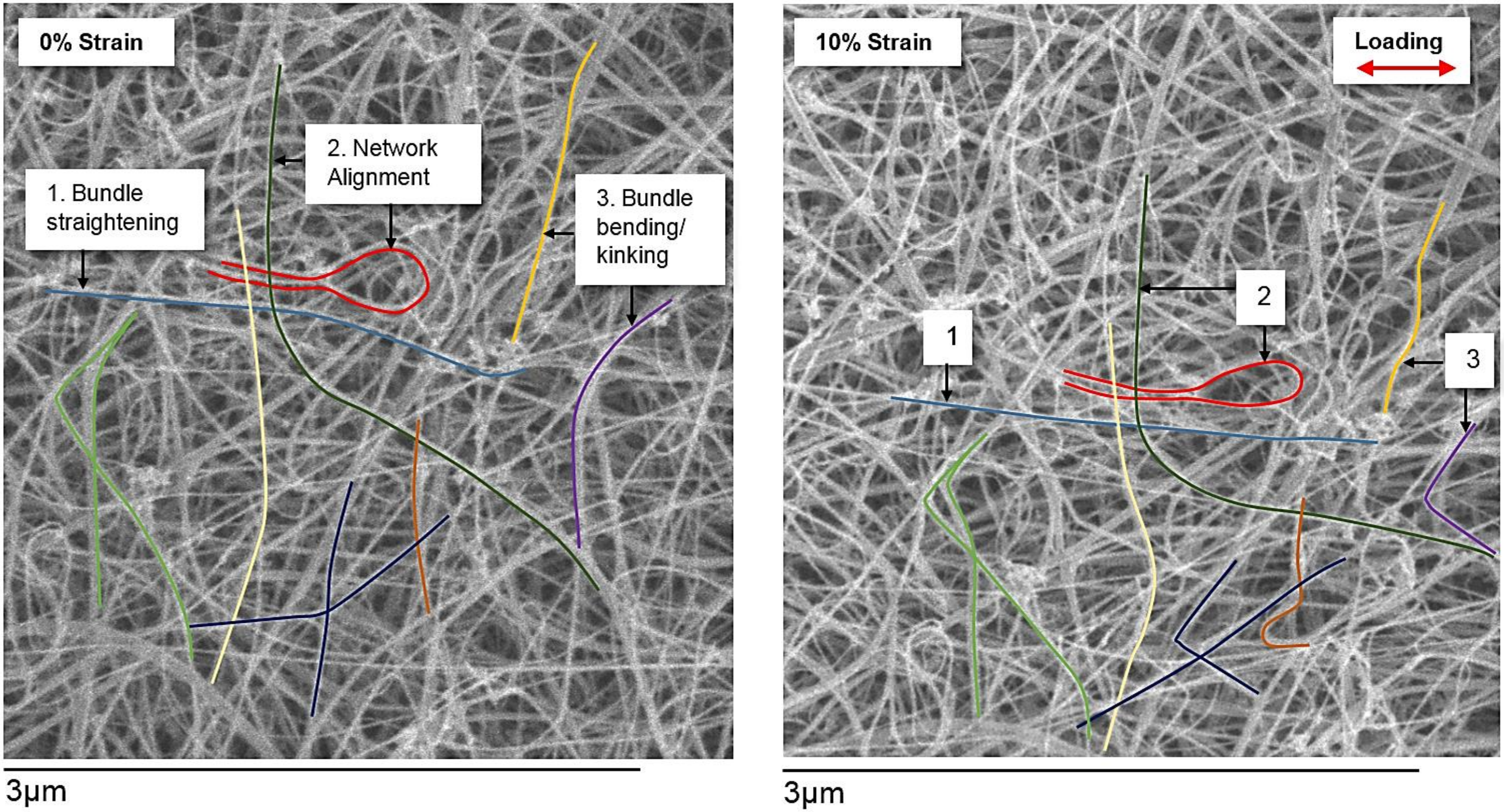
CNT volume fraction



UNIVERSITY OF CAMBRIDGE

- How to model the porous CNT-epoxy composites?

In-situ test: deformation mechanism of CNT mat

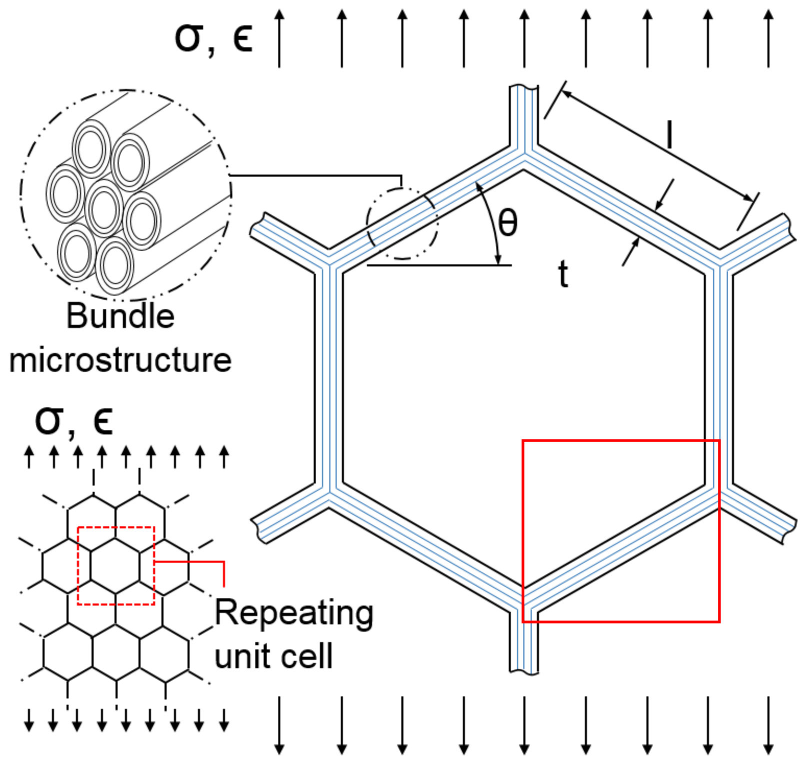


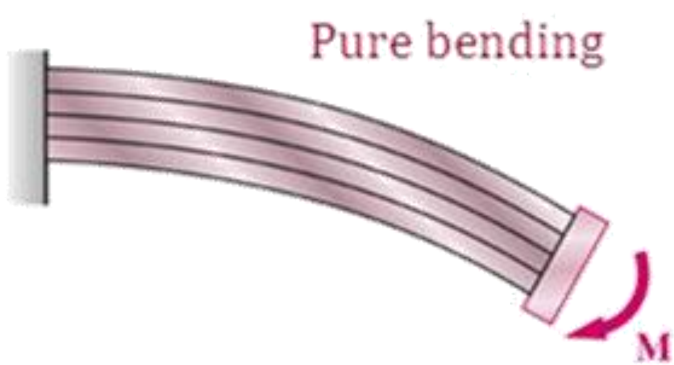
- Rope-like CNT bundles form random interlinked bundle network.
- Network deforms like a foam, with transverse deflection (bending/shear) of struts.

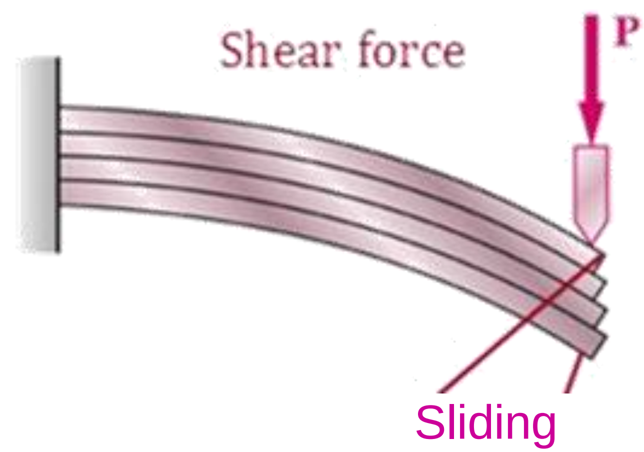
UNIVERSITY OF CAMBRIDGE

[1] J.C. Stallard, W. Tan, F.R. Smail, A.M. Boeis, N.A. Fleck. ***Extrem.Mech.Lett***, 2018

Micromechanical model



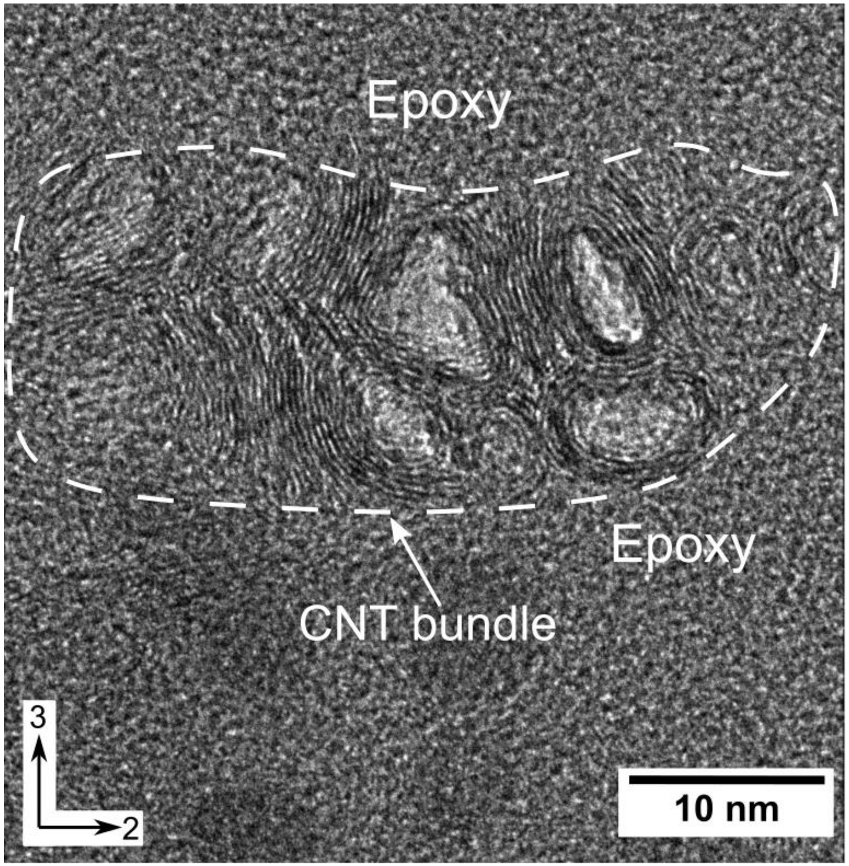




UNIVERSITY OF CAMBRIDGE

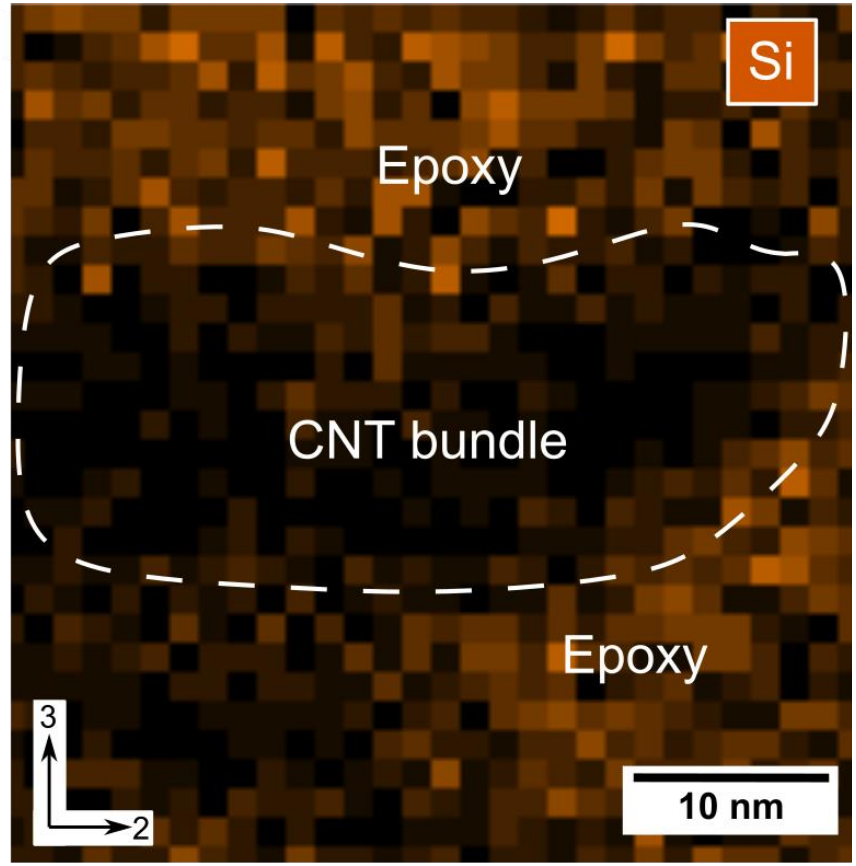
Whether epoxy has infiltrated into CNT bundle ?

TEM



Composite (9)

EDX mapping



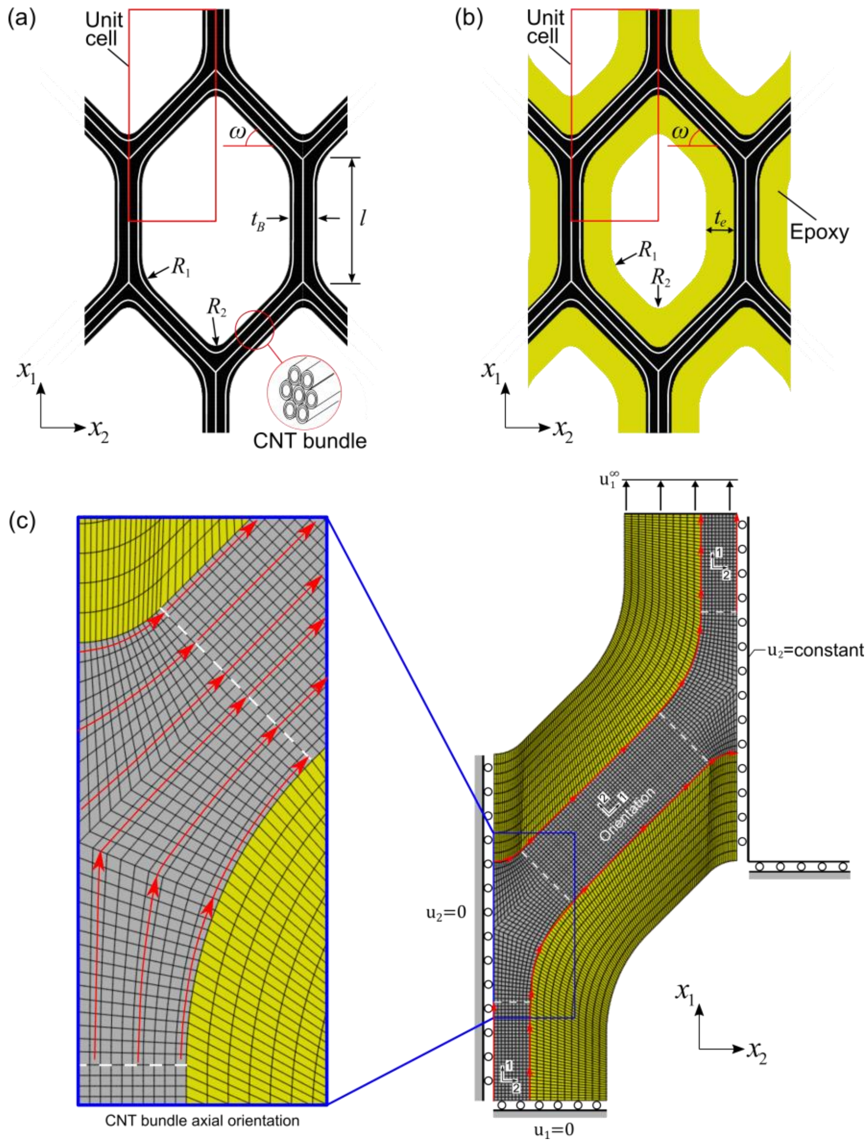
Composite (9)

* Epoxy contains silicon side-groups

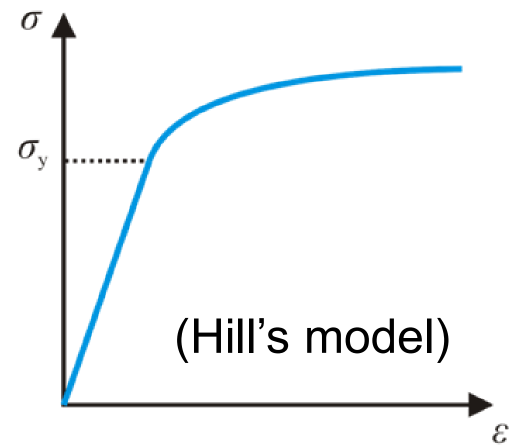
- Epoxy does not infiltrate into the gaps between adjacent CNTs.

UNIVERSITY OF CAMBRIDGE

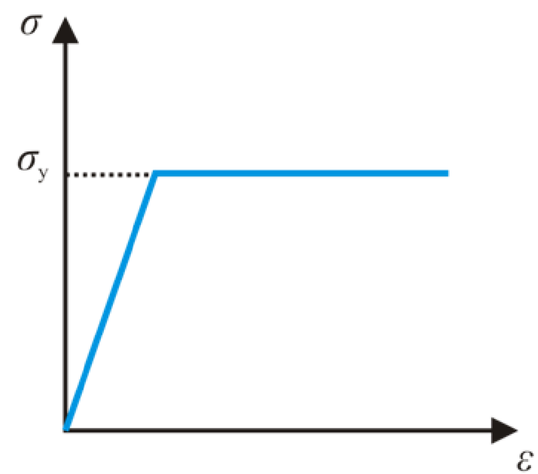
Unit cell model in the finite element analysis



CNT bundle: anisotropic, elasto-plastic



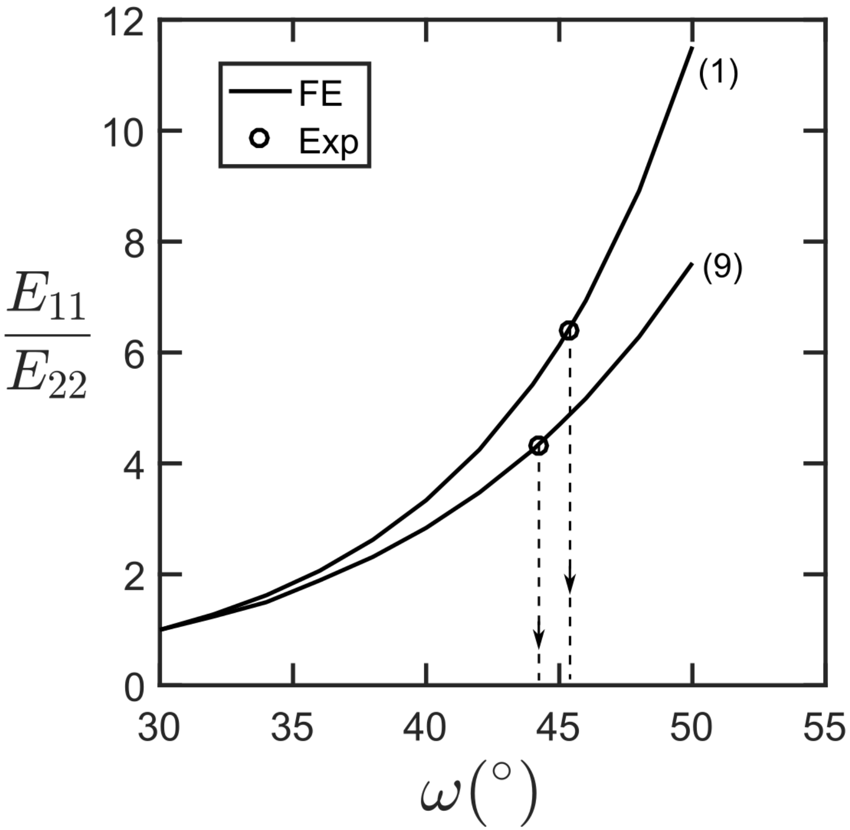
Epoxy: isotropic, perfect-plastic



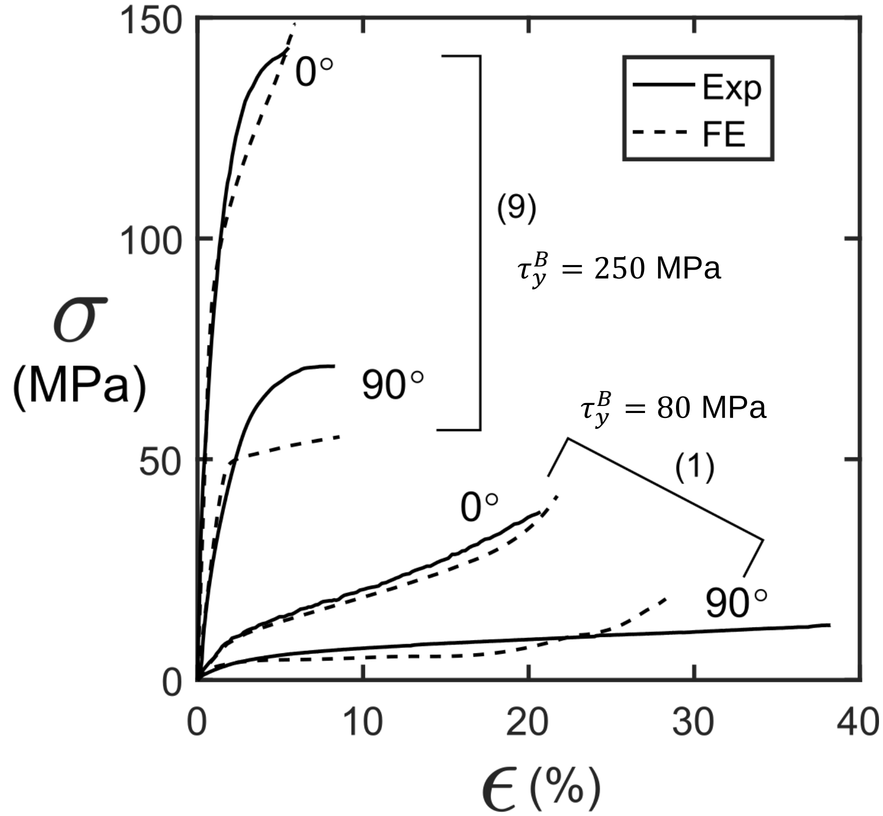
UNIVERSITY OF CAMBRIDGE

Calibration of anisotropy and bundle shear strength

Anisotropy: $\boldsymbol{\omega}$



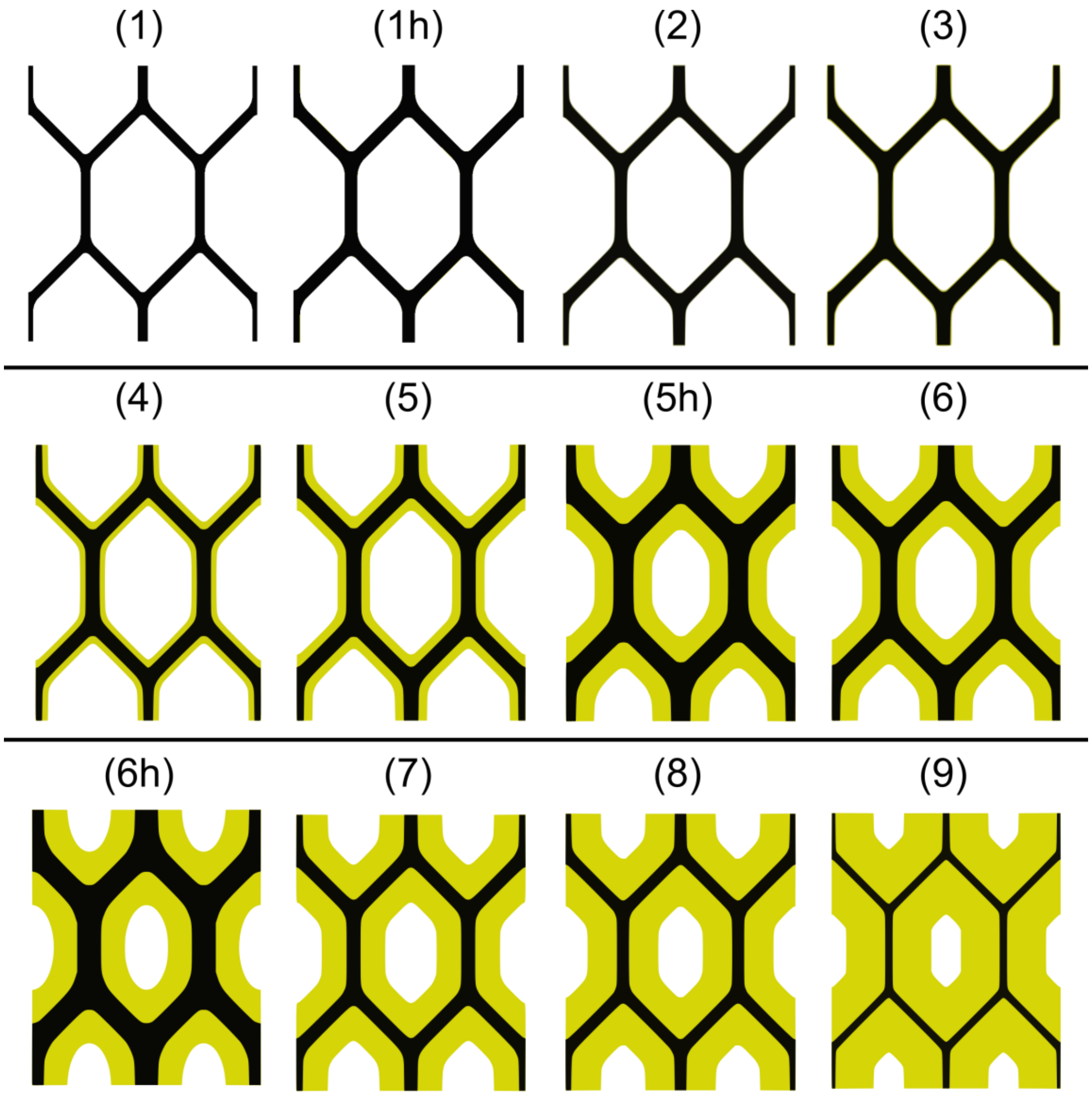
Bundle shear strength: $\boldsymbol{\tau_y^B}$



- Calibrate the degree of anisotropy ω from measured values.
- Calibrate the shear yield strength of CNT bundle.

UNIVERSITY OF CAMBRIDGE

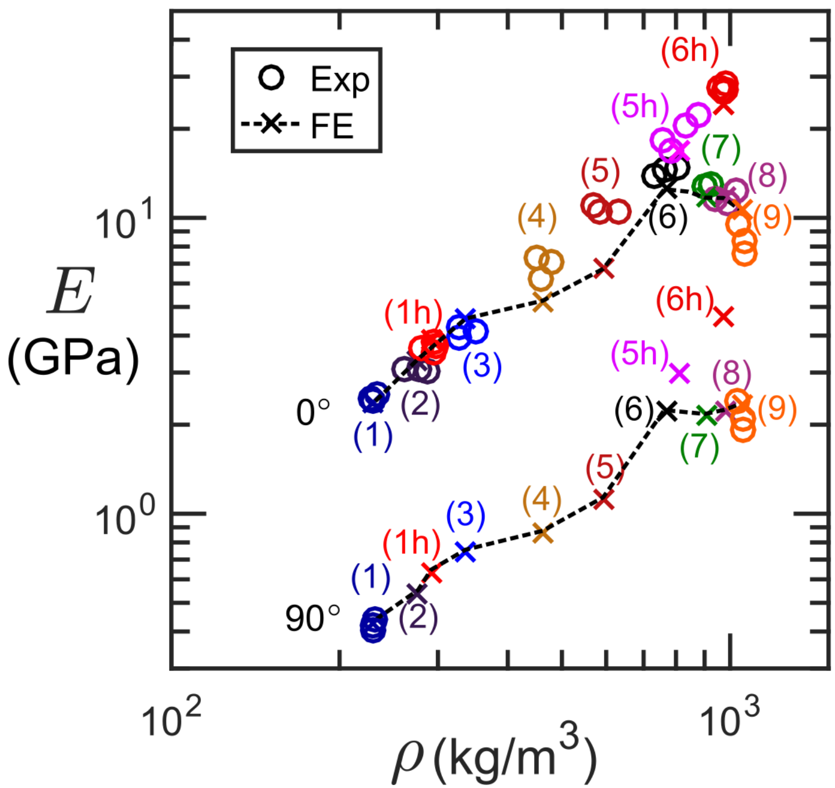
Finite element model of each composition

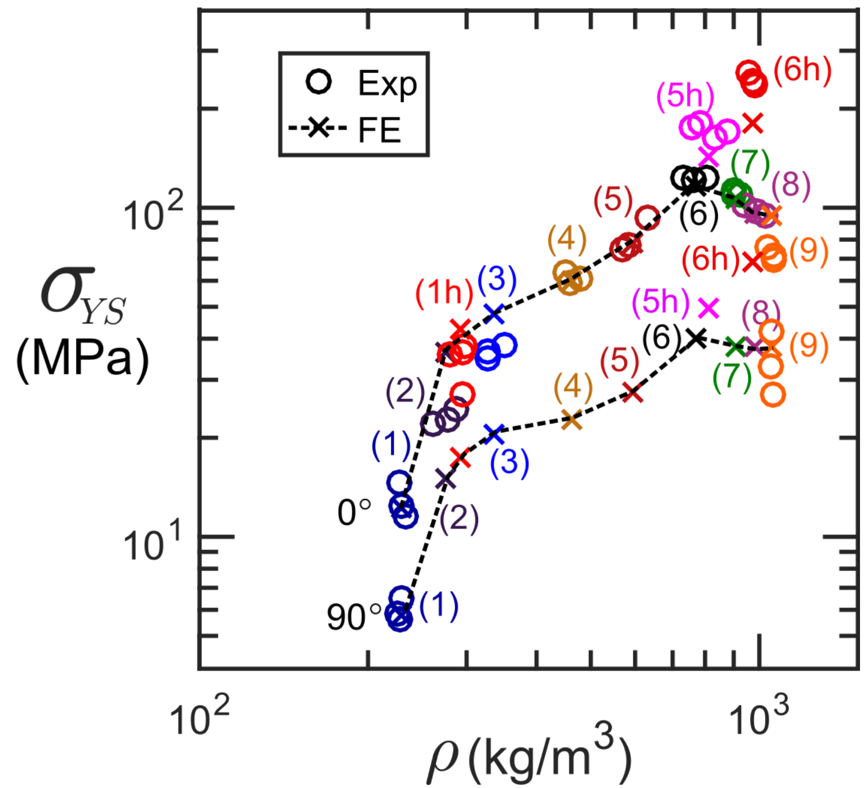


- FE based on the measured volume fraction of CNT and epoxy

UNIVERSITY OF CAMBRIDGE

Comparison between predication and experiment





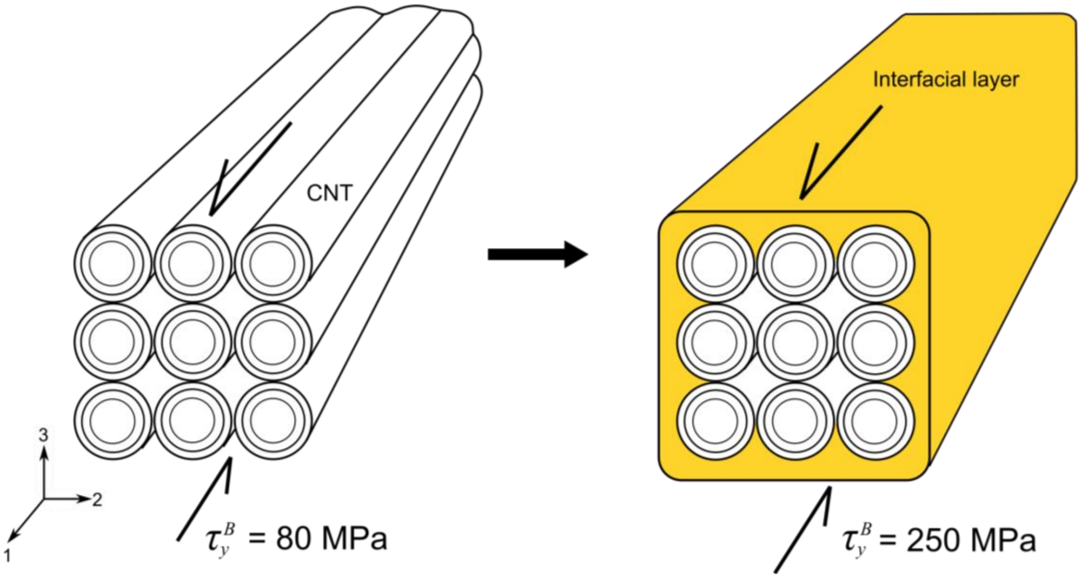
- Micromechanical model achieves a reasonable agreement with the measured **modulus** and **yield strength** of CNT-epoxy composite.

UNIVERSITY OF CAMBRIDGE

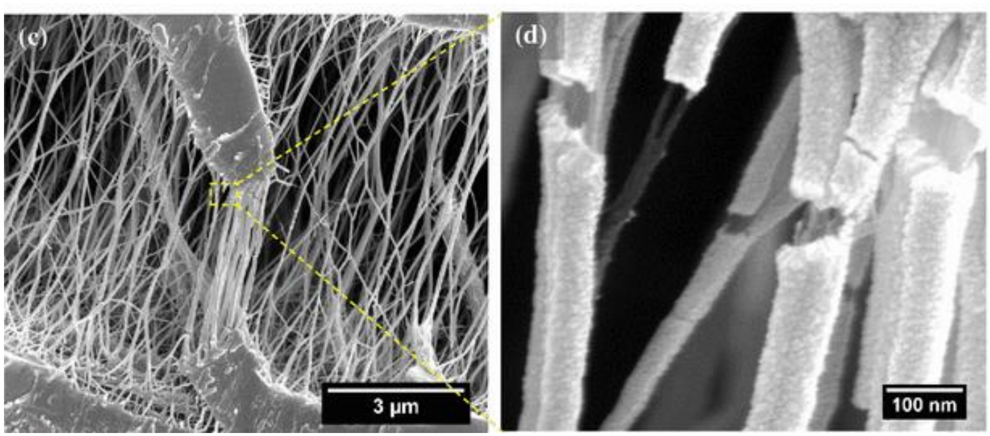
[2] W. Tan, J.C. Stallard, F.R. Smail, A.M. Boeis, N.A. Fleck. ***Carbon***, 2019

The origin for the enhanced bundle shear strength

A significant increase in the longitudinal shear strength of CNT bundles τ_y^B.

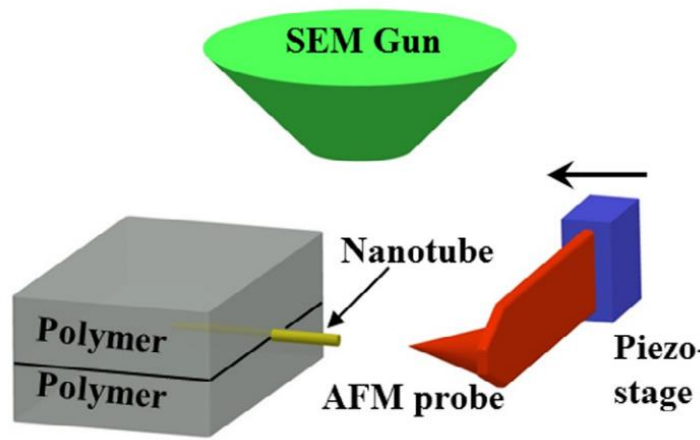


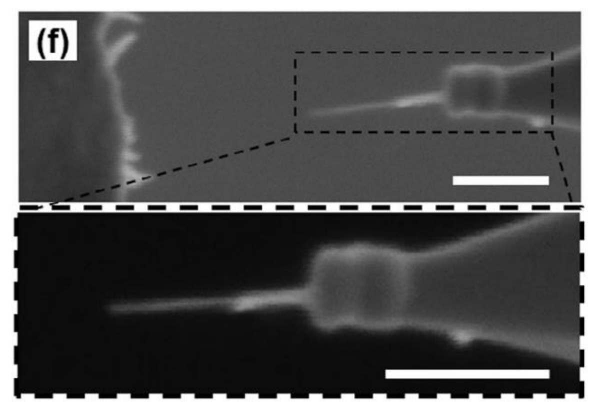
CNT bundles are coated with a sheath of epoxy



[Mikhalchan, Gspann, Windle, 2016]

CNT bundle pulled out from epoxy

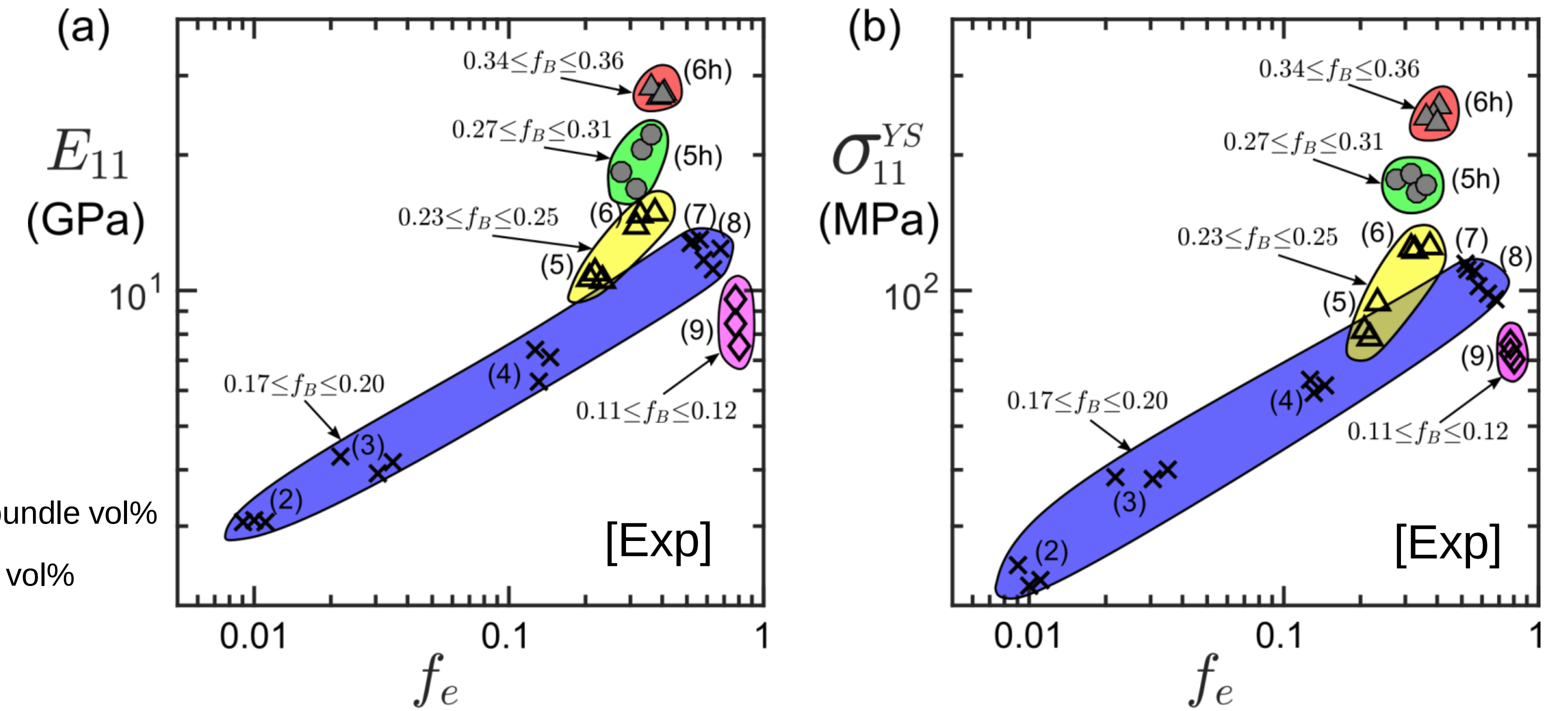




[Chen et al, 2016]

τ_I = 350-630 MPa

The effect of increasing epoxy fraction

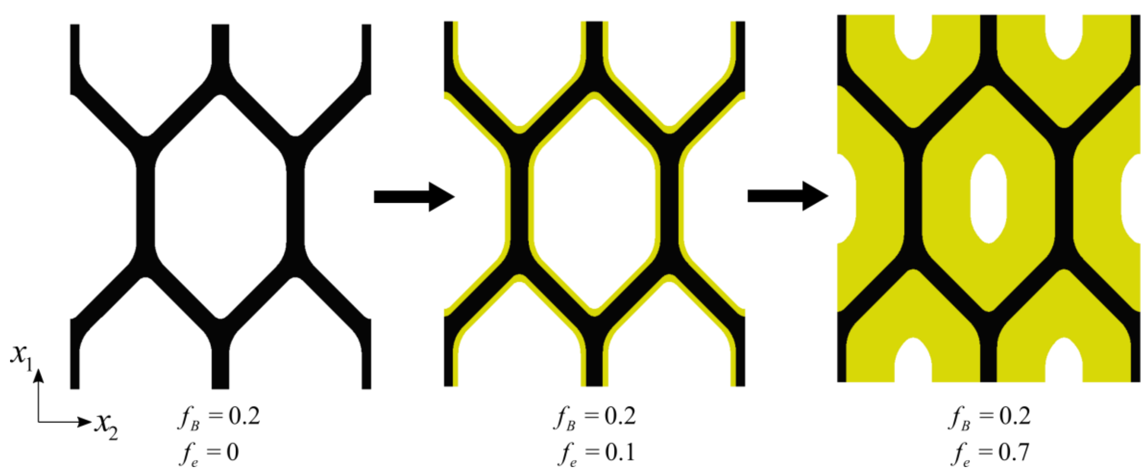


f_B: CNT bundle vol%

f_e: Epoxy vol%

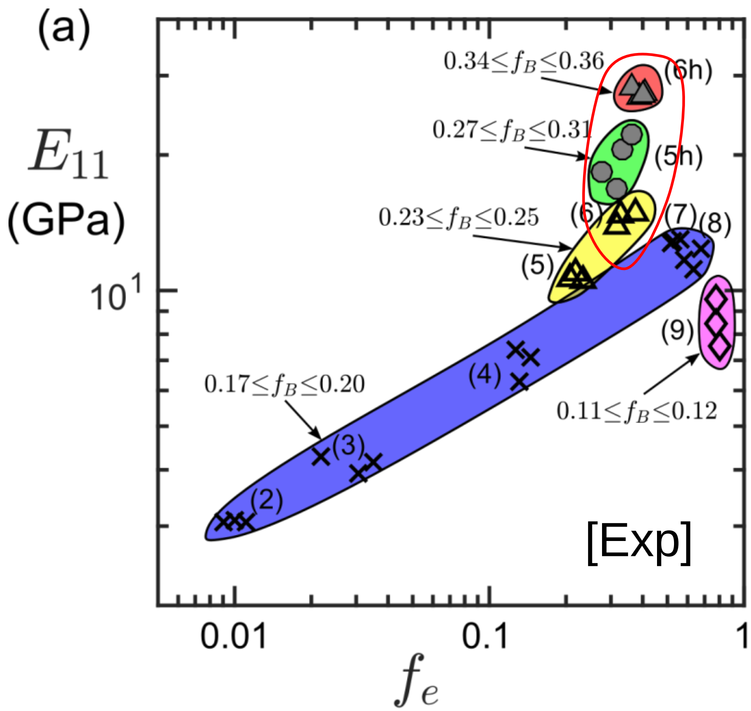
1. Increasing epoxy volume fraction f_e, promote the **tension** of CNT bundle, instead of bending and shearing.

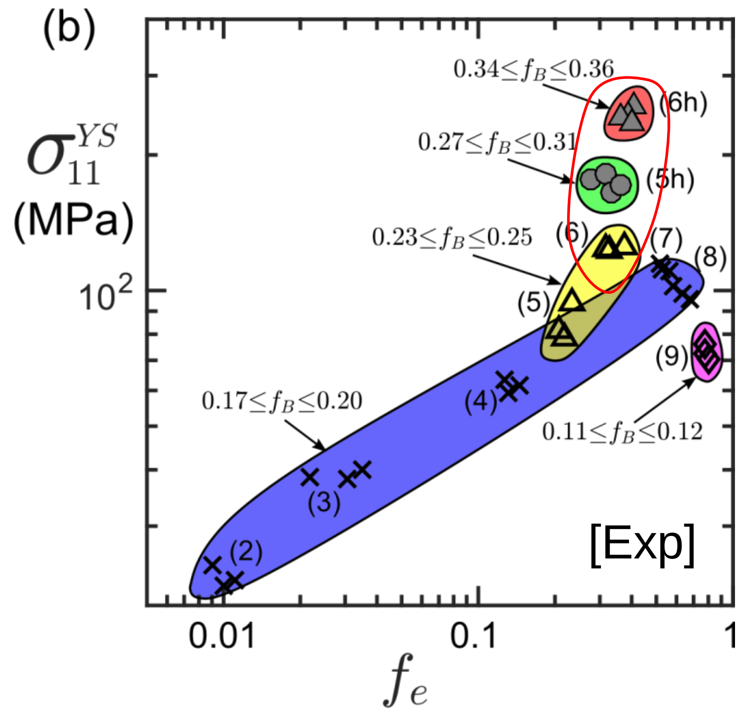
Progressive filling of the pores within the CNT bundle network



UNIVERSITY OF CAMBRIDGE

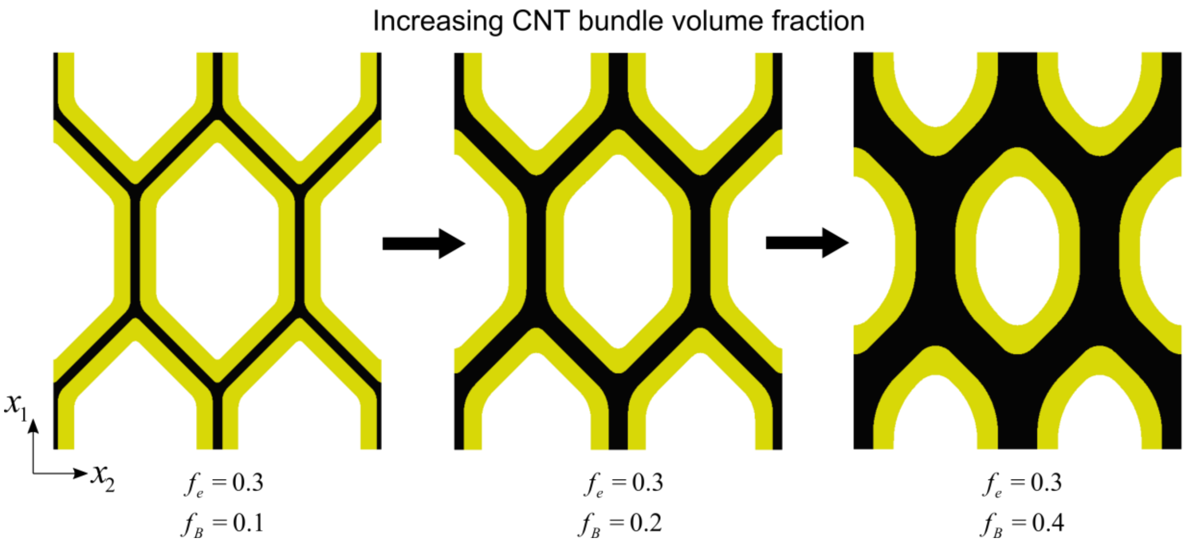
The effect of increasing CNT bundle fraction





2. Increasing CNT bundle volume fraction f_B.

$$E \propto f_B^3$$

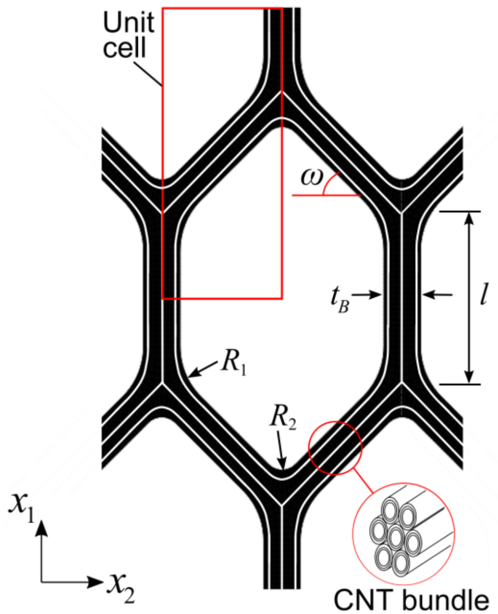


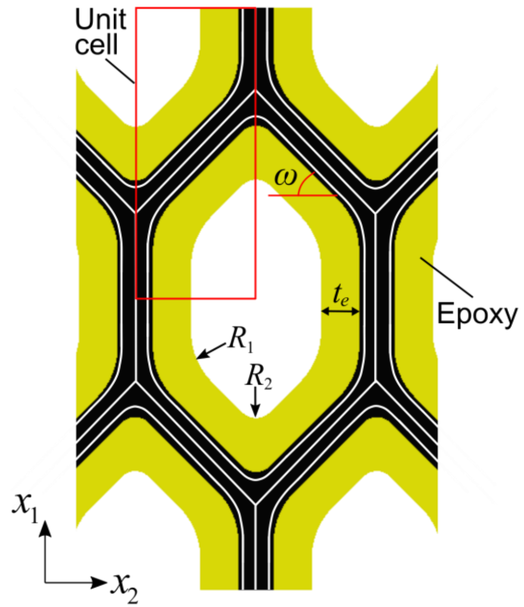
UNIVERSITY OF CAMBRIDGE

Concluding remarks

- The mechanical properties of the composite are sensitive to **epoxy coating**, the **epoxy volume fraction** within the pores, and the **CNT bundle** volume fraction.

- Micromechanical model achieves a reasonable agreement with measured **modulus** and **yield strength** of CNT-epoxy composite.





UNIVERSITY OF CAMBRIDGE

Acknowledgement

Colleagues:

Prof. Norman Fleck
Mr. Joe Stallard
Dr. Harika Tankasala
Dr. Adam Boies
Dr. Michael De Volder
Dr. Fiona Smail
Dr. Changshin Jo
Prof. Alan Windle

SIEMENS
TORTECH nano Fibers
MAGNA
BAE SYSTEMS INSPIRED WORK
EPSRC Engineering and Physical Sciences Research Council
Marshall
ANAM Initiative
UNIVERSITY OF CAMBRIDGE
University of ULSTER

Thank you for your attention !

UNIVERSITY OF CAMBRIDGE