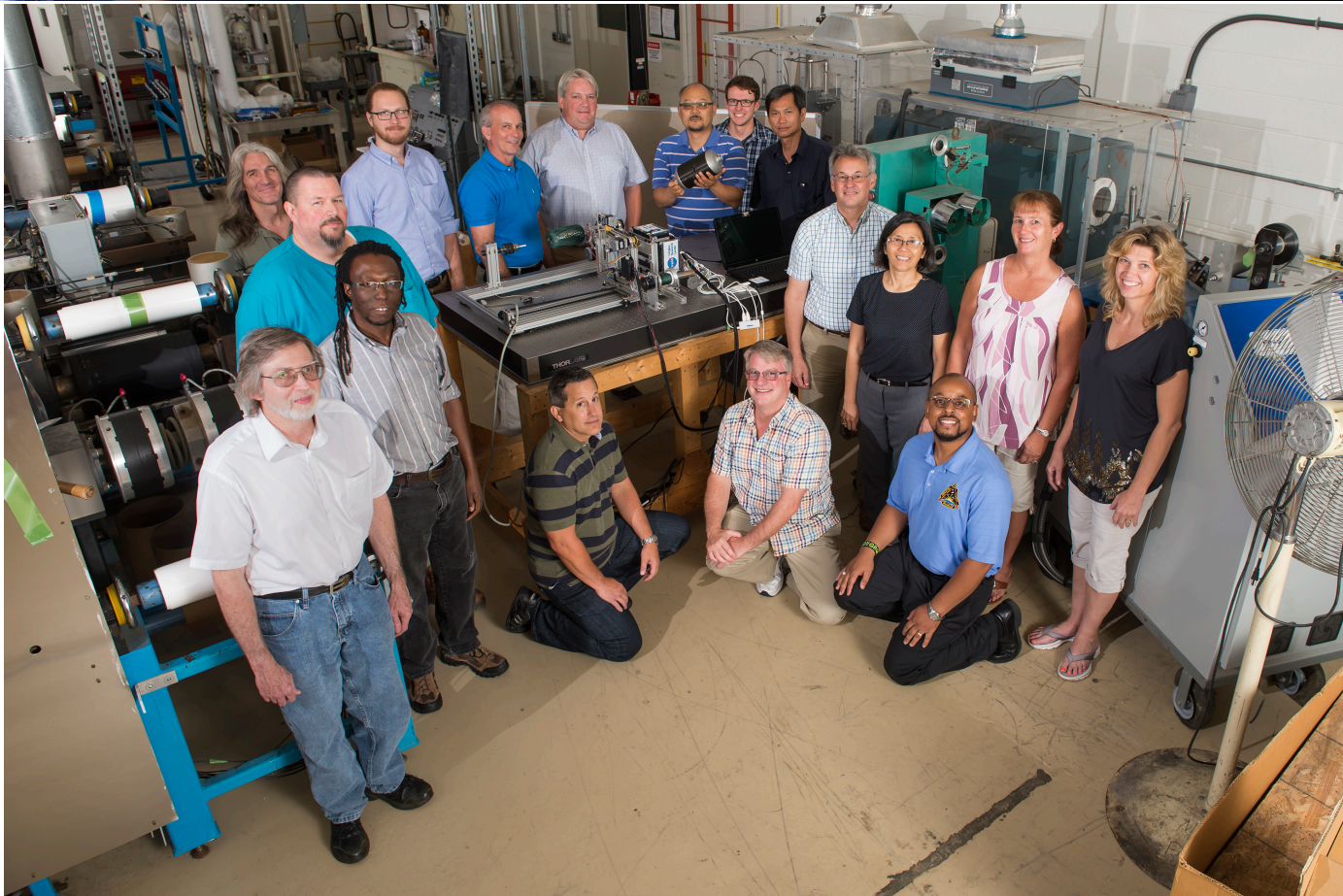


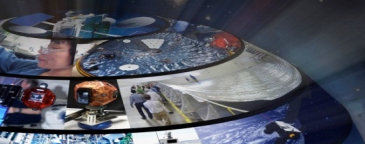


Structural Carbon Nanotube Development *Lessons Learned*

Mia Siochi

Presentation to
ExxonMobil Research & Engineering
Company
June 12, 2020

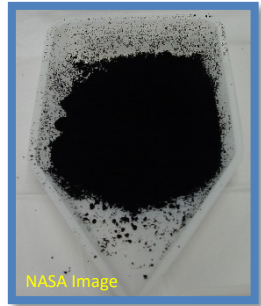




Types of Carbon Nanotubes



2000s



Powder

2004



Sheets

2011 - 2012

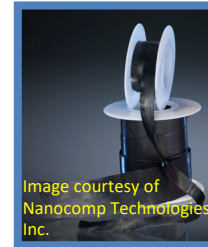


Image courtesy of Nanocomp Technologies, Inc.

Tape

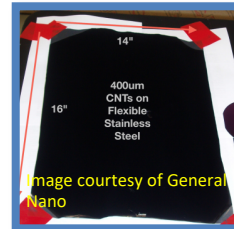


Image courtesy of General Nano

Vertical Array

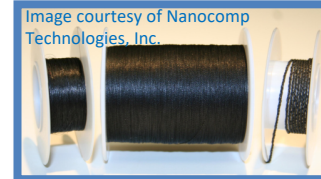
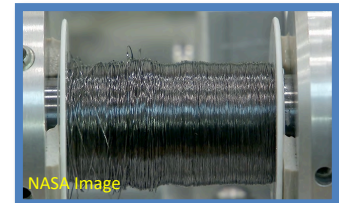


Image courtesy of Nanocomp Technologies, Inc.

Yarn from Floating Catalyst

2015



NASA Image

High Strength Yarn

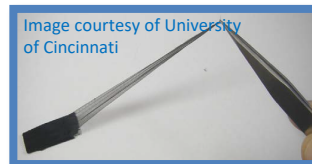


Image courtesy of University of Cincinnati

Vertical Array



Image courtesy of Rice University

Acid Spun Yarn

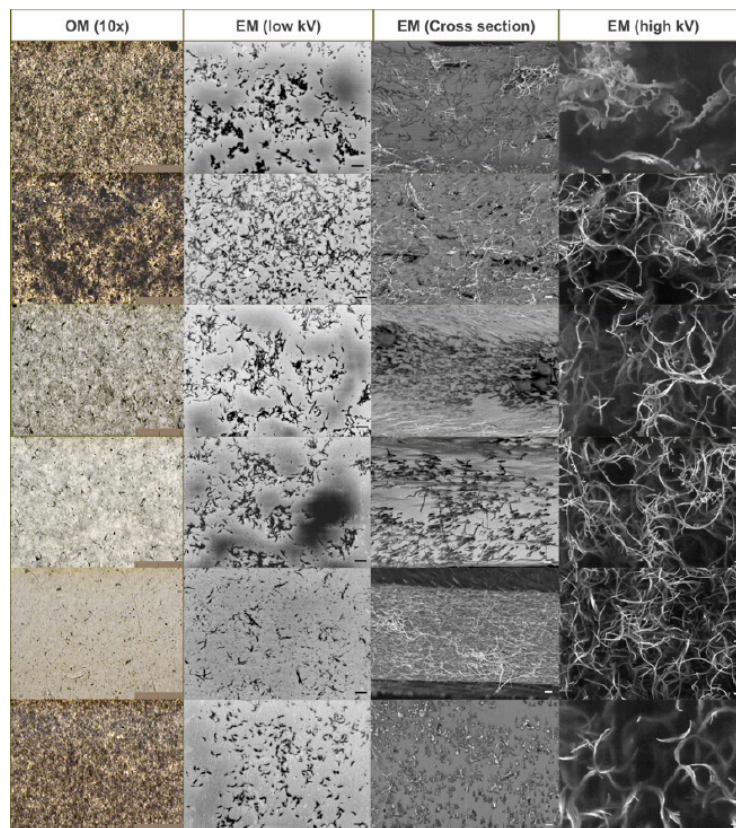


Characterization of Dispersion

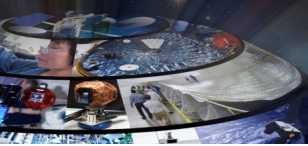


OM = Optical Microscopy

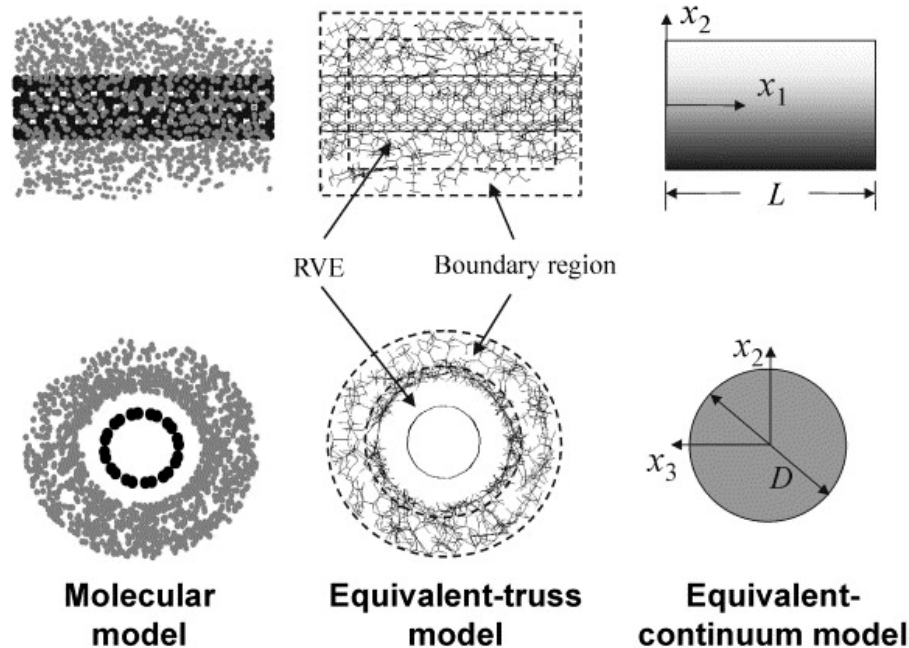
EM = Electron Microscopy



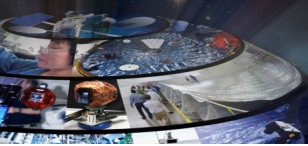
- [2008 NIST Recommended Practice Guide: Measurement Issues in Single Wall Carbon Nanotubes](#) (Washington, DC: US Government Printing Office), Chapter 5.
- A Quantitative Assessment of Carbon Nanotube Dispersion in Polymer Matrices, *Nanotechnology*, **20** (2009), 325708.



Computational Modeling of Carbon Nanotube Composites



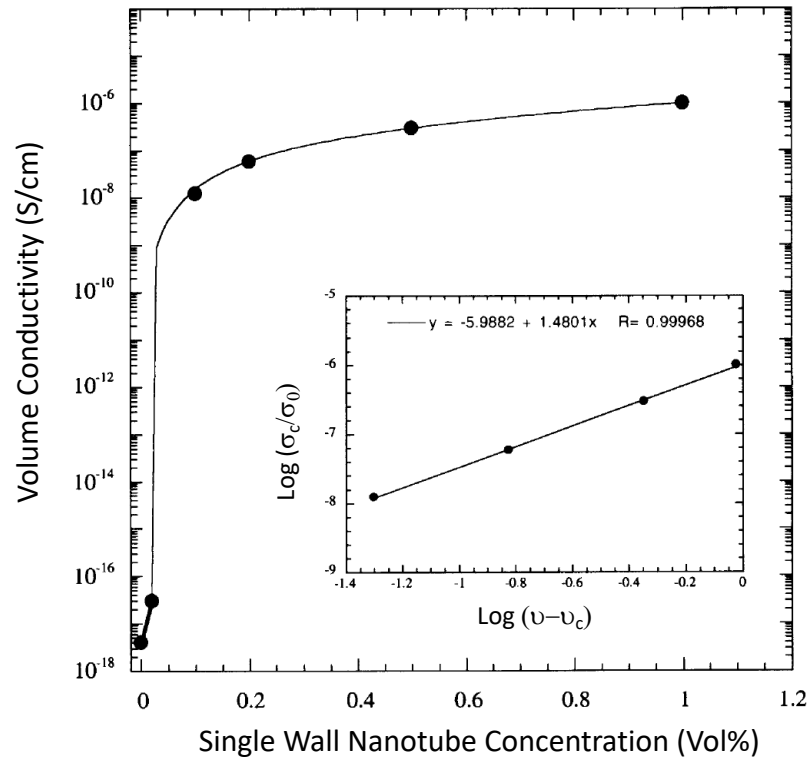
RVE = representative volume element



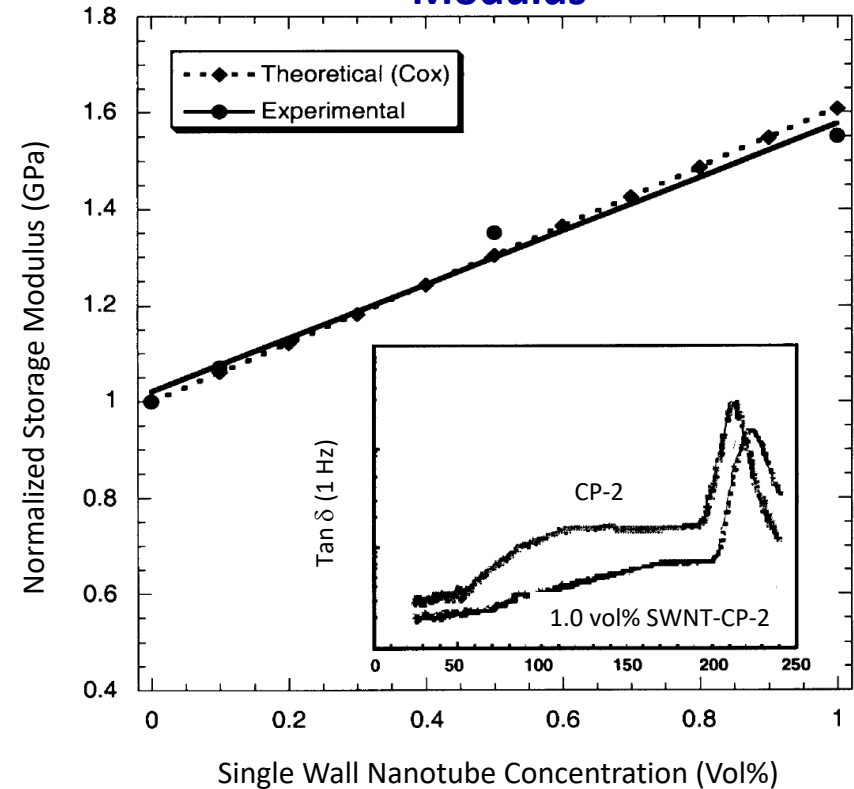
Properties of Lightly Doped Nanocomposites

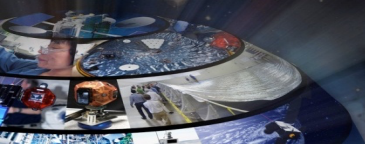


Electrical Conductivity

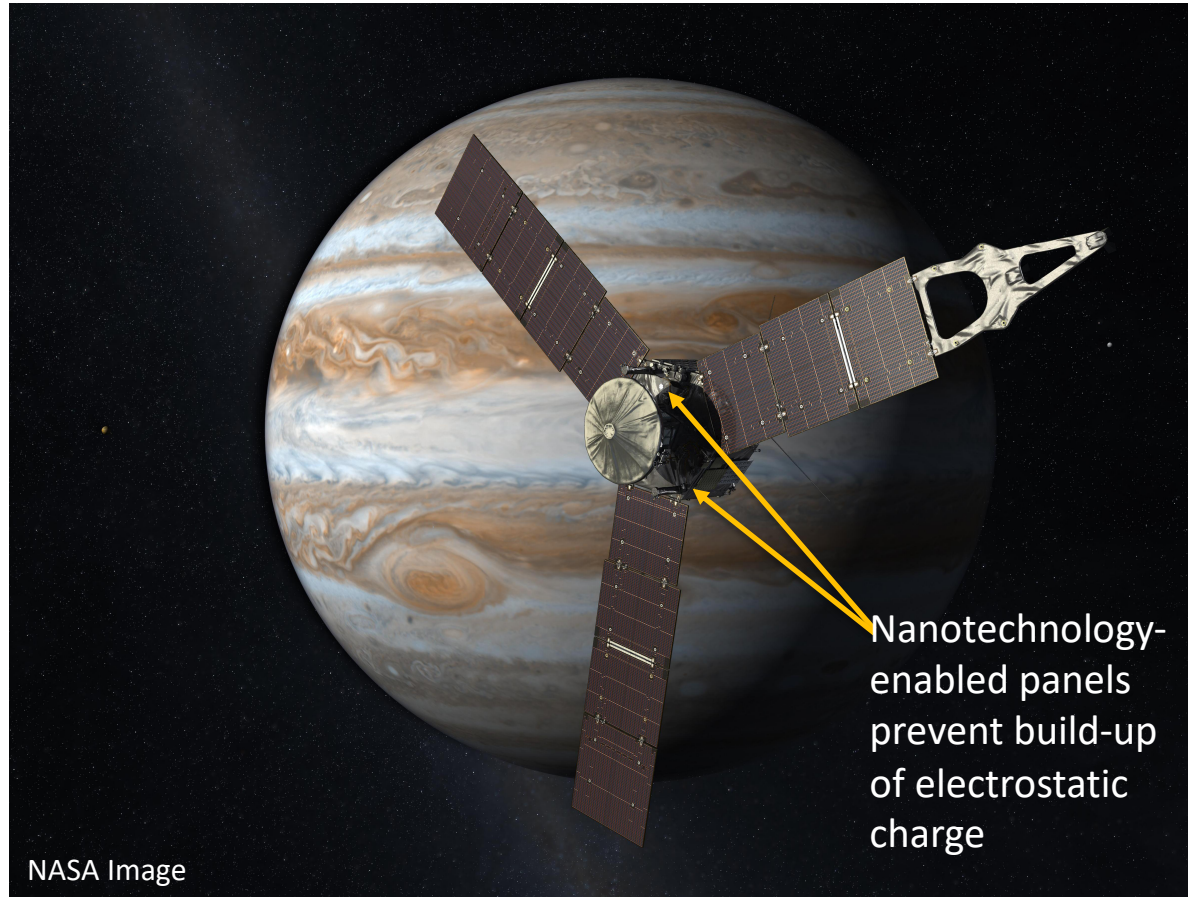


Modulus



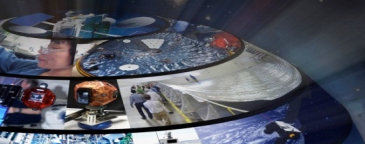


Carbon Nanotube on Juno Spacecraft

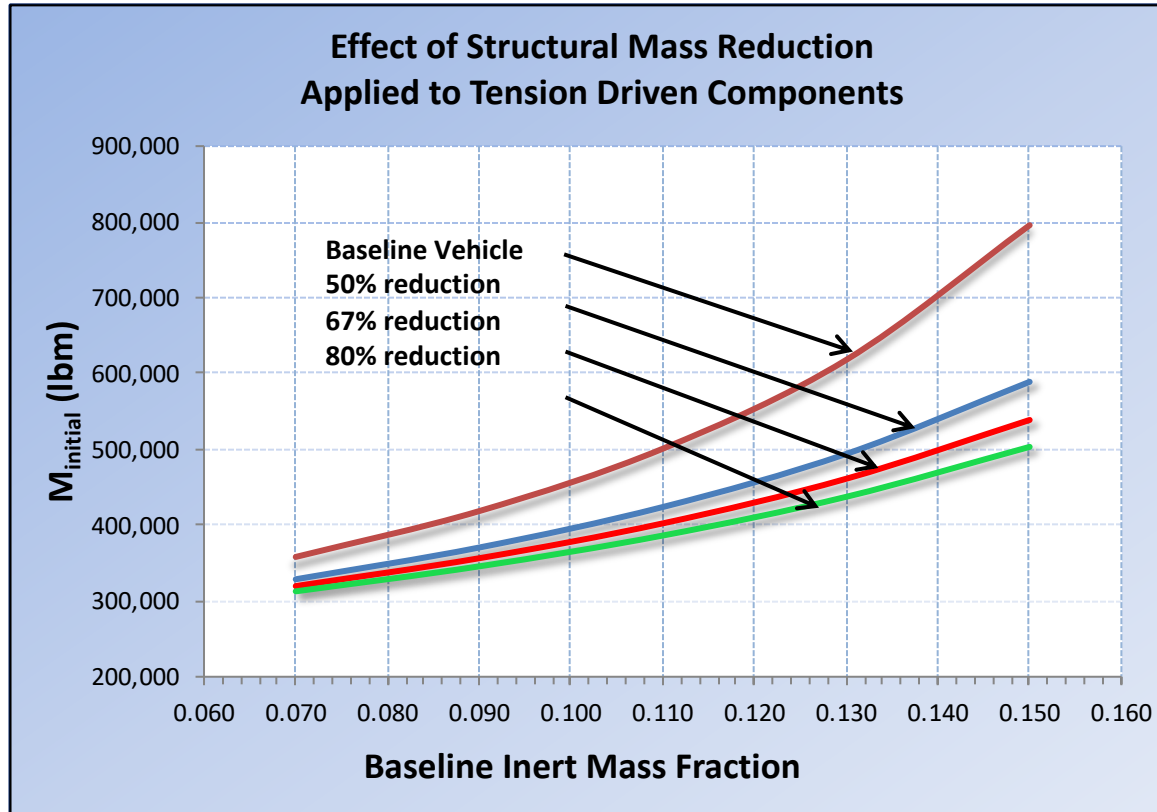


NASA Image

Nanotechnology-enabled panels prevent build-up of electrostatic charge



Setting Goals

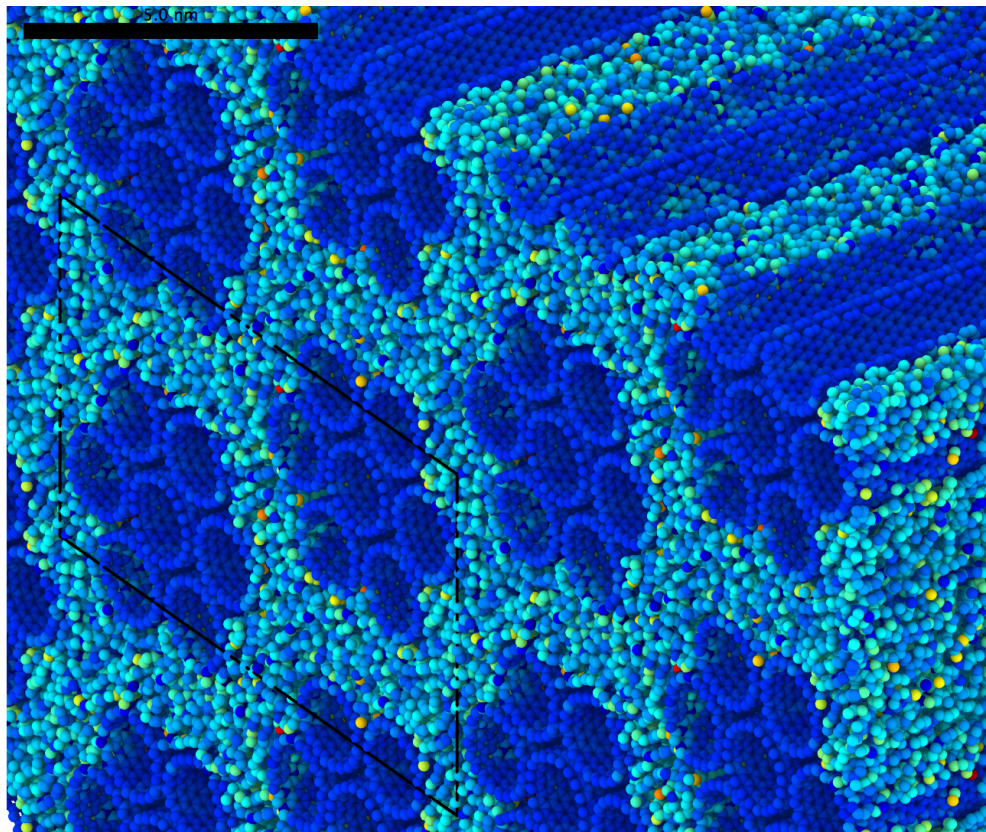
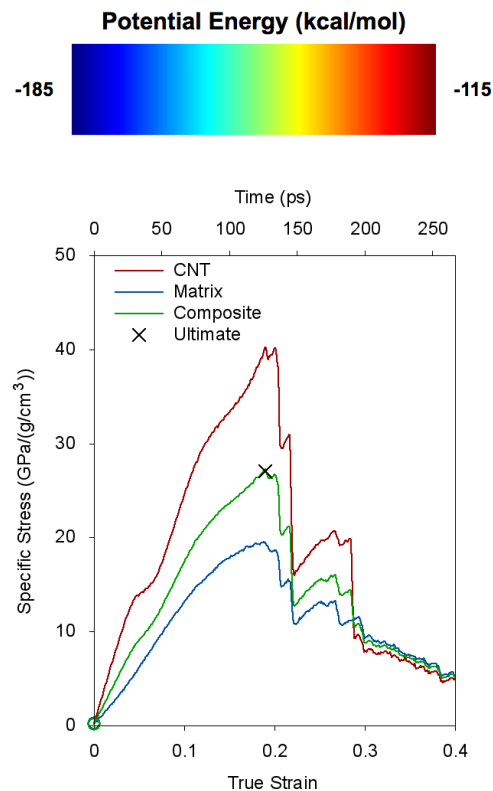


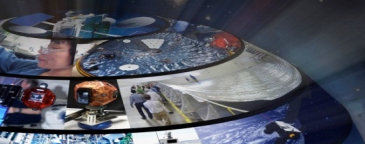
State of the Art Lightweight Aerospace Structure



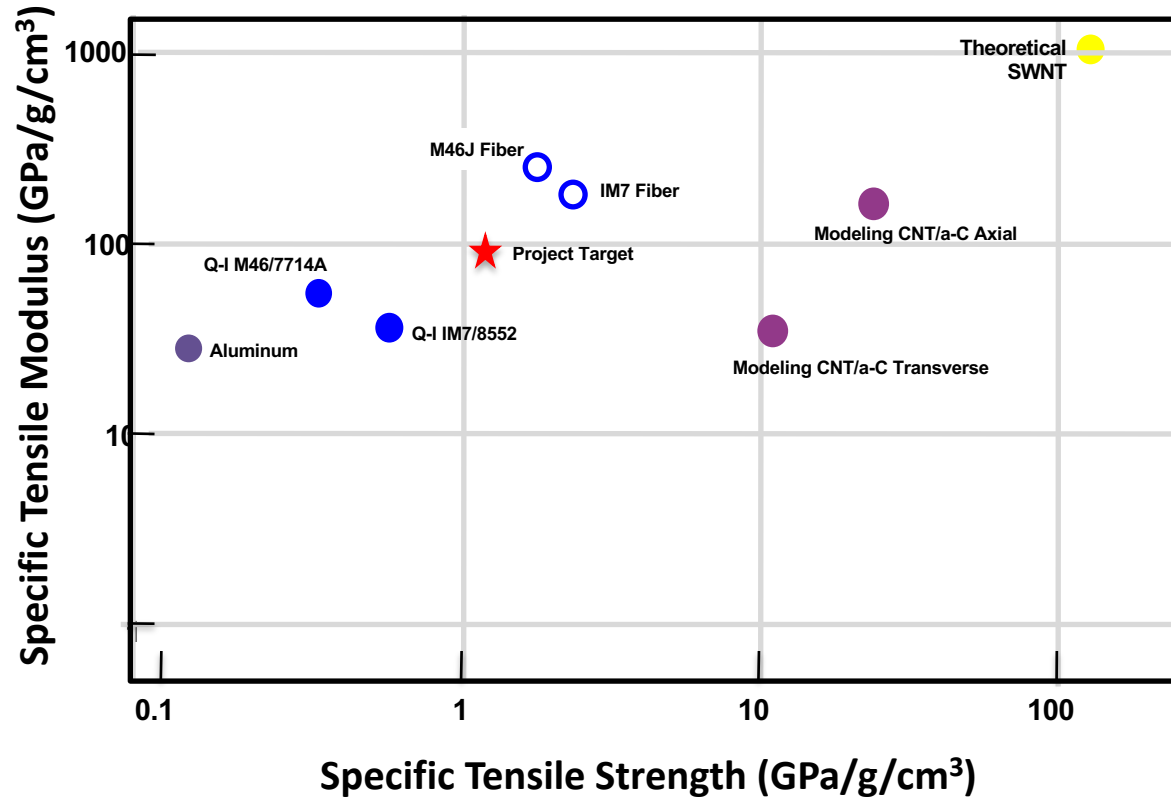


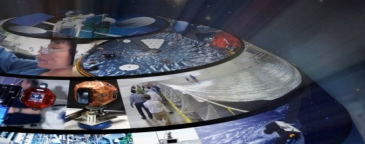
SWNT Bundle Axial Fracture Modeling



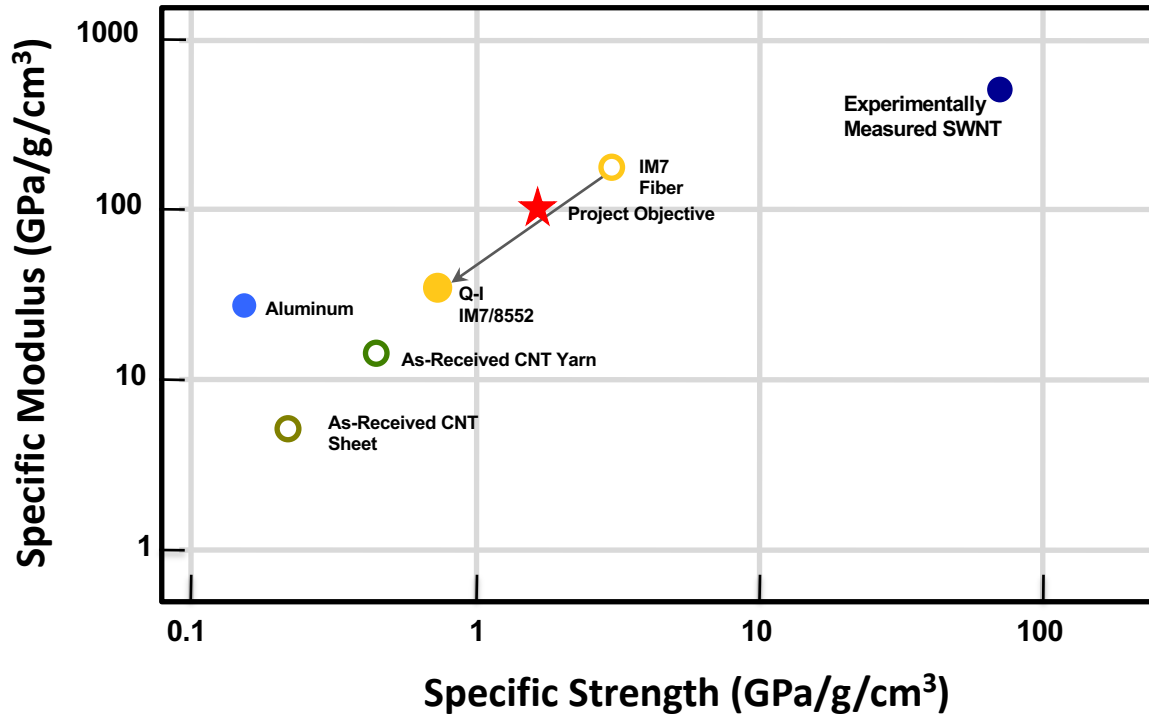


Modeling Validation of Objective

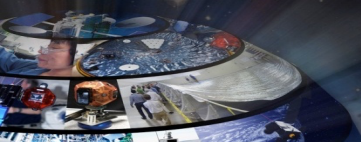




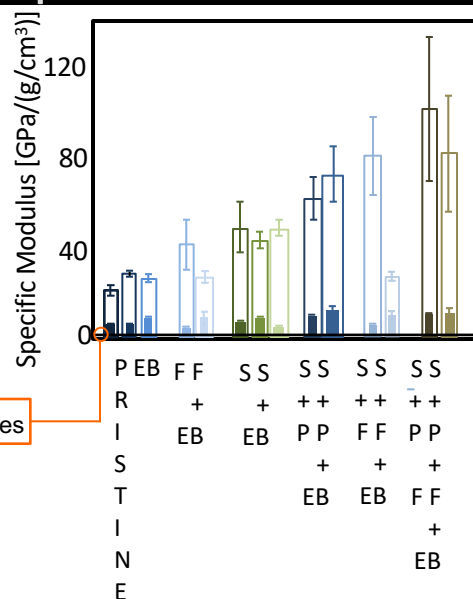
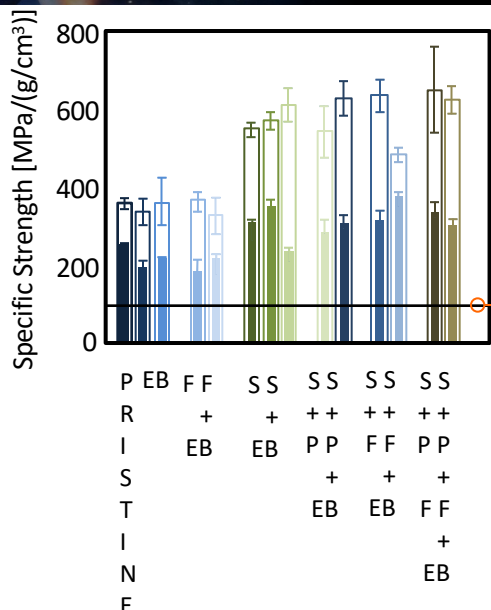
Nano to Macro Challenge



- Available materials have starting mechanical properties inferior to other SOA materials.



Effect of Post Processing Steps on Mechanical Properties



BMI Resin Properties

Pristine: Pristine CNT sheet (Lot#70044-Acetone treated)

EB: EB (40 min)

EB: EB (90min)

F: m-CPBA Functionalized

F + EB: m-CPBA Functionalized + EB (90min)

S: Stretched (41%)

S + EB: Stretched (49%) + EB (90min)

EB (90min) Stretched (20%)

S + P:

Stretched (46%) + purified

S + P + EB:

Stretched (33%) + purified + EB (90min)

S + F:

Stretched (43%) + m-CPBA Functionalized

S + F + EB:

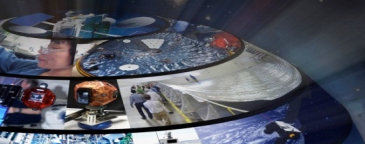
Stretched (43%) + m-CPBA Functionalized + EB (90min)

S + P + F:

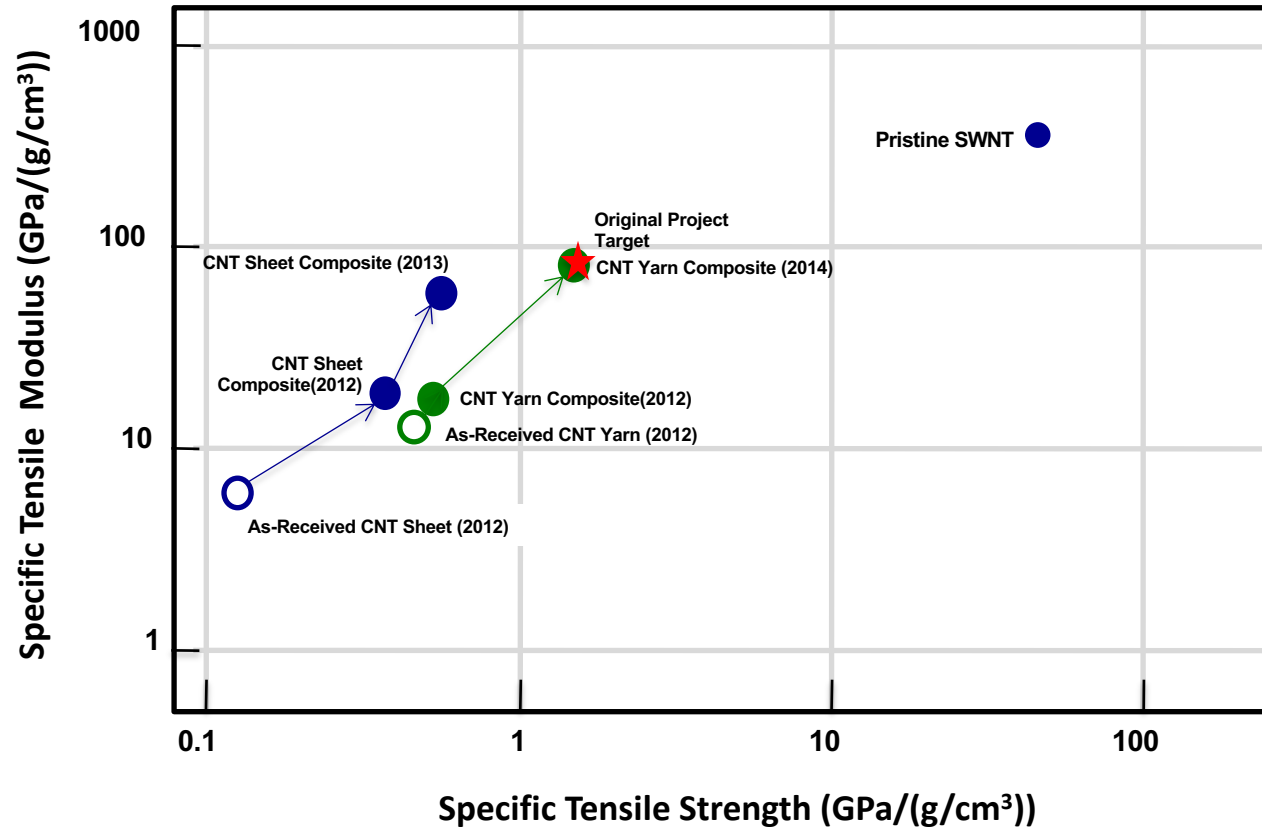
Stretched (46%) + purified + m-CPBA Functionalized

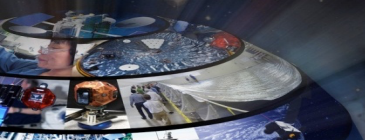
S + P + F + EB:

Stretched (33%) + purified + m-CPBA Functionalized + EB (90min)



Progress in CNT Composites

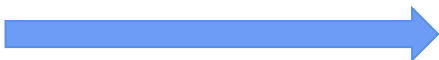
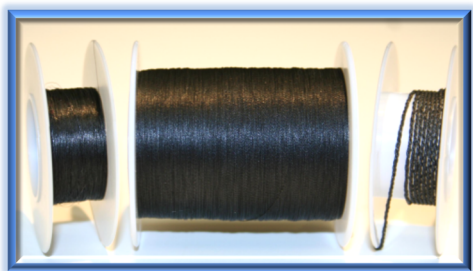




Structural CNT Composite Development



CNT Yarn



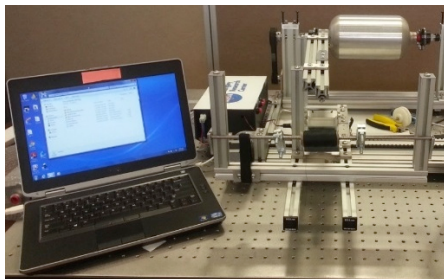
CNT Yarn Composite Wound Rings



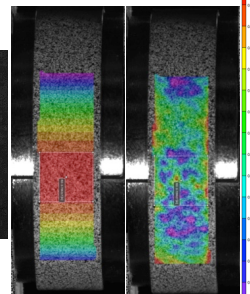
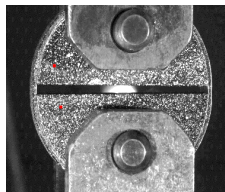
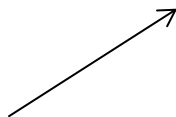
CNT Yarn COPV



**Commercial
Filament Winding**



CNT Composite Fabrication



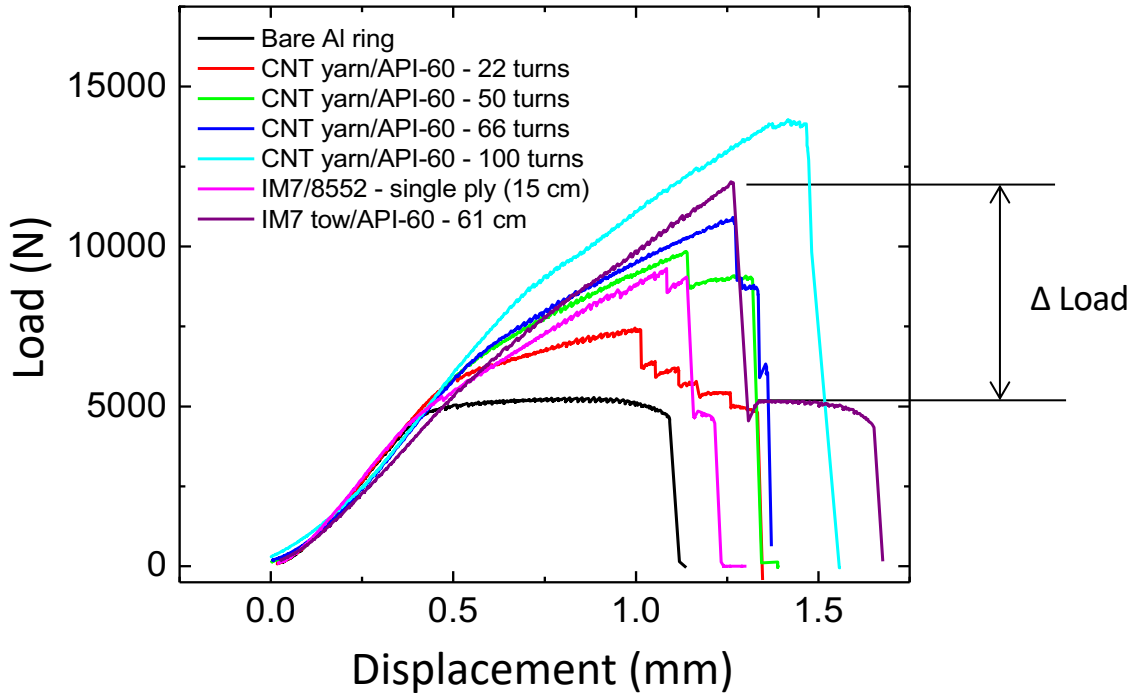
CNT Composite Mechanical Testing

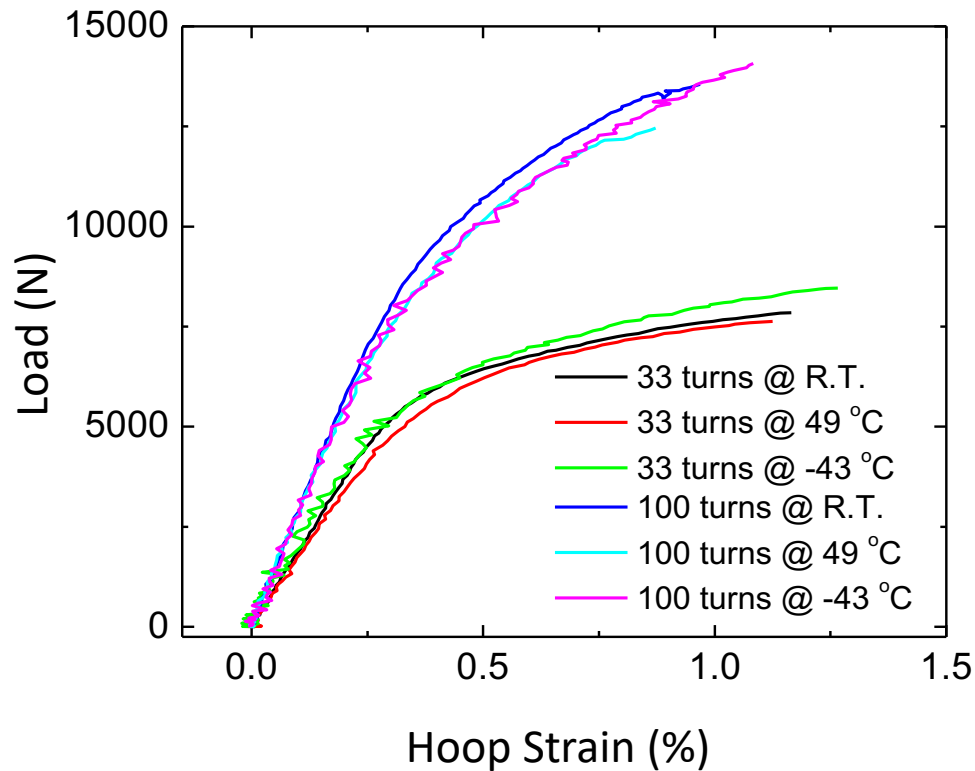


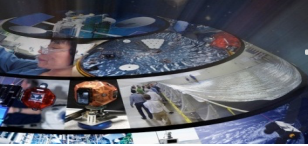
Assessment of Carbon Nanotube Yarns as Reinforcement
for Composite Overwrapped Pressure Vessels, *Composites:
Part A*, **84** (2016), pp. 256-265.



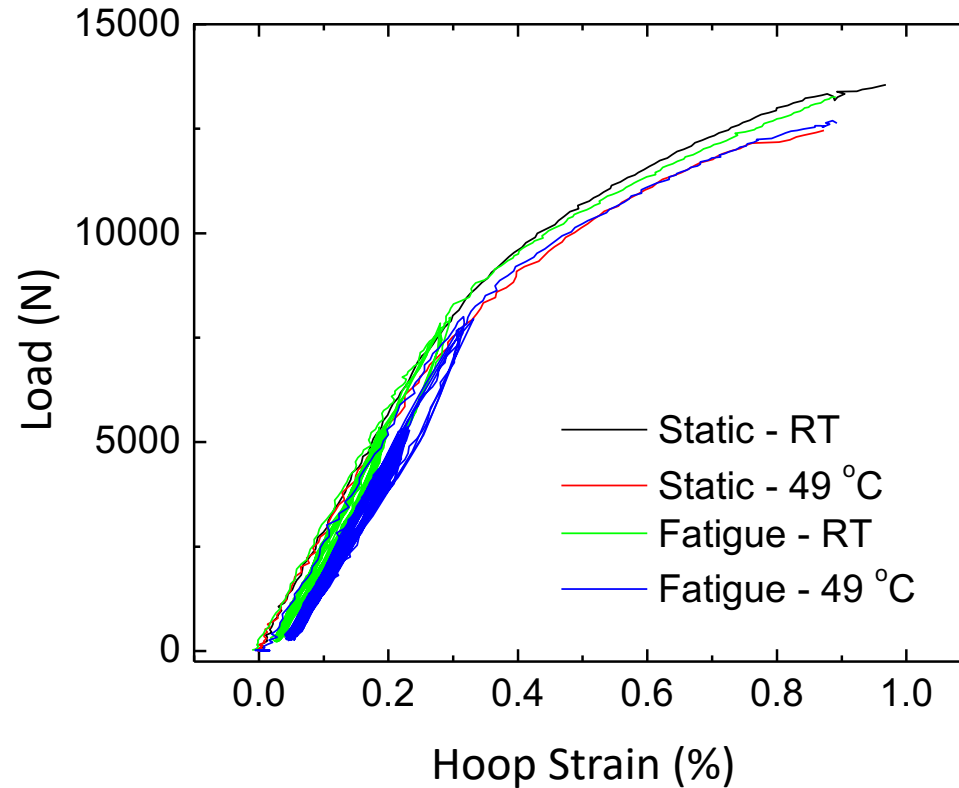
Load-Displacement Curves of Composite Wound Rings

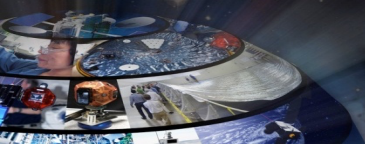




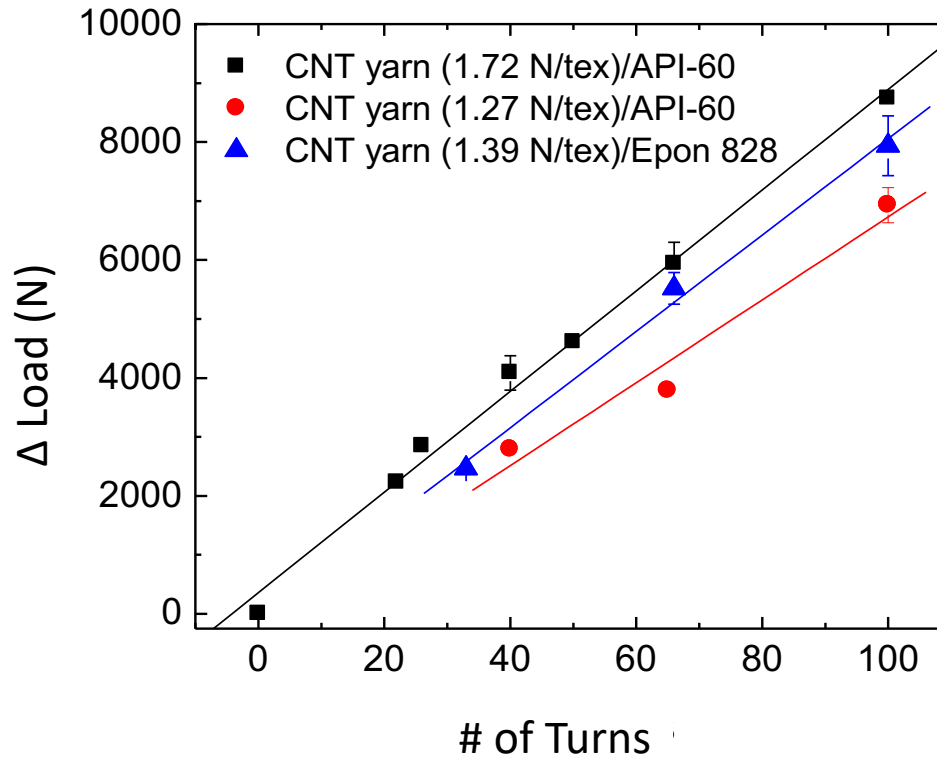


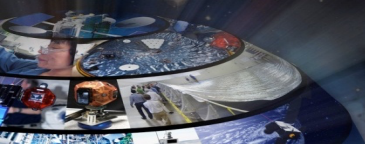
Temperature Dependent Fatigue Performance



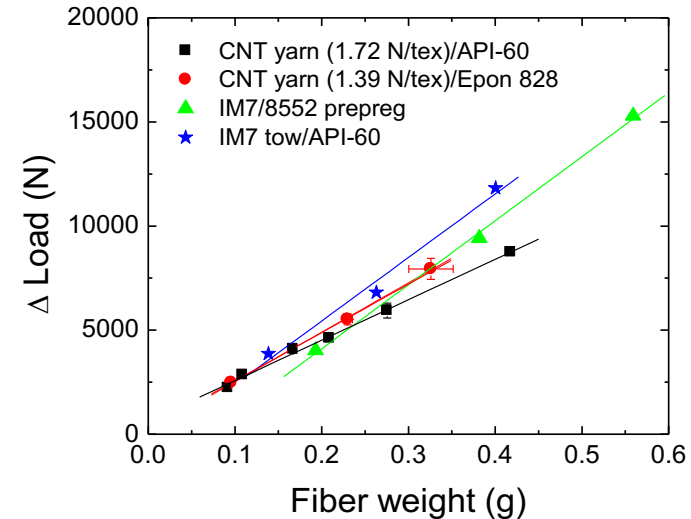
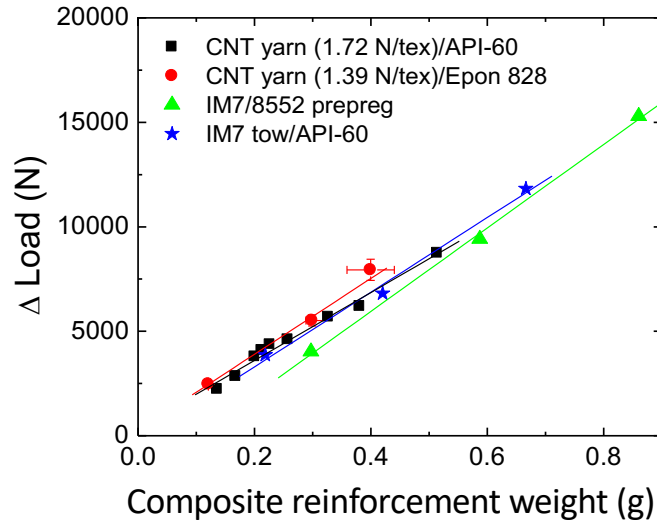


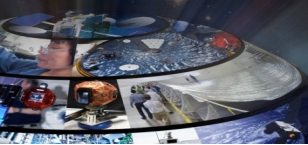
Mechanical Performance Summary



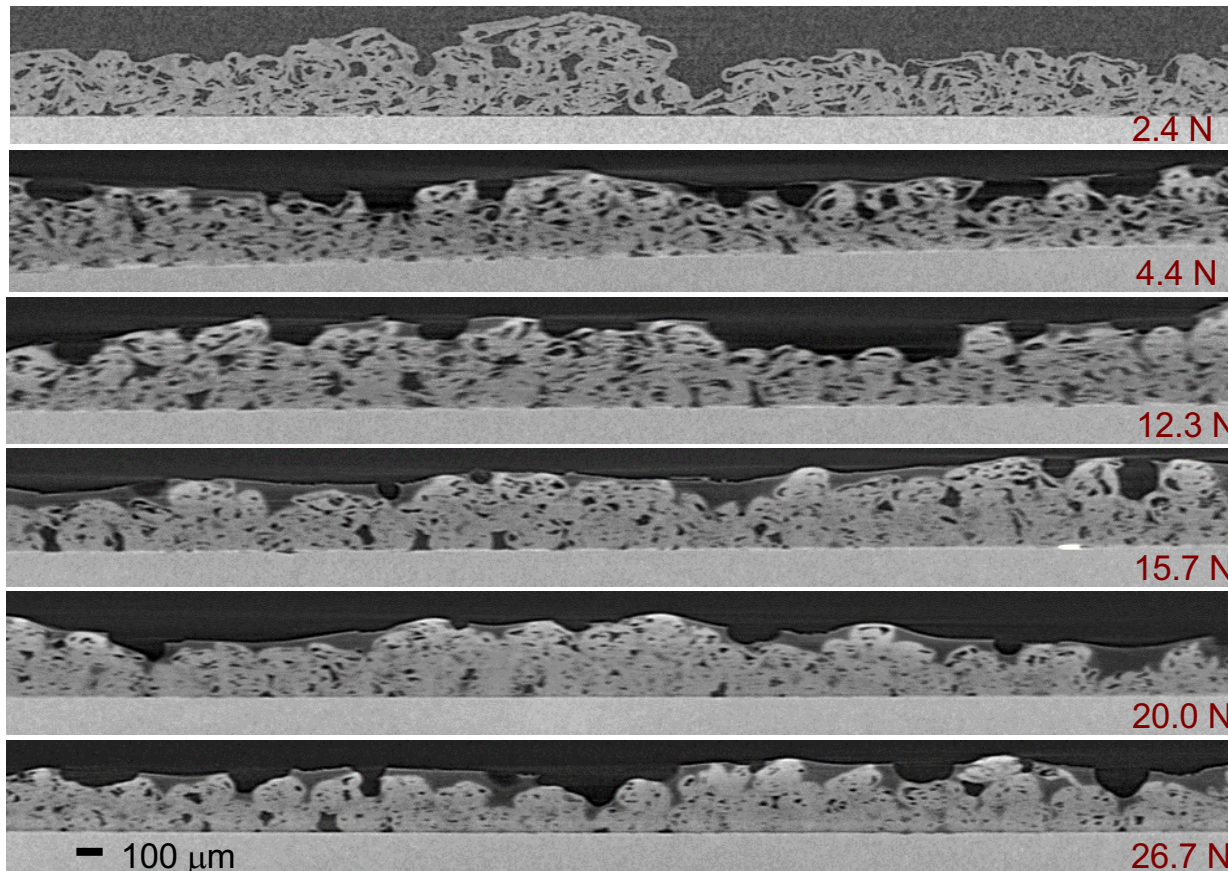


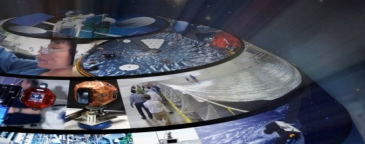
Mechanical Performance Summary



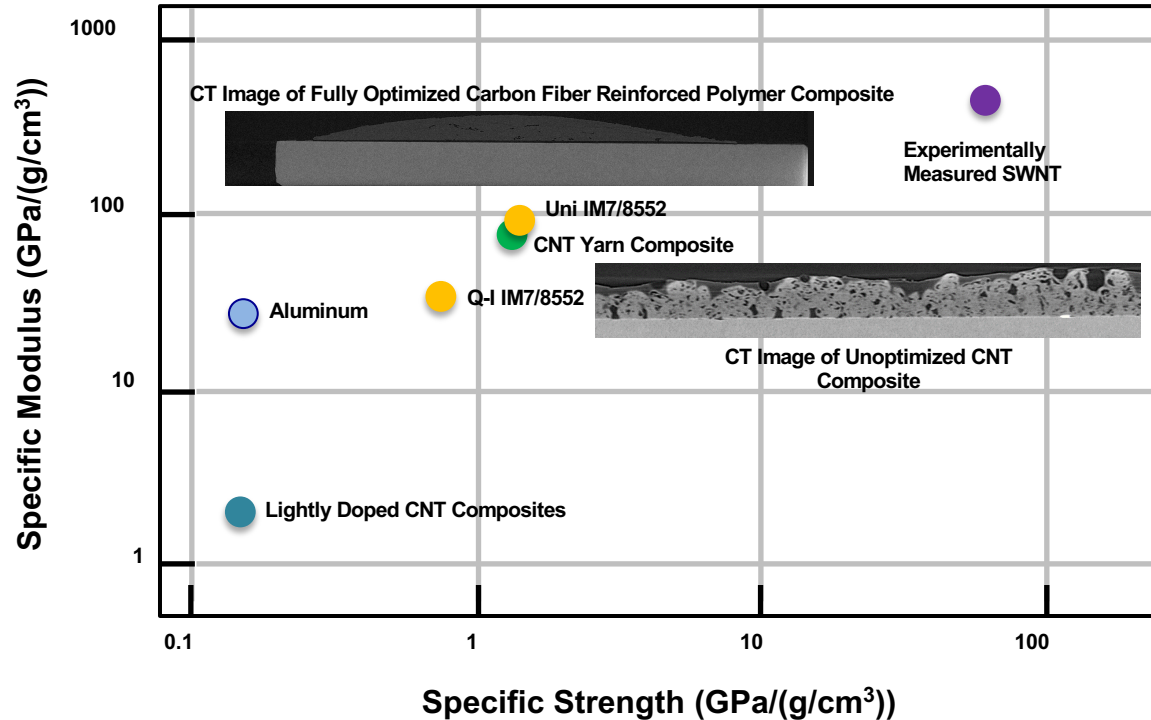


Effect of Winding Tension on CNT Composite



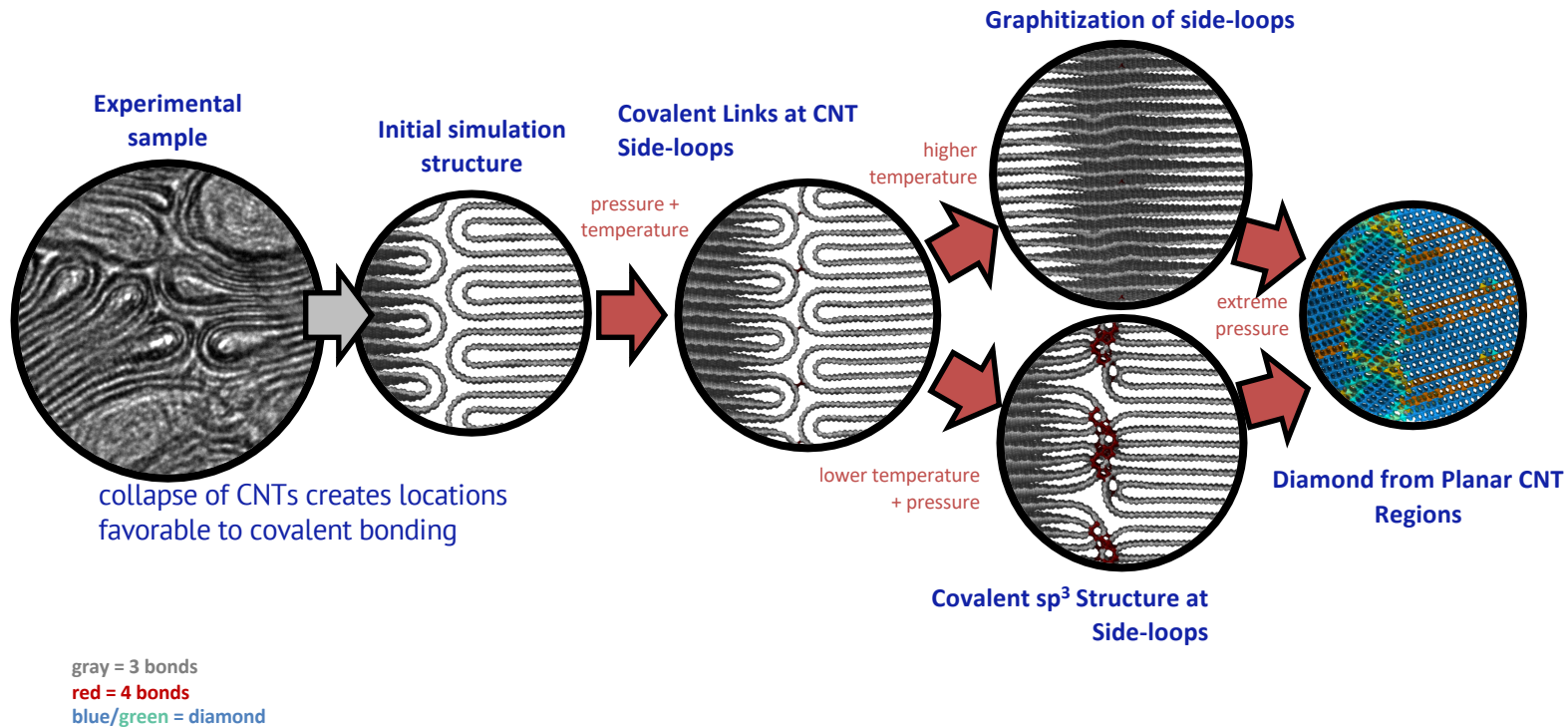


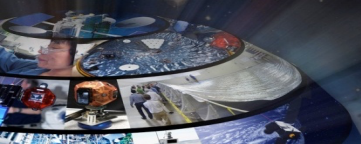
Motivation for Continuing Research



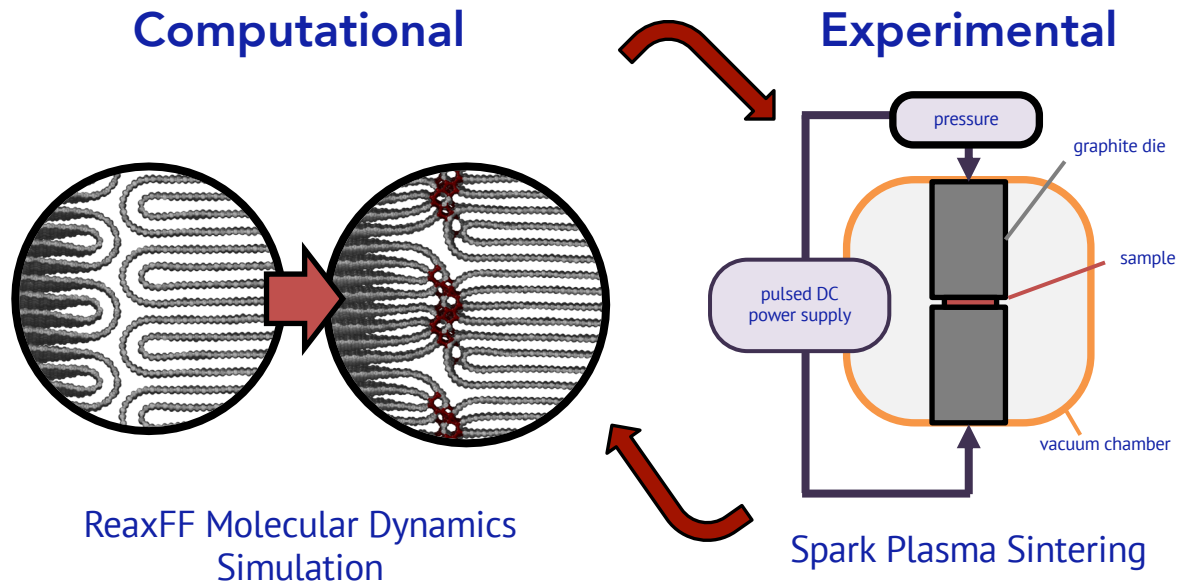
Structural Outcomes

Pressure/Temperature Conditions

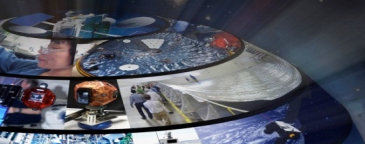




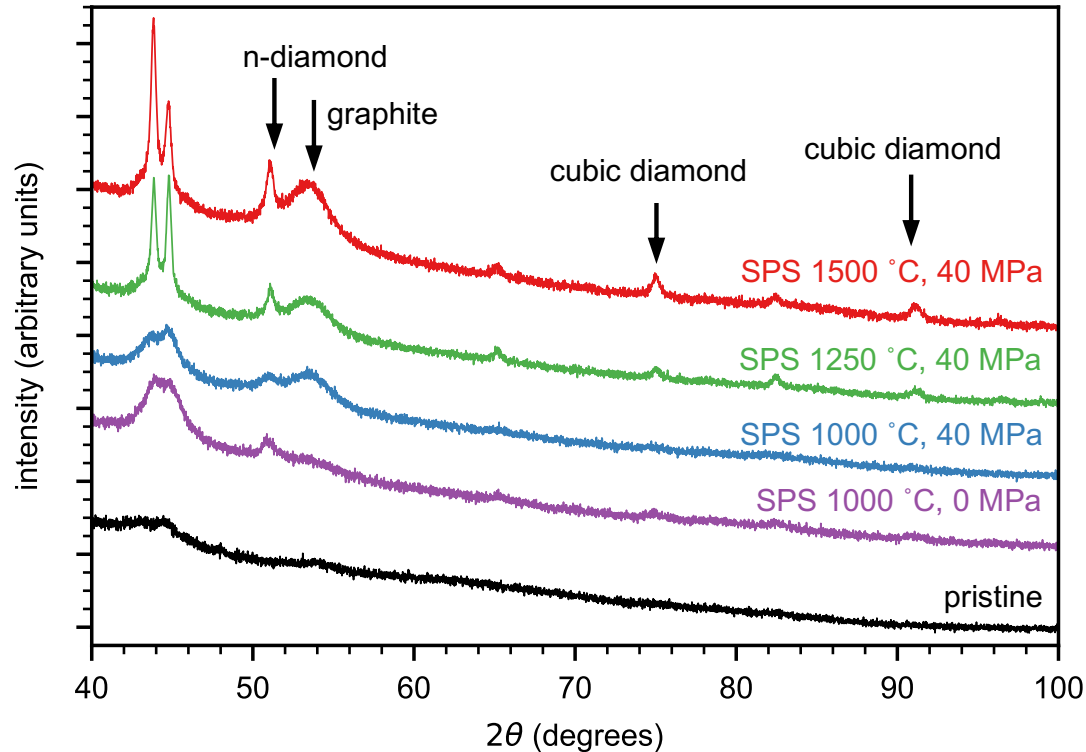
High Strength Structures by Covalent Links



ReaxFF = Reactive Force Field
SPS – Spark Plasma Sintering



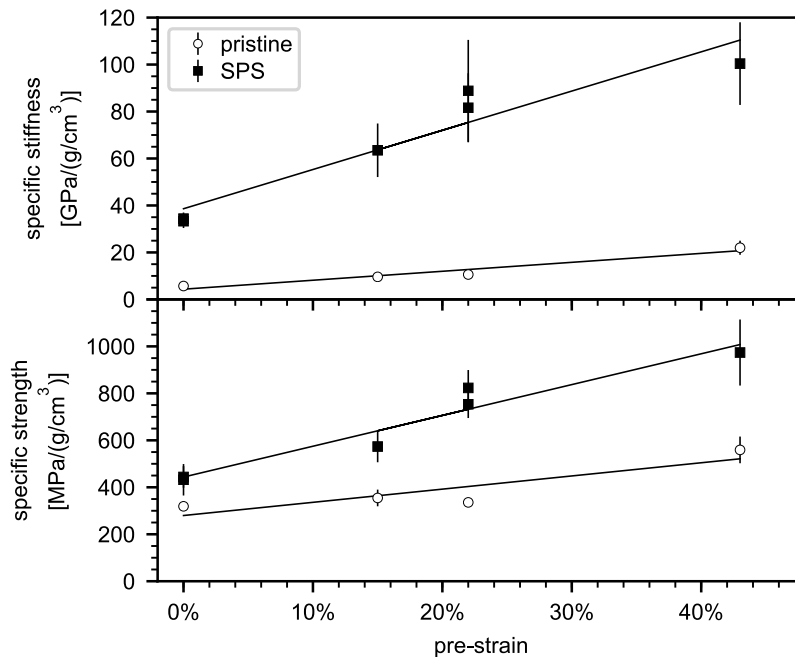
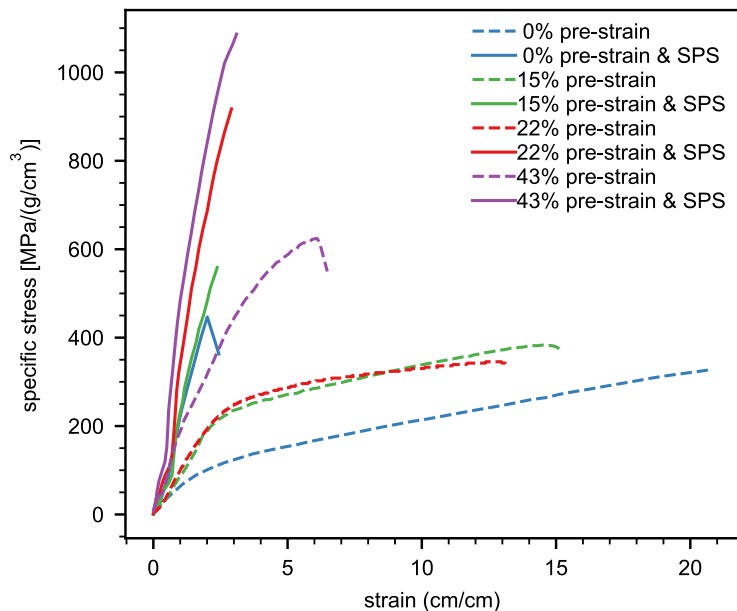
X-Ray Diffraction Analysis



CNT sheet
(5.08 cm x 5.08 cm)

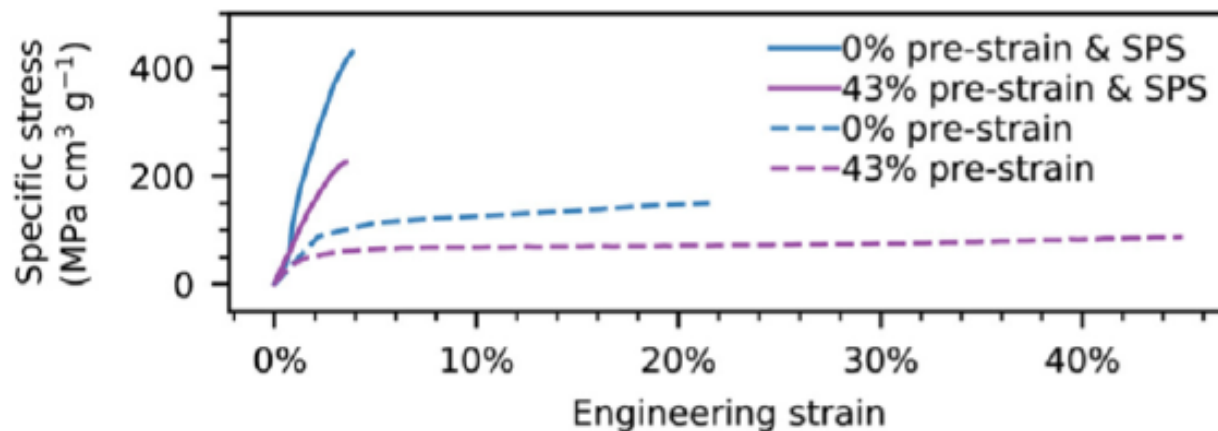
- 1000 °C → n-D vs. 1250 or 1500 °C → n-D and c-D
- MD simulation pressure vs. SPS global pressure

Mechanical Response of Processed CNT Sheets



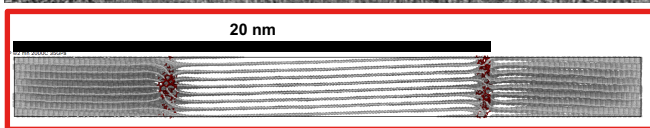
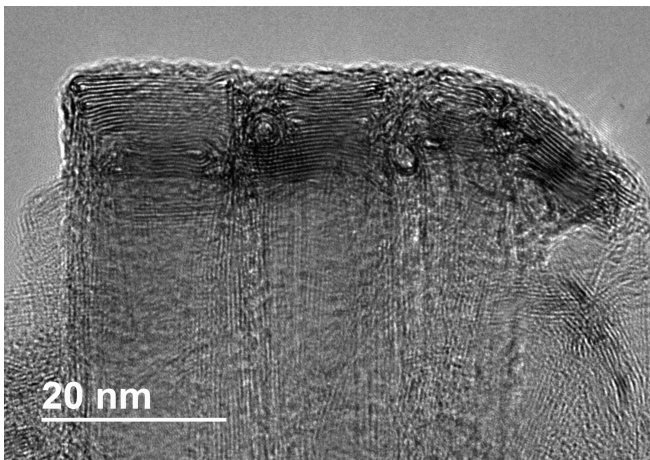


Transverse Mechanical Properties

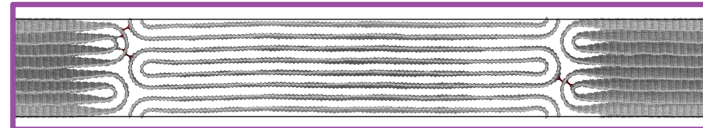
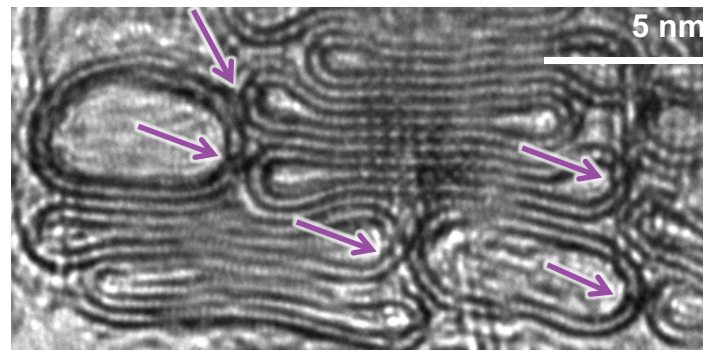


Transmission Electron Microscopy of SPSe Sheets

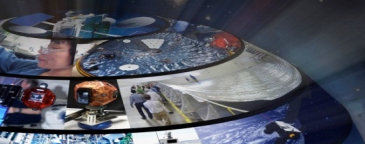
SPS
1000 °C, 20 MPa



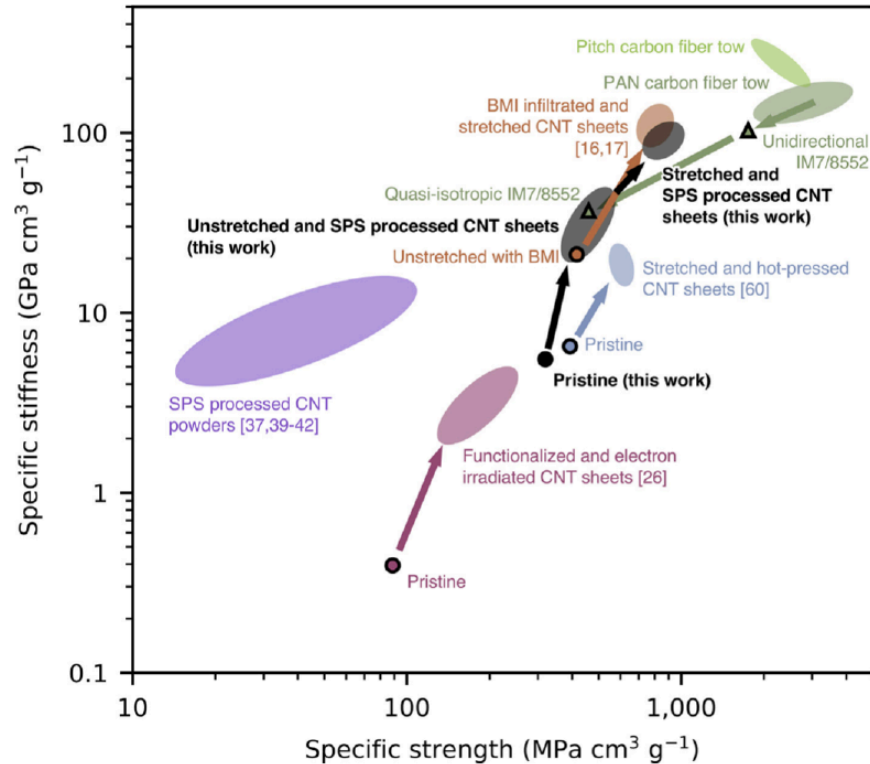
Simulation
2000 °C, 35 GPa

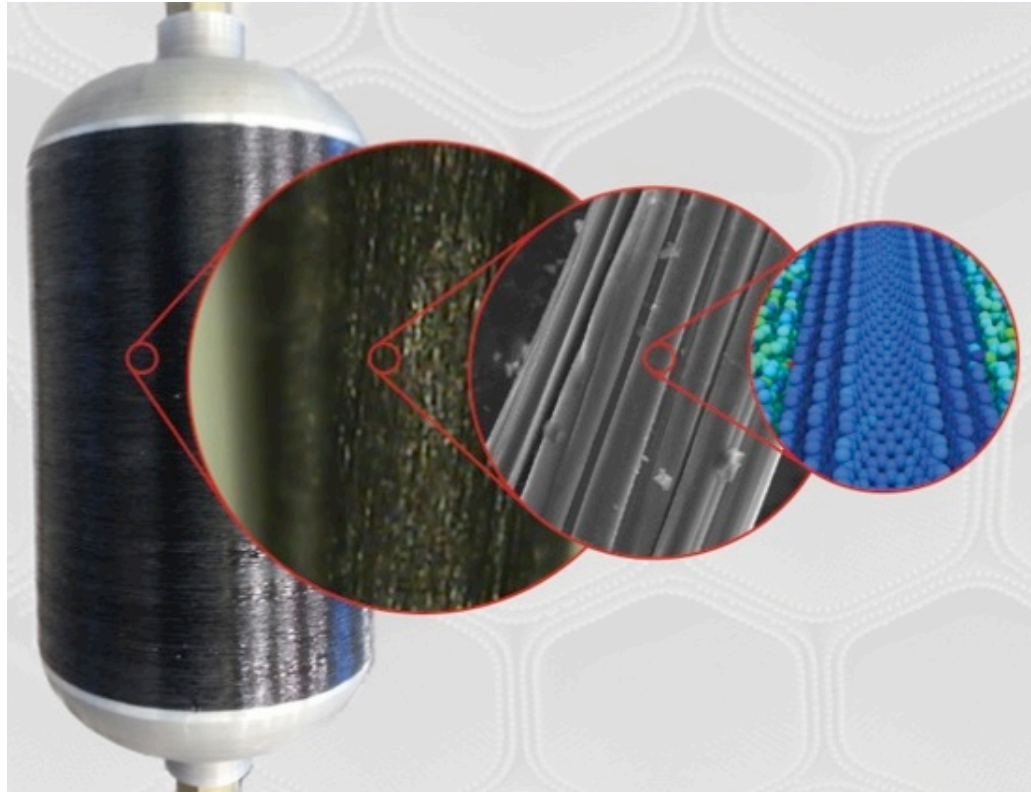


Simulation
2000 °C, 25 GPa

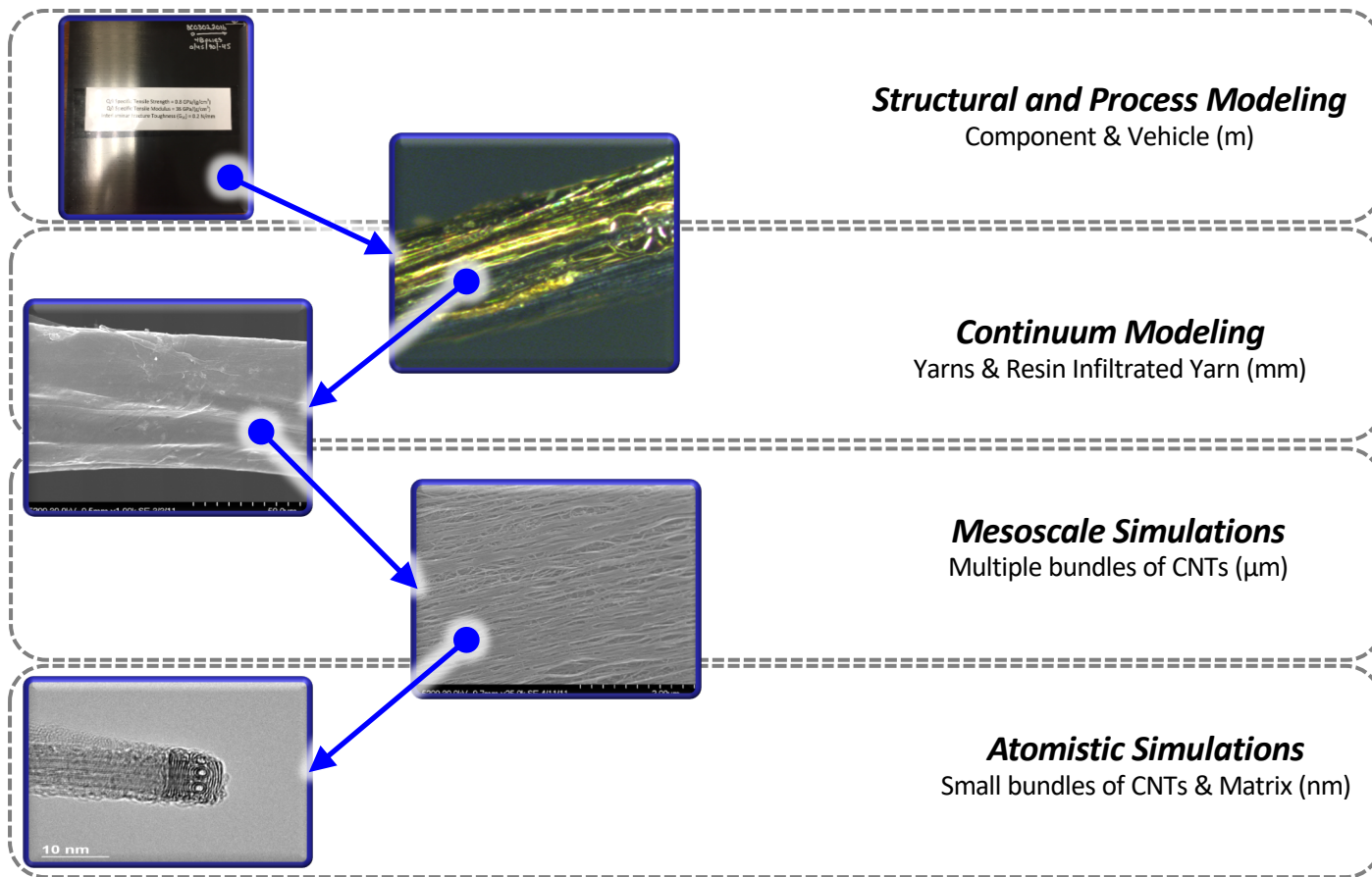
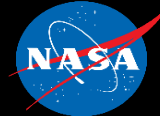


Comparison with Literature Data





Coordinated Modeling Across Relevant Scales



3D Printing of Carbon Nanotube Yarn

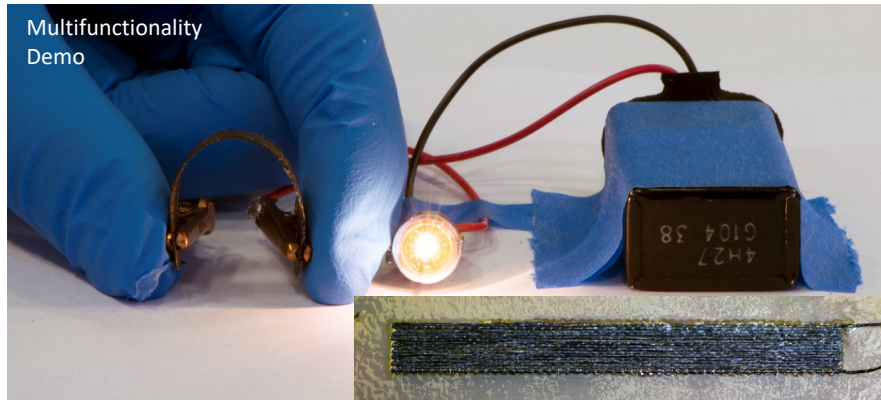
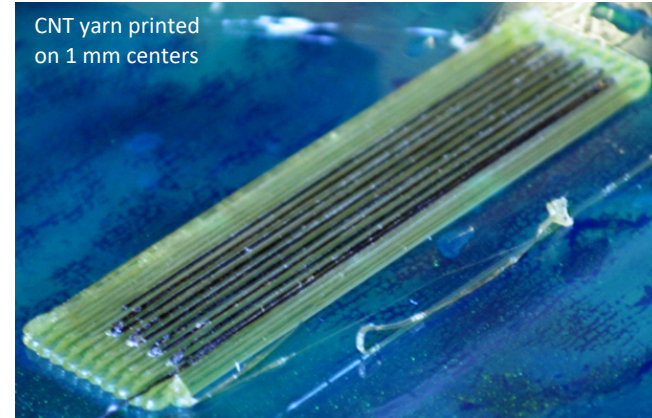
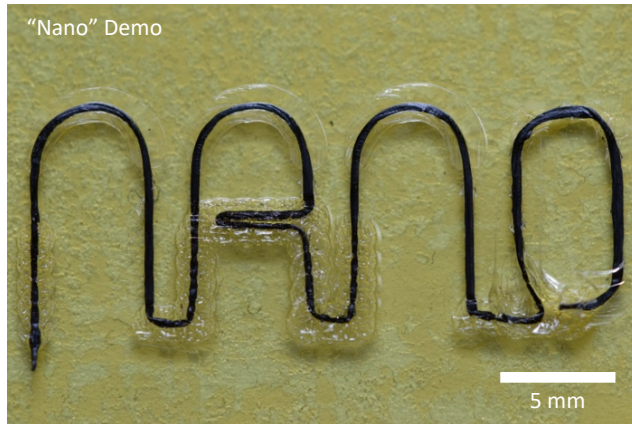
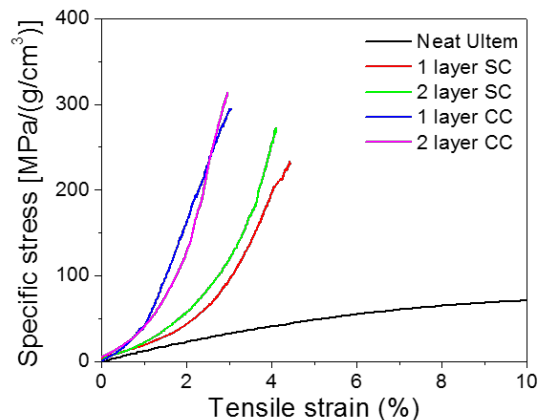


Image Credit: NASA

- CNT compliance allows for high fidelity printing
- Minimum turn radius equal to half the yarn diameter
- Multifunctionality of CNTs retained



Part Characterization



- Selective vs Continuous
 - Tensile test of one and two layer samples
- Strain Sensor
 - Cyclical 3-point bending
 - 5 kg load at 5% strain
- Heating Element
 - Current cycled from 0-0.5 A

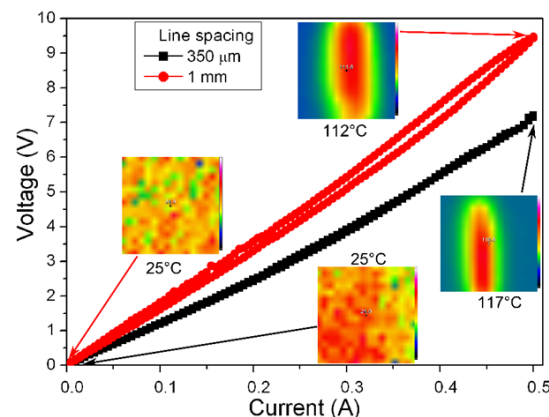
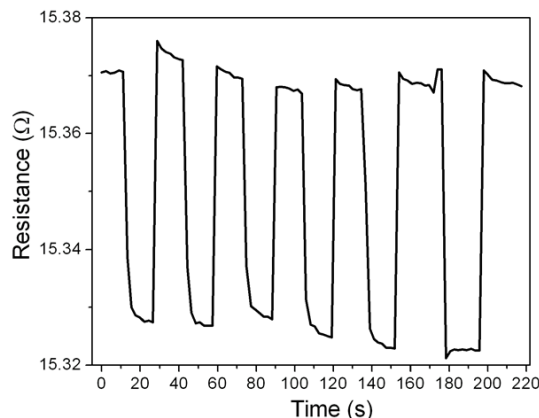


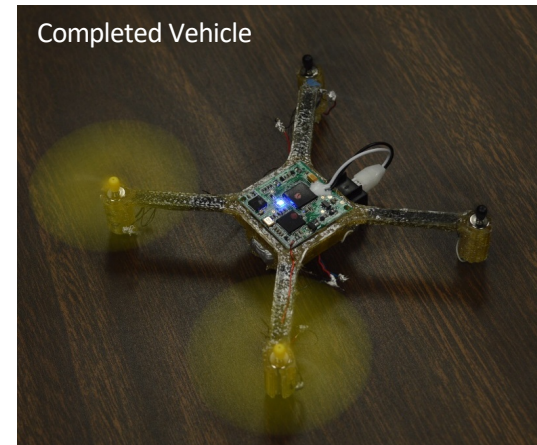
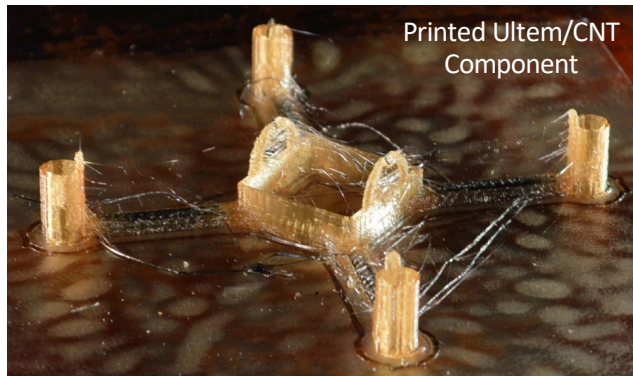
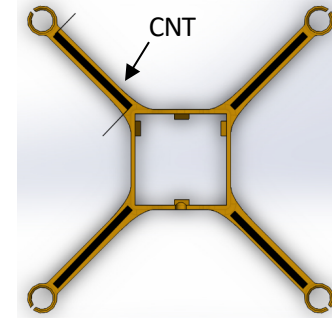
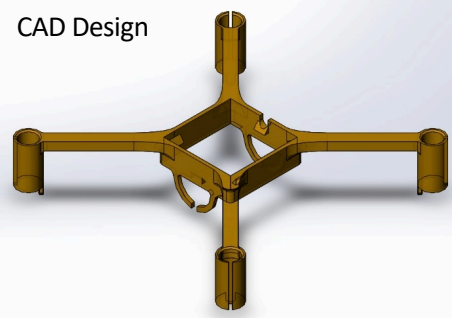
Image Credit: NASA

Functional Component

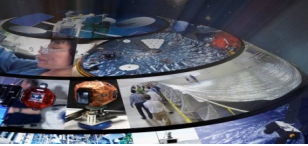


Quadcopter

- Dimensions (rotor centers): 75 x 75mm
- Two 9-line CNT raster pattern (structural) depositions in each arm
- CNT yarn used to power motors



All NASA Images



Summary



- Structural carbon nanotube composites for aerospace applications were benchmarked against state-of-the-art carbon fiber composites.
- Advances in mechanical performance of carbon nanotube composites were accelerated via use-inspired research.
- Coupling computational modeling with experimentation yielded insights on composite processing methods tailored to the inherent characteristics of carbon nanotubes.
- Recent advancements in the development of structural carbon nanotubes suggest their hierarchical microstructures can enable unique performance attributes.

The background of the entire image is a composite of space and Earth scenes. In the upper half, a deep blue space scene features a large, detailed white and grey moon on the left, a smaller reddish planet (Mars) above it, and a small rocket ship with a bright blue and white engine plume flying towards the right. The lower half shows a silhouette of a person's head and shoulders on the right, looking out over a landscape under a sunset or sunrise sky with orange and yellow clouds.

EXPLORESPACE TECH

TECHNOLOGY DRIVES EXPLORATION

Thank You