Recent Advances in Structural Carbon Nanotube Composites

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Image Credit: NASA

Acknowledgements

- Financial Analysts
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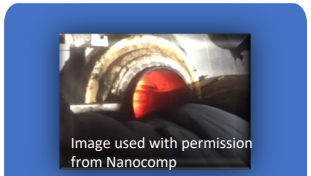
  - Lauren Bonine
  - Damon Sheaffer

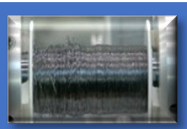
- Joseph Smith
- Scott Zavada

Resin Optimization



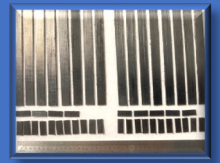
CNT* Manufacturing

- Nanocomp Technologies/Huntsman



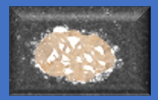
CNT* Yarn Characterization and Development

- Jae-Woo Kim
- John Gardner
- Godfrey Sauti
- Russell Wincheski



Composite Processing

- Jae-Woo Kim
- John Gardner
- Sean Britton
- Godfrey Sauti
- Roberto Cano
- Hoa Luong

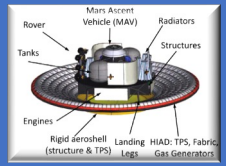


CNT*/Resin Interface Modeling

- Benjamin Jensen
- Kristopher Wise
- Jacob Gissinger

Composite Testing

- Russell Wincheski
- Jae-Woo Kim
- Godfrey Sauti



Systems Analysis

- Jamshid Samareh
- Sasan Armand
- Alex Chin
- Hilmi Alkamhawi

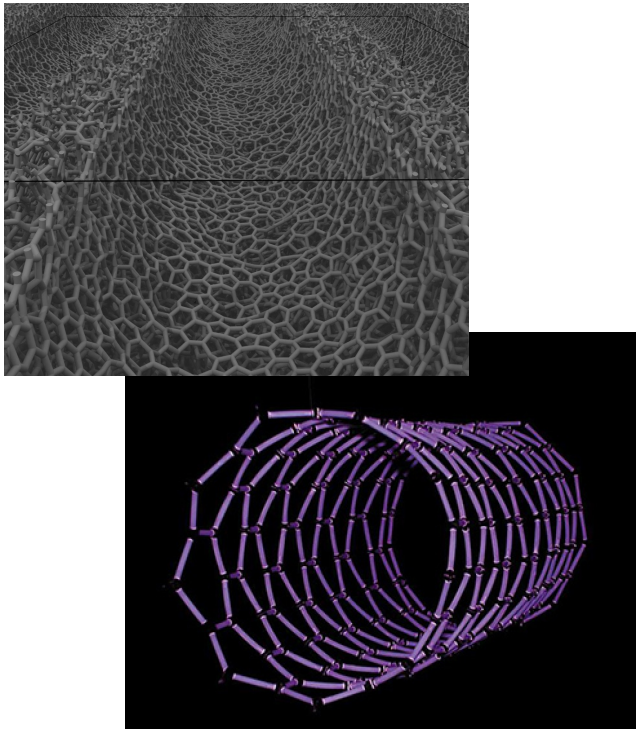
Prototyping

- Godfrey Sauti
- Mia Siochi

*CNT – Carbon Nanotube

Image credits: NASA

Motivation



Carbon Nanotubes

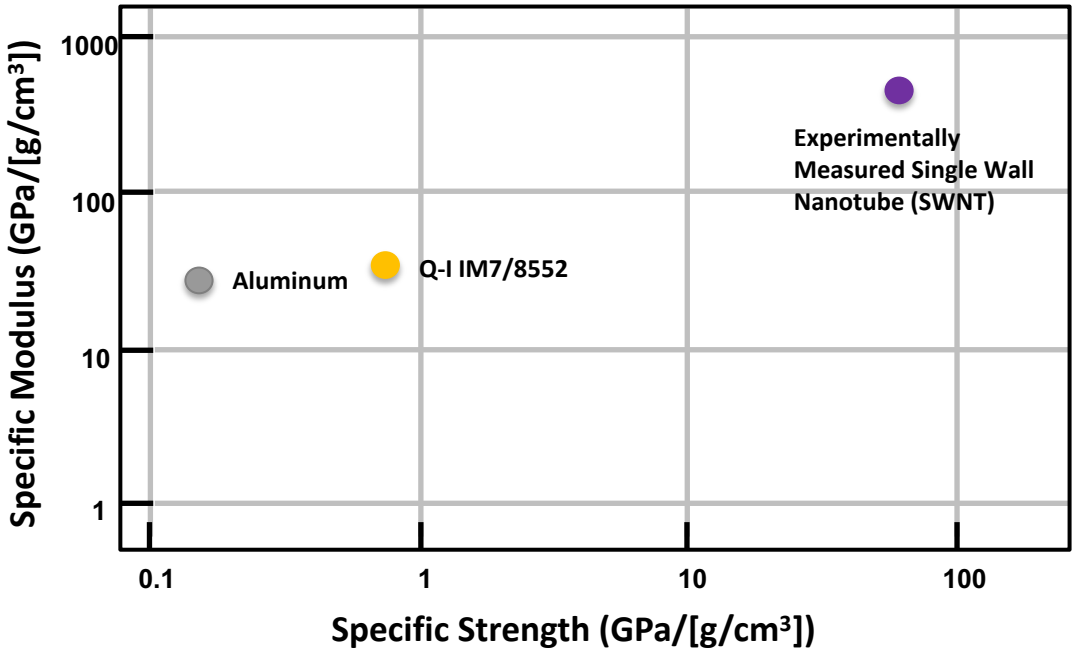


Image credits: NASA

Harris, C. E. et al., NASA TM 211664, 2002.

Motivation

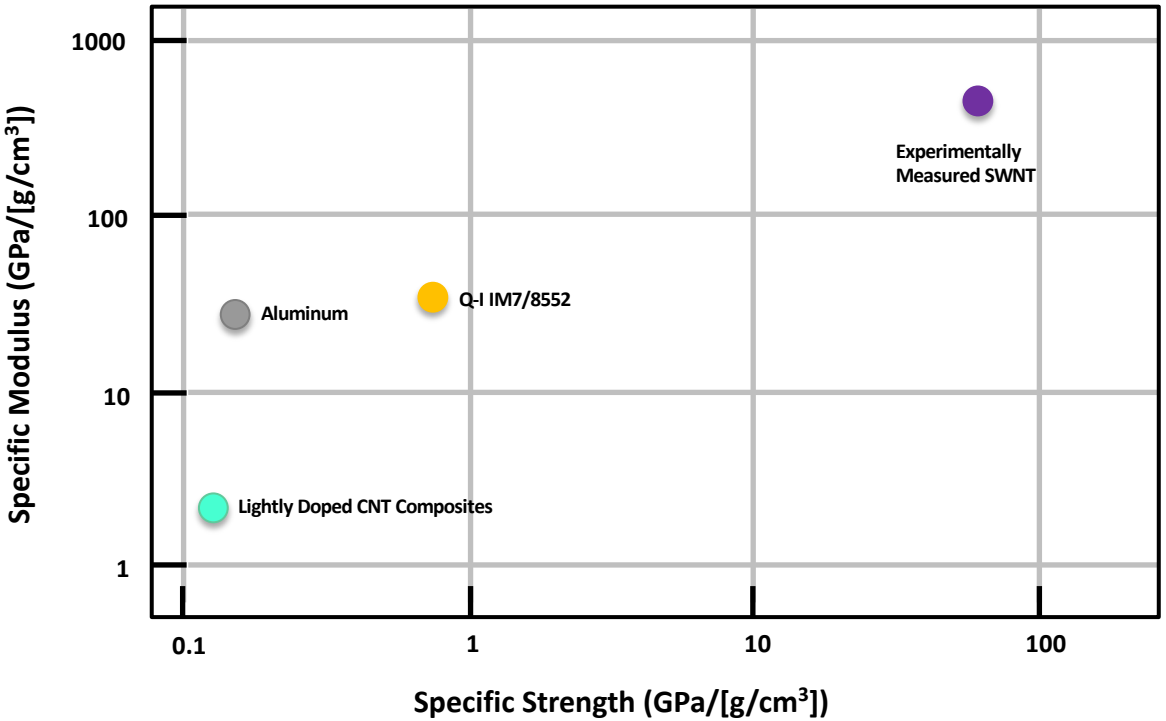
Summary of the Problem

	Mass Ratio*	Cost per pound*
Low Earth Orbit	20	$4,000
Earth to Moon	200	$40,000
To Moon, Return to Earth	500	$100,000
Earth to Mars	500	$100,000
To Mars, Return to Earth	5000	$1,000,000

- Cost increases in proportion to the mass ratio.
- Mass ratio increases linearly with the dry mass and exponentially with $\Delta\upsilon$.
- Costs for exploration escalate beyond low Earth orbit.
- Reducing structural mass reduces mission cost at constant payload or increases mission capability at constant cost.

*Gordon, G. D., AIAA SPACE 2007, paper 6278.

Outcomes

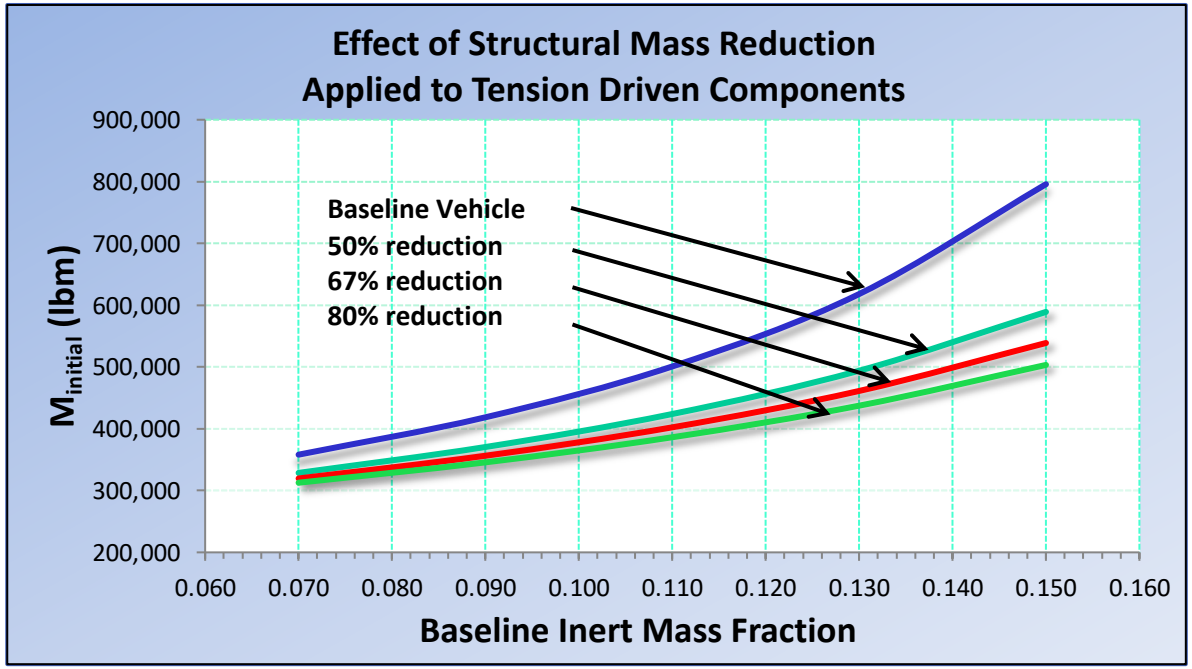


Lessons Learned

- Analogous to very short chopped fiber composites
- Limited by material supply and quality
- Very low volume fraction (< 5%)
- Limited improvement over matrix mechanical properties
- Payoffs noted in electrical/multifunctional properties
- Output: Papers, presentations, patents
- Structural applications envisioned did not materialize

Representative data point from Siochi, E. J. et al., *MRS Bulletin*, **40**, 829-835, 2015.

Setting Goals Using Systems Analysis



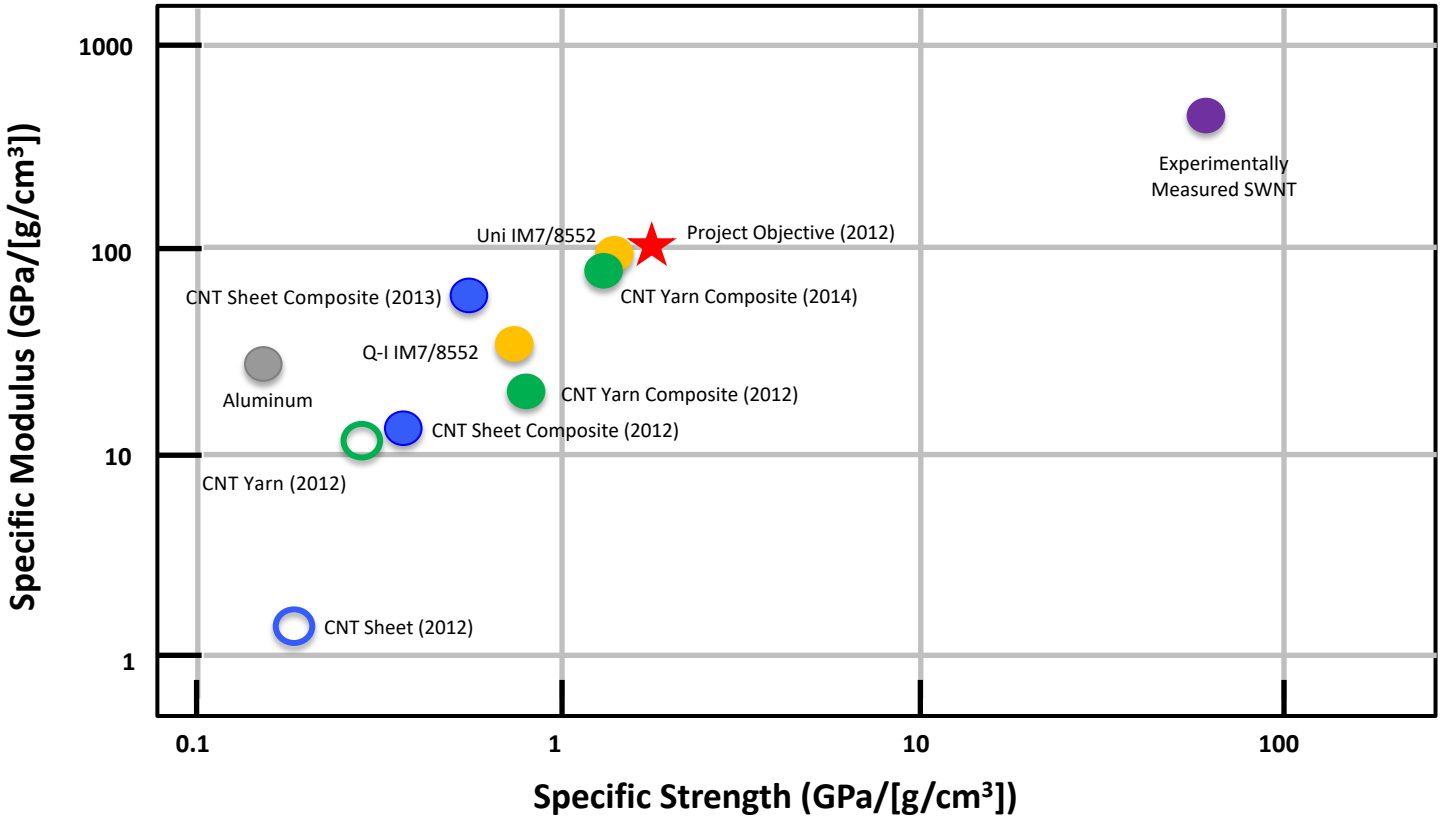
- A 2x to 3x improvement in specific mechanical properties will permit substantial mass reduction in structural and non-structural components.

McMillan, M., White Paper, March, 2013.

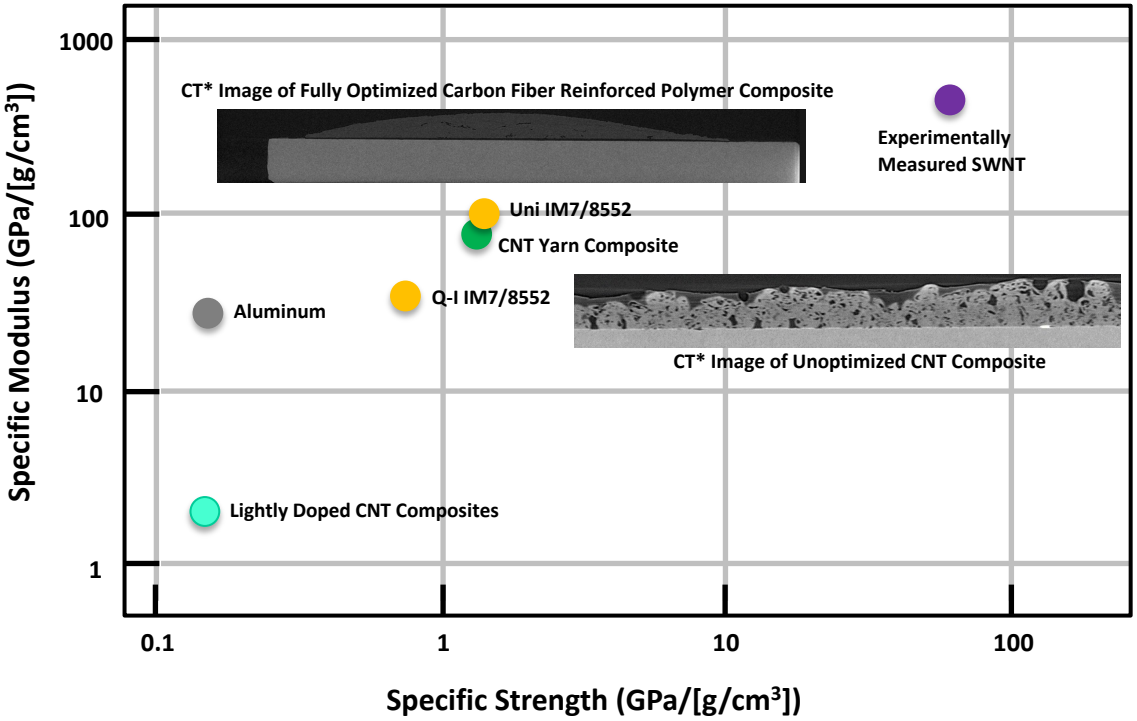
State-of-the-Art Lightweight Structural Material

6 ft x 10 ft PETI-5/IM7 Skin Stringer Panel from High-Speed Research (HSR) Program

Nano to Macro Challenge



Outcomes for Early CNT Fibers



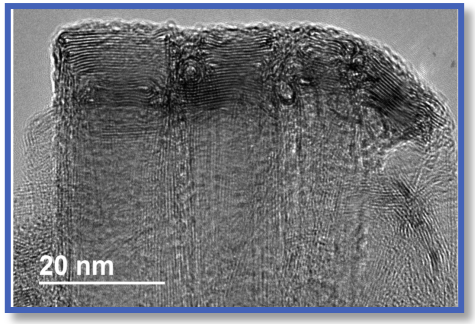
Measurable Advancements

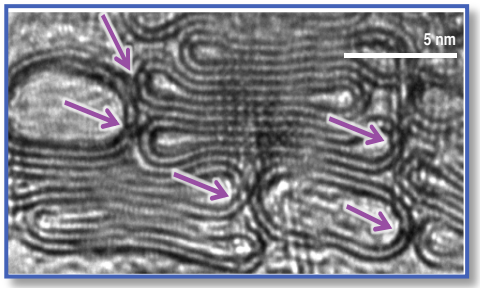
- Improvement in mechanical properties
  - Systems level guided, goal focused research
  - Project objective provided basis for objective decisions
- Increase in Manufacturing Readiness Level
  - Volume – material available in spool lengths of hundreds of meters
  - Consistency – materials met A-basis allowable of at least 20 N breaking force

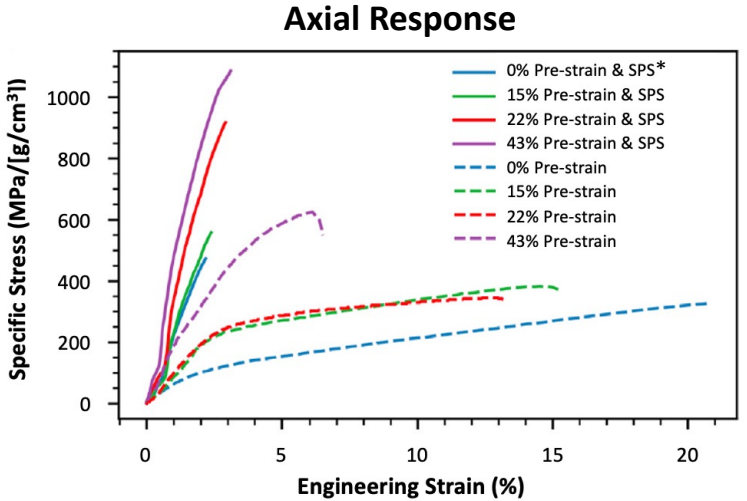
Image Credit: NASA

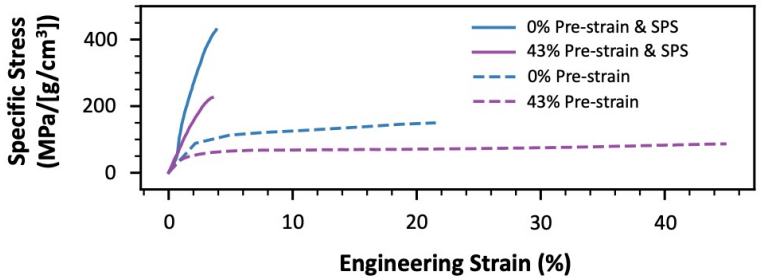
* Computerized Tomography

Experimental Validation of Simulation Results







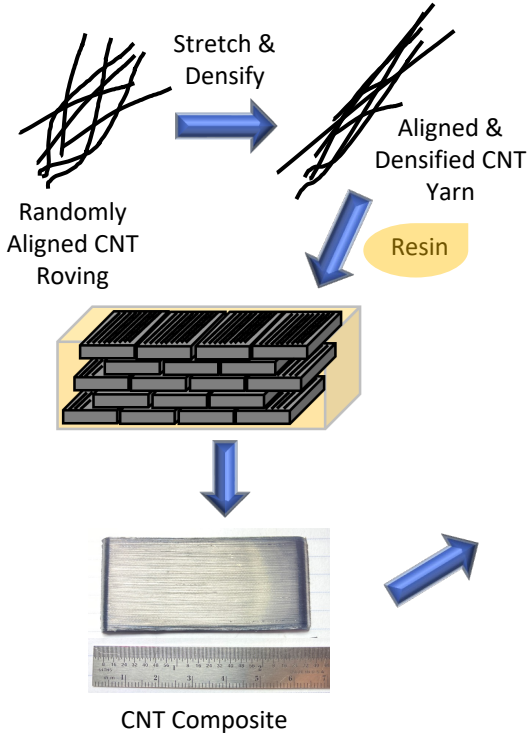


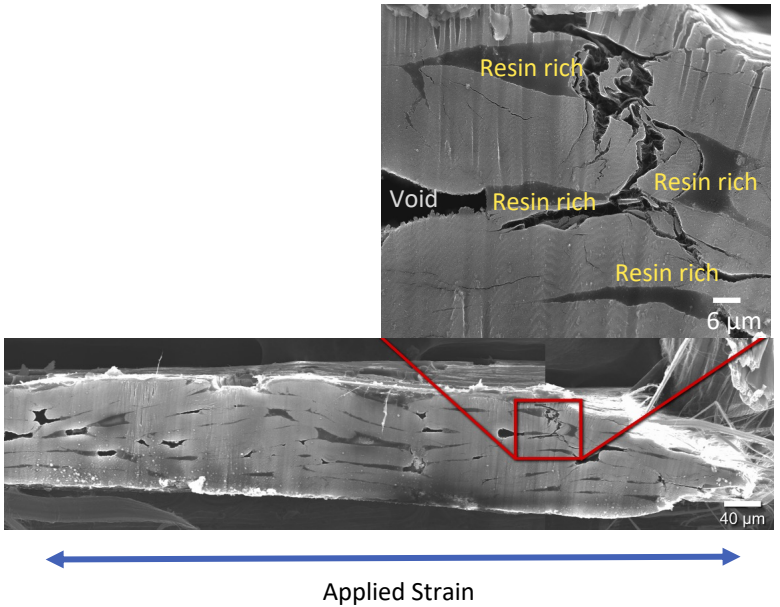
* Spark Plasma Sintering

Image Credits: NASA

Jensen, B. D., et al., *Carbon*, **156**, 538-548, 2020.

Transverse Mechanical Performance



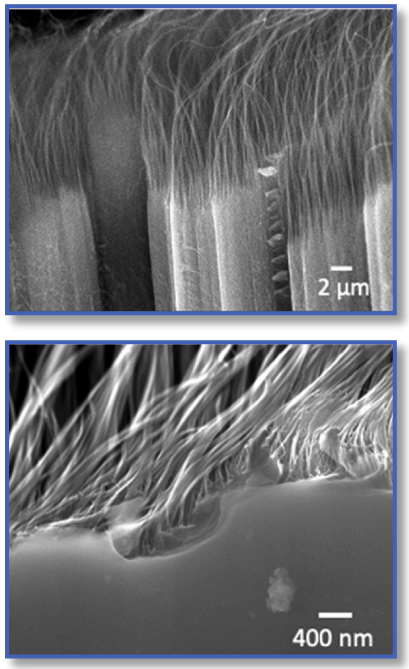


Failure Mode of Unidirectional
CNT Yarn Composite

Image Credits: NASA

Kim, J-W., et al., *Composites Part A*, **167**, 107449, 2023.

Challenge: Poor CNT Yarn/Resin Interface



Representative Failure Surfaces

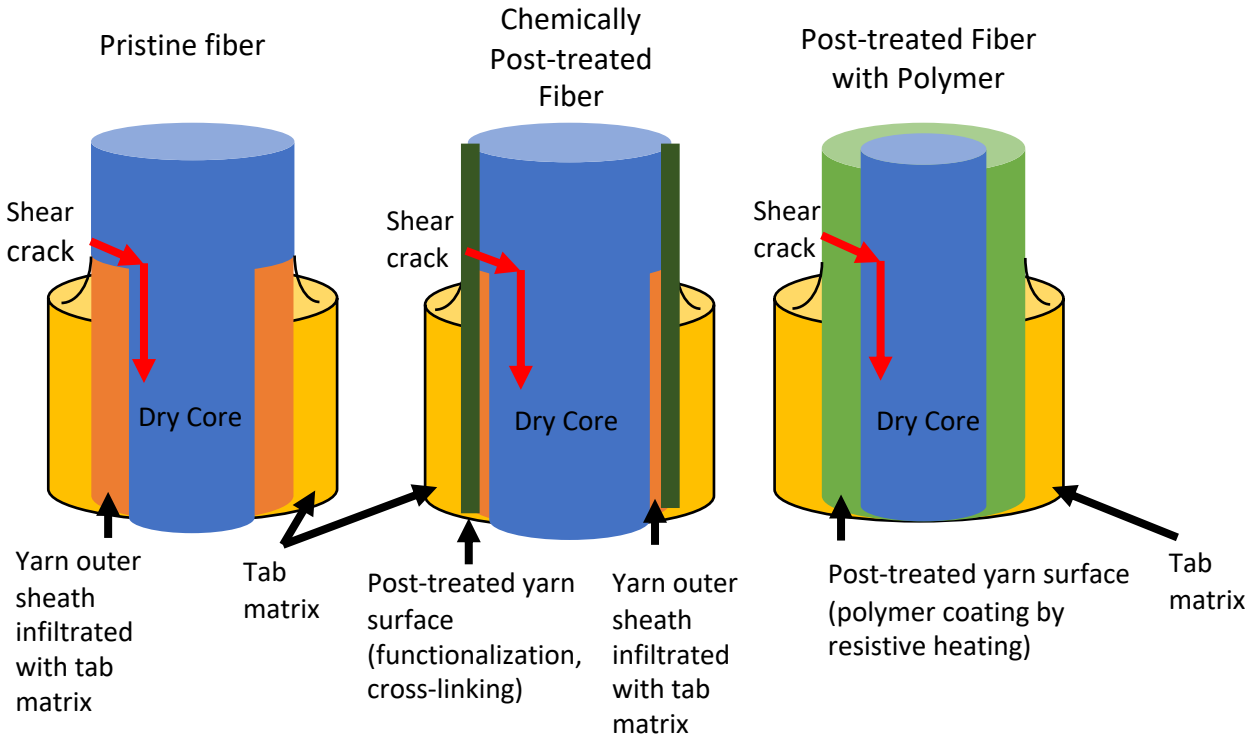
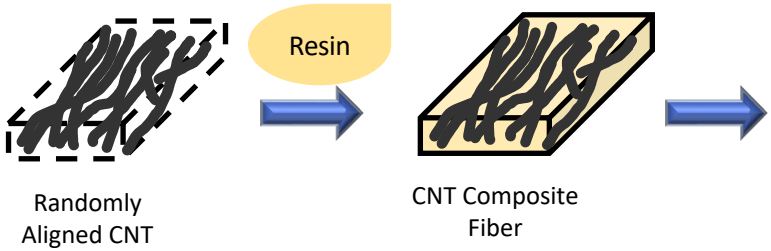


Image Credits: NASA

Kim, J-W., et al., *Carbon*, **173**, 857-869, 2021.

Improving Resin Infiltration



Single Fiber Pull-Out Test

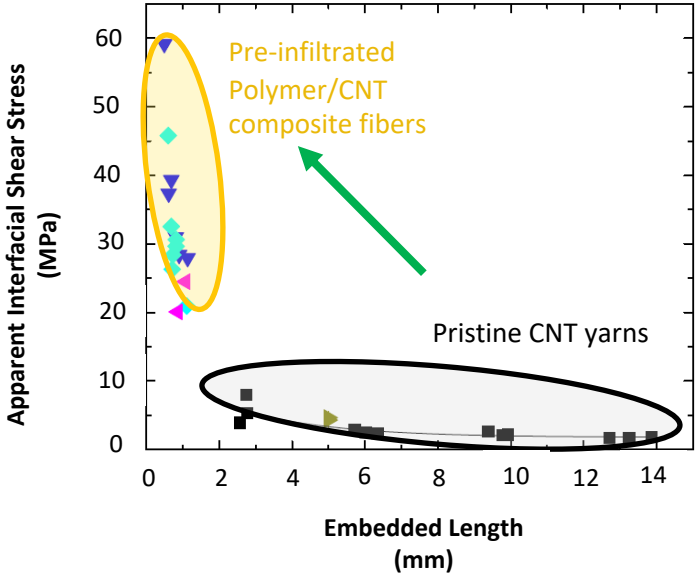
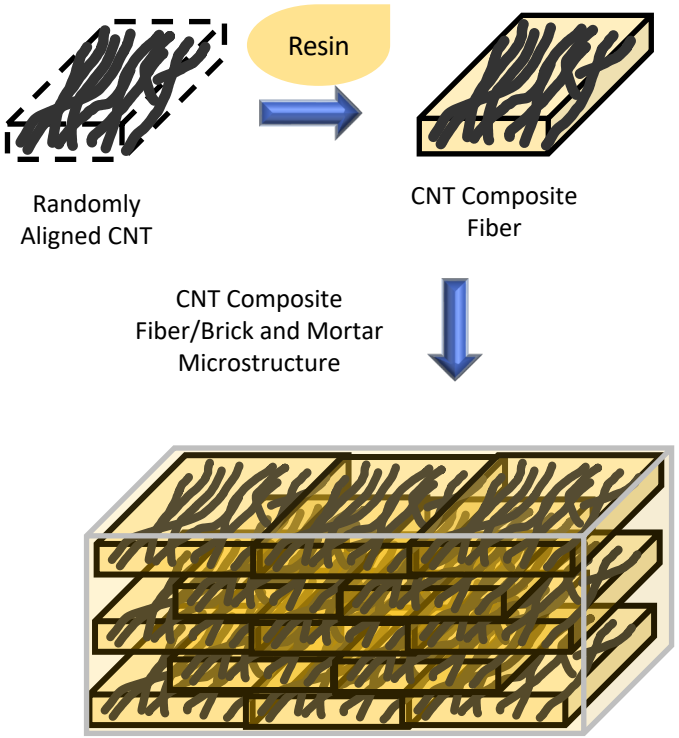


Image Credits: NASA

Kim, J-W., et al., *Carbon*, **173**, 857-869, 2021.

Multiscale Hierarchical CNT Composite Fabrication



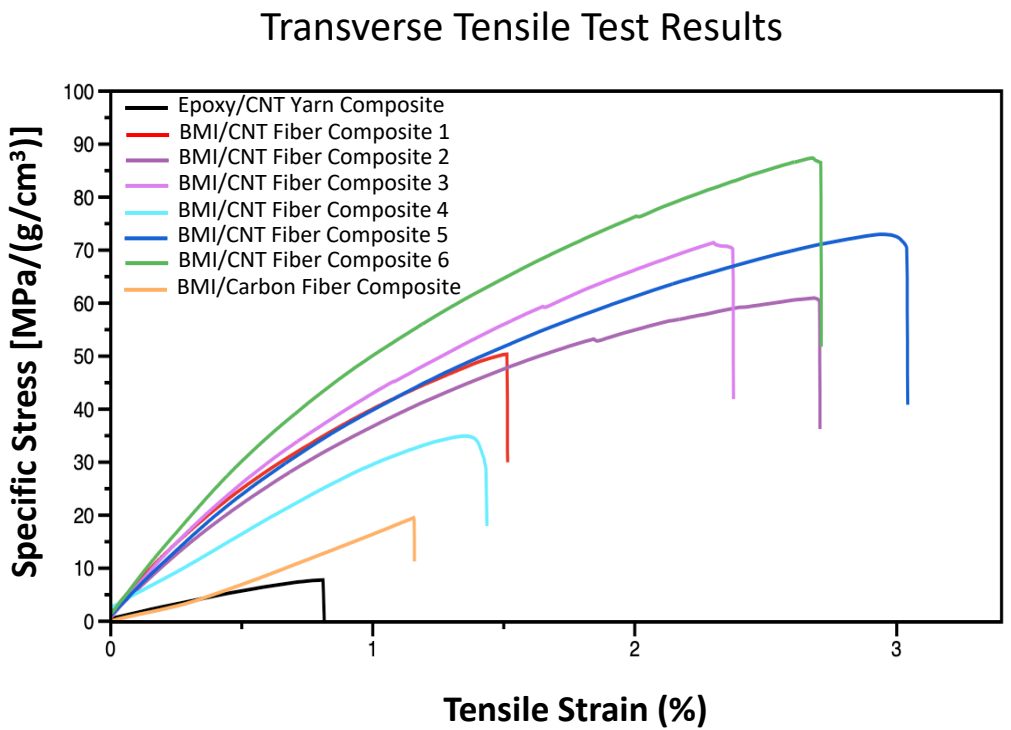
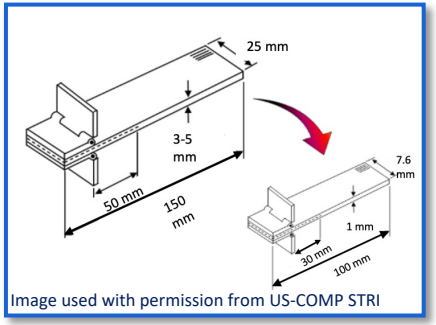


Image Credits: NASA

Kim, J-W., et al., *Composites Part A*, **167**, 107449, 2023.

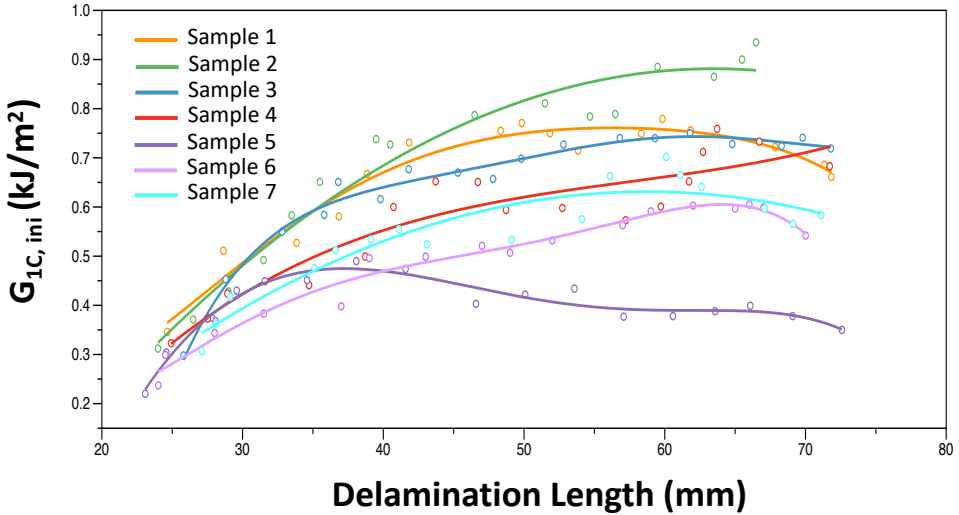
CNT Composite Fracture Toughness



Based on ASTM D5528
Double Cantilever Beam (DCB) Test

CNT Composite DCB Samples

Fracture Toughness Data



Kim, J-W., et al., *Composites Part A*, **167**, 107449, 2023.

Systems Defined Goal Provides Common Objective

NASA Centers
- LaRC
- MSFC

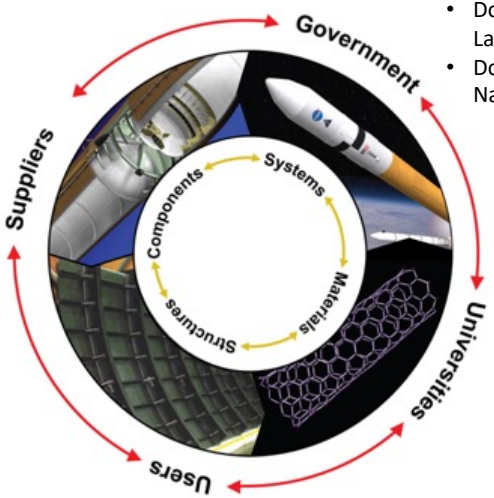
Public/Private Partnerships
- Northrup Grumman
- University of Dayton Research Institute/State of Ohio

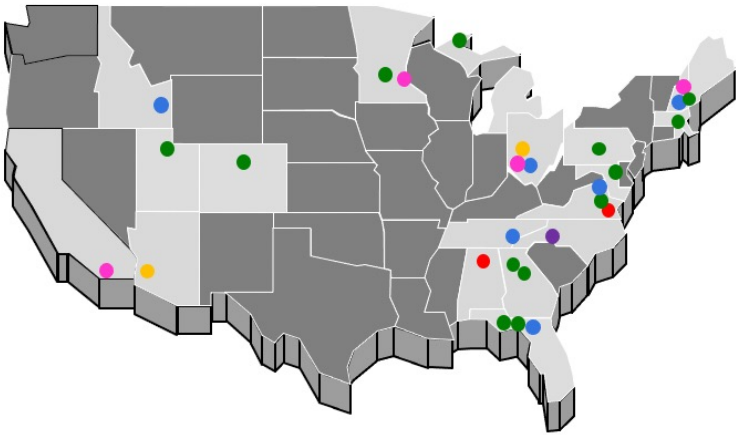
OGA Leveraging
- AFOSR
- AFRL – ManTech Program
- DoD
- DoE - ARPA-E
- DoE – Idaho National Lab
- DoE – Oak Ridge National Lab

Small Business
- Textum, Inc.

SBIR/STTR
- Nanocomp
- Cornerstone Research Group
- Minnesota Wire & Cable
- Applied Composites

STRI
- Florida State U
- MIT
- VCU
- Ga Tech
- Penn State U
- FL A&M U
- Solvay
- Michigan Tech
- U of Utah
- U of Colorado
- Johns Hopkins
- U of Minnesota
- Nanocomp

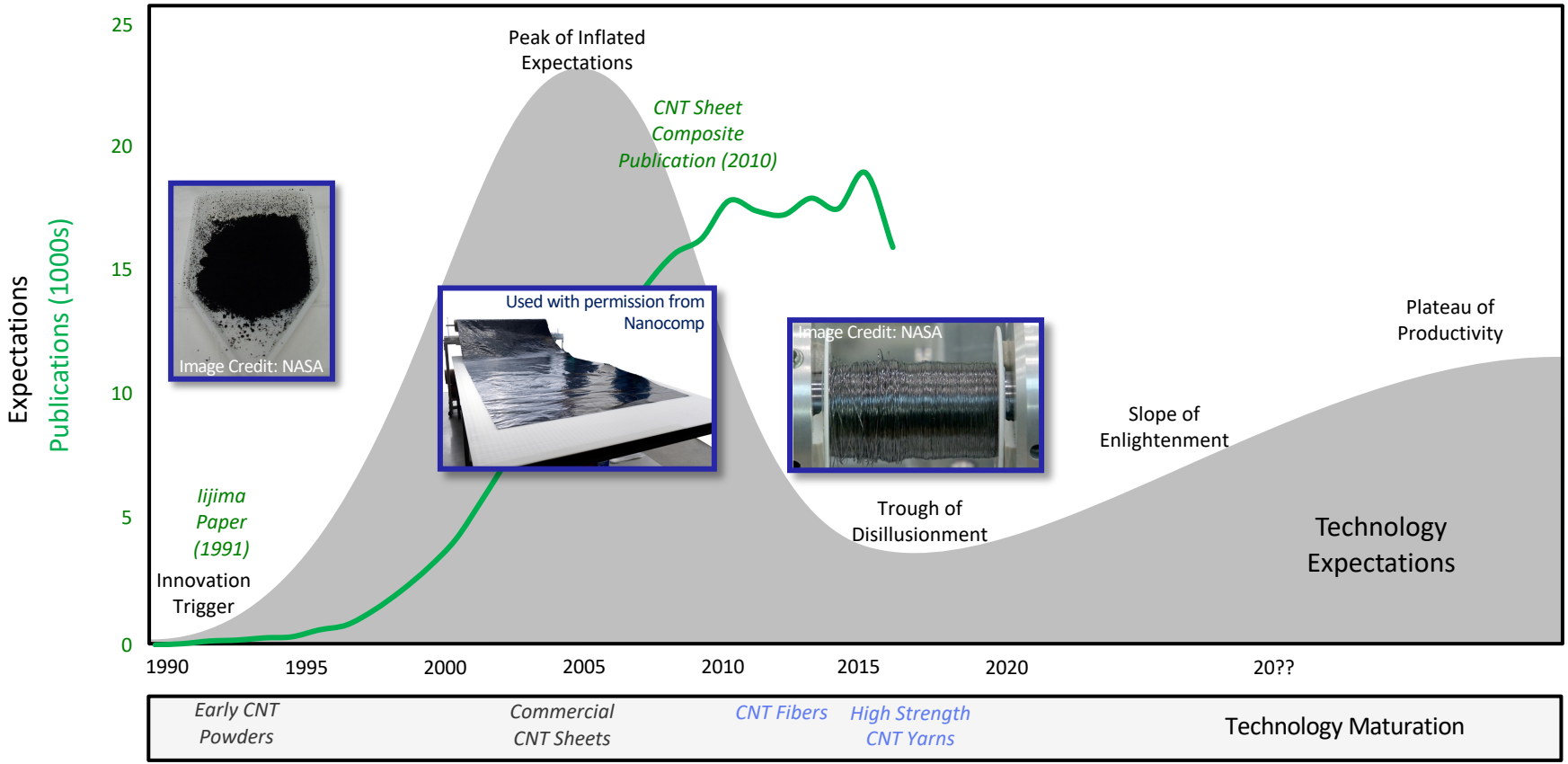




Incentivize multidisciplinary partnerships to accelerate maturation of an emerging material ecosystem.

Image Credit: NASA

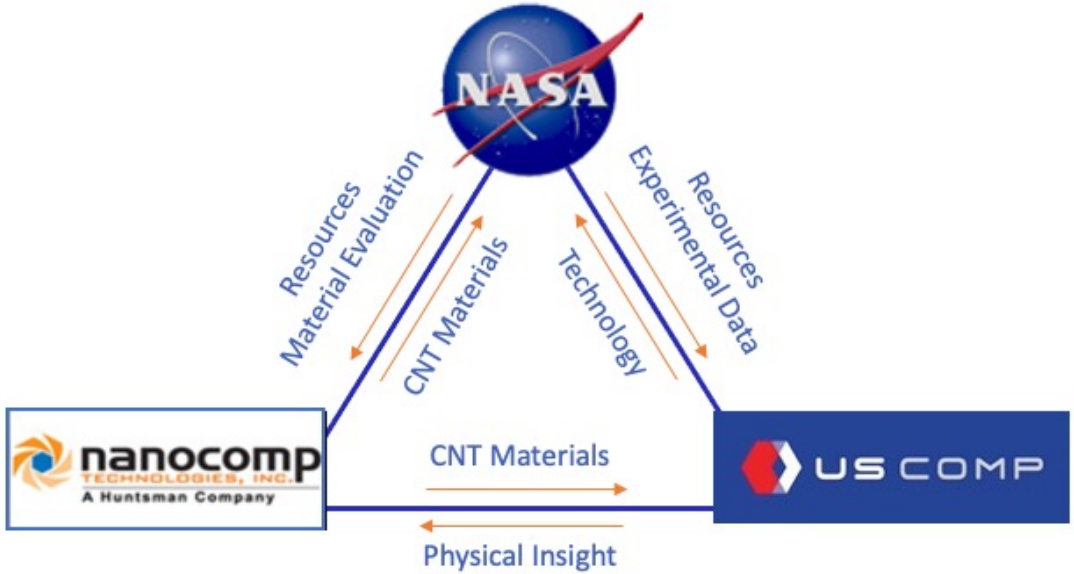
Use Driven Technology Maturation



Summary

- Advances in structural CNT development
  - CNT material is available in formats and quantities that permit their evaluation as structural materials.
    - CNT composite mechanical properties presented included axial tensile, transverse tensile, and fracture toughness.
  - CNT microstructure is different from carbon fiber.
    - Hierarchical structures in CNTs present resin infiltration challenges that require a different approach for composite fabrication.
  - CNT/matrix interface needs to be improved for further enhancements in mechanical properties.
    - Modeling guided CNT composite processing helps to accelerate optimization of CNT composite fabrication method.

Summary – Role of NASA



NASA mission needs serve as technology pull to guide accelerated maturation of emerging technologies.

Maturing Emerging Technologies . . .

For Societal Benefits on Earth . . . And Beyond

Image Credit: NASA