Structural Health Monitoring using CNT-Enhanced Composites

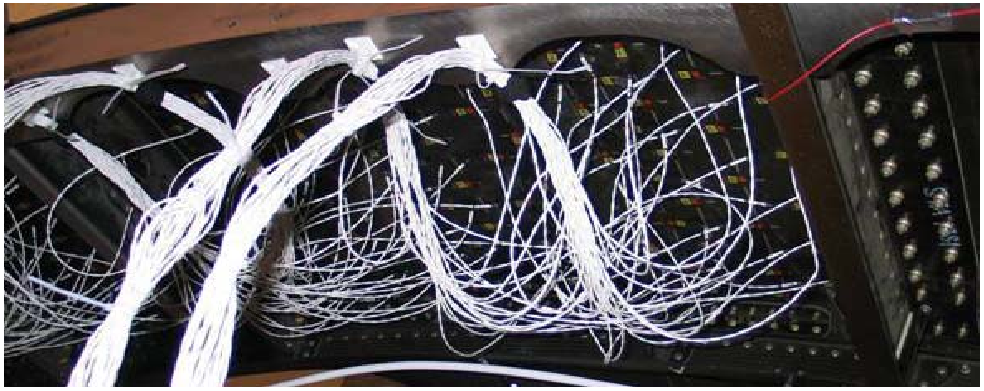
Dr. Ajay Raghavan, Dr. Seth S. Kessler & Dr. Christopher Dunn
Metis Design Corporation

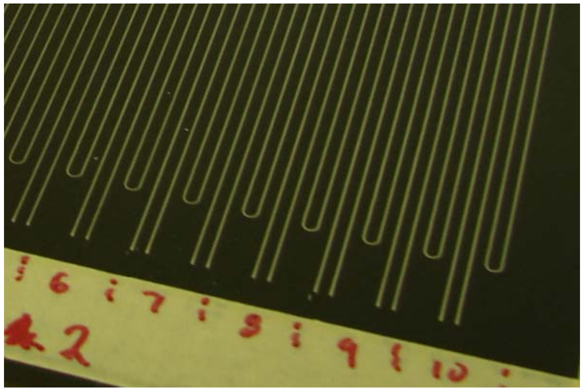
Derreck Barber, Sunny Wicks & Prof. Brian L. Wardle
Massachusetts Institute of Technology

10 Canal Park • Cambridge, MA 02141 • 617.661.5616 • http://www.metisdesign.com

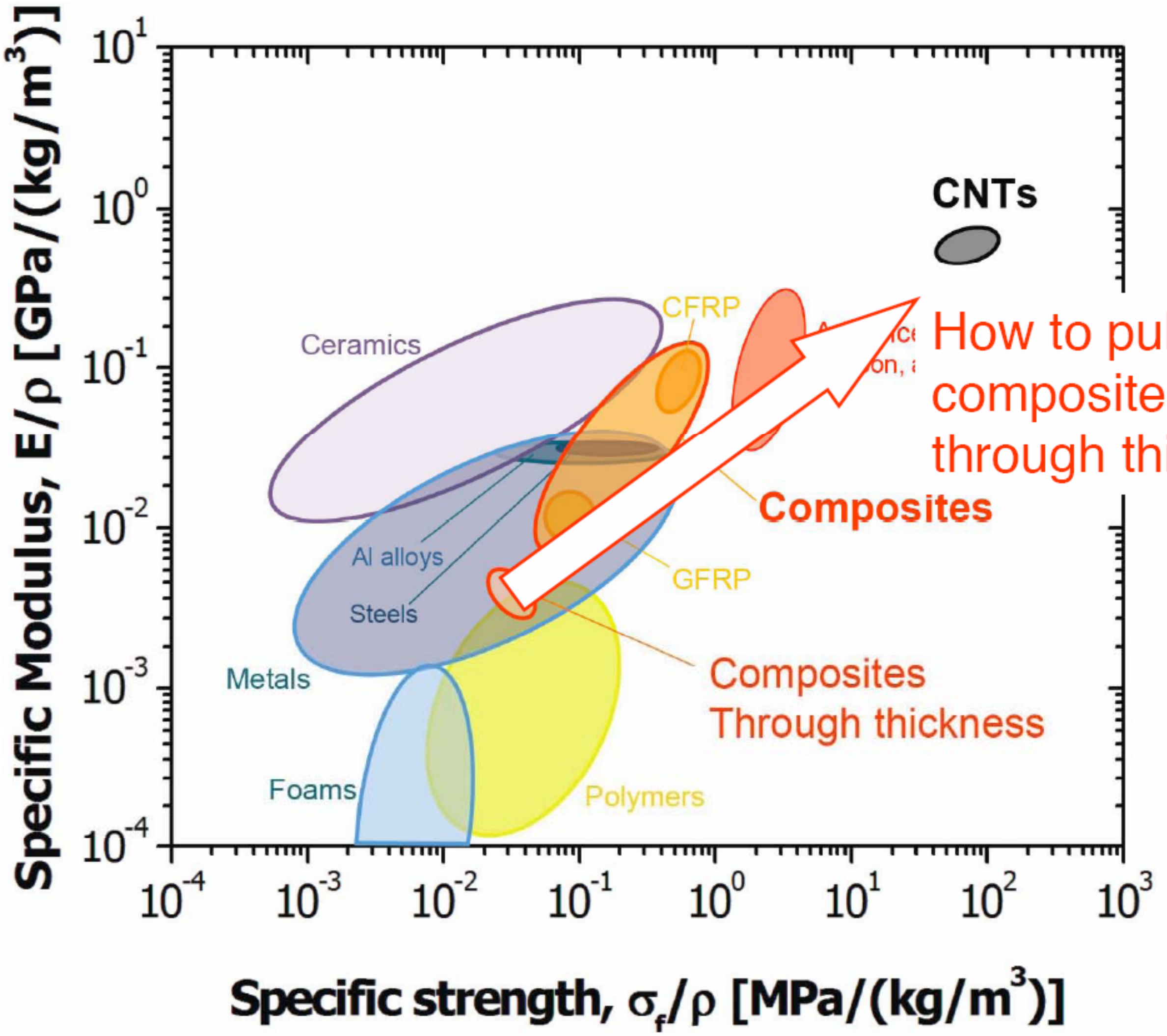
Motivation For CNT-based SHM

- SHM improves reliability, safety & readiness @ reduced costs
  - sensors add weight, power consumption & computational bandwidth
  - cables add weight, complexity, as well as durability & EMI concerns
  - scaling SHM for large-area coverage has presented challenges
- Advantages of proposed CNT-based SHM methodology
  - sensing elements actually *improve* specific strength/stiffness of structure
  - conformal direct-write (DW) electrodes lighter & more durable than cable
  - simple to scale over large structure, maintains good local resolution





Density Normalized Comparison



How to pull up composites, esp. through thickness?

Carbon Nano-Tube (CNT) laminates are a natural progression for aerospace composites due to their superior specific strength & stiffness

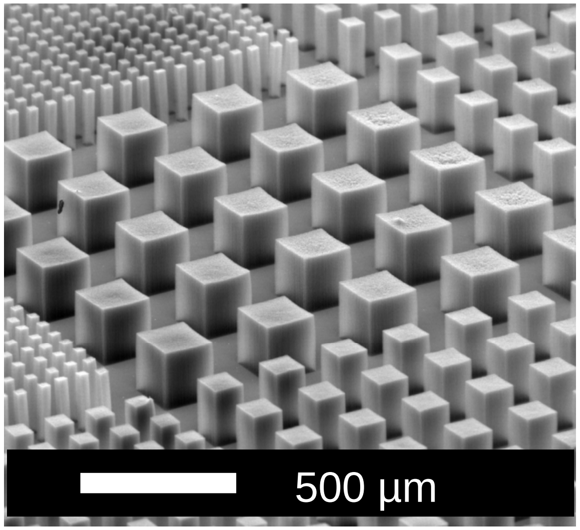
Present CNT Challenges

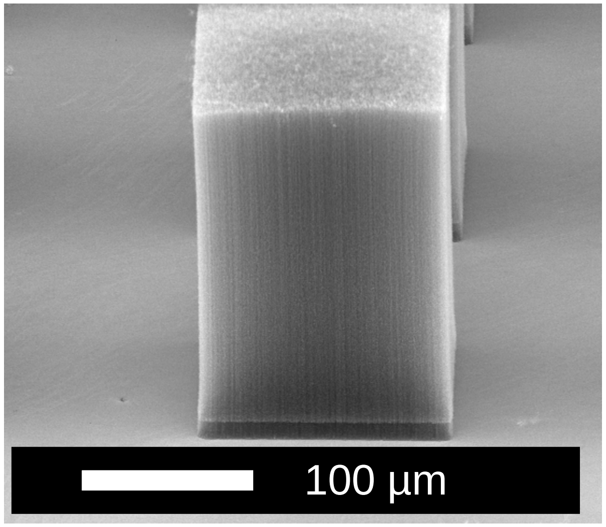
- Several issues have hindered effectiveness of CNT engineering
  - dispersion: uniform distribution of CNTs in epoxy matrix for homogeneity
  - adhesion: CNT-matrix interfacial bonding for effective load transfer
  - orientation: non-random alignment of CNTs to amplify properties
  - forests: building larger macroscopic structures by linking individual CNTs

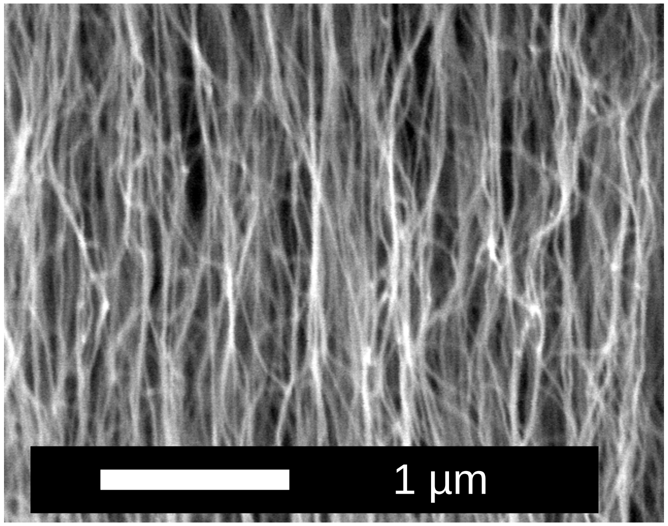
- Most investigators focus on addressing 1-2 of these issues individually, yielding marginal improvements

- Simultaneously achieving all 4 necessary to achieve true potential of CNTs for enhanced composite structures

Growth of Aligned CNTs





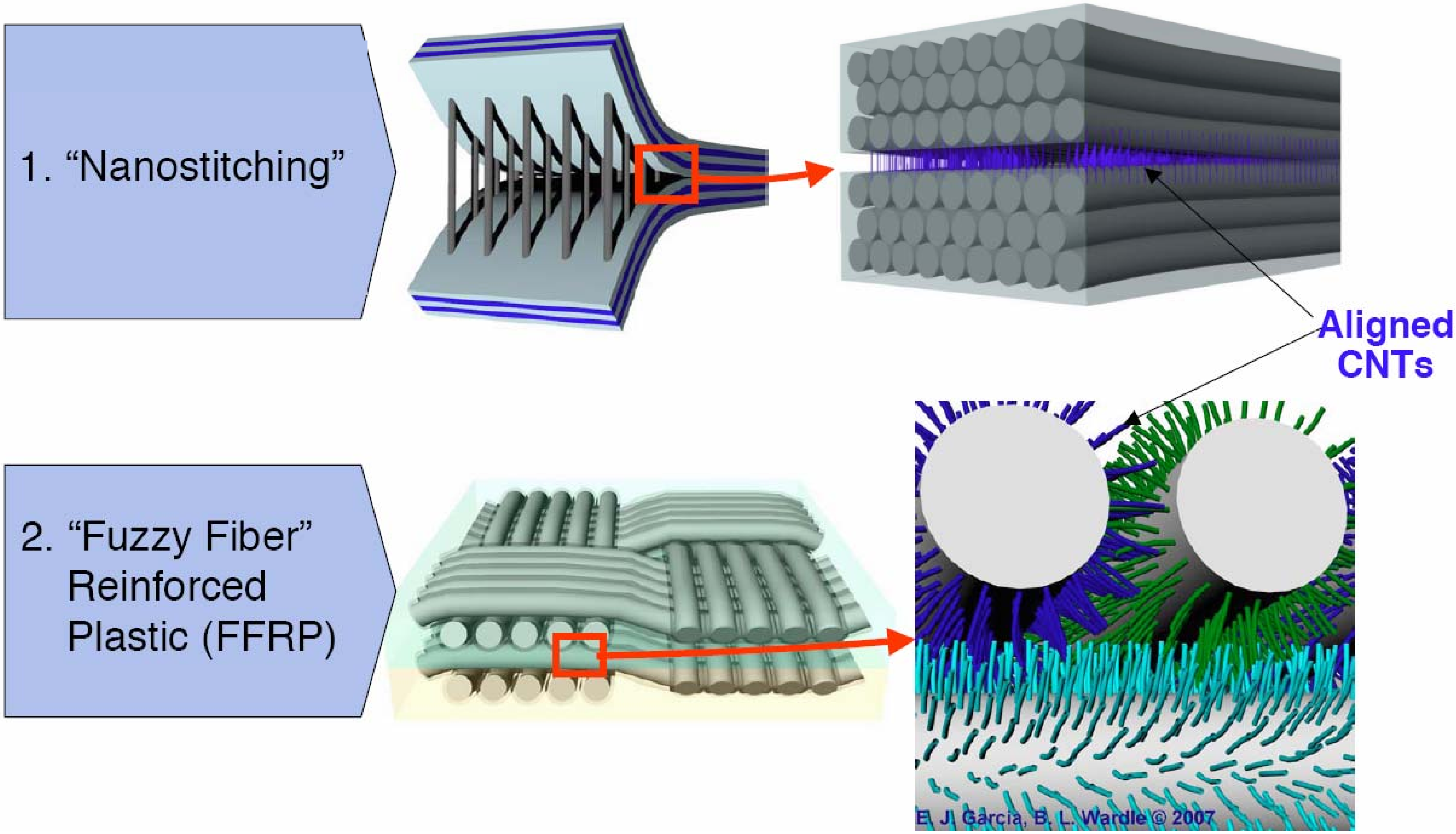


- MIT has developed a novel (patent pending) CNT process
  - good alignment, dispersion & adhesion yields high CNT volume fraction
  - provides excellent *in-plane* & *<u>through thickness</u>* conductivity

- Atmospheric pressure chemical vapor deposition (CVD)
  - self-aligned morphology 10^{10}-10^{11}/cm^2 of continuous CNTs (7-10 nm OD)
  - rapid forest growth of > 2 microns/second (up to 5 mm long)

Nano-Engineered Composites

Use aligned CNTs to reinforce and tailor existing advanced composites

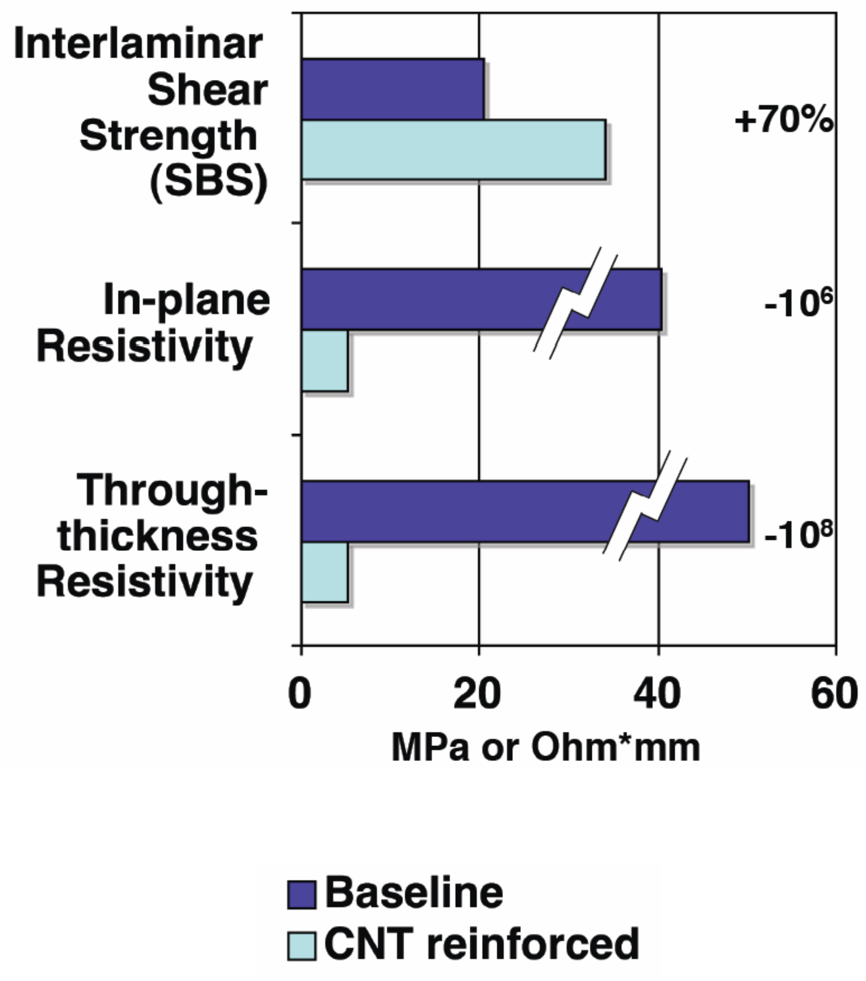


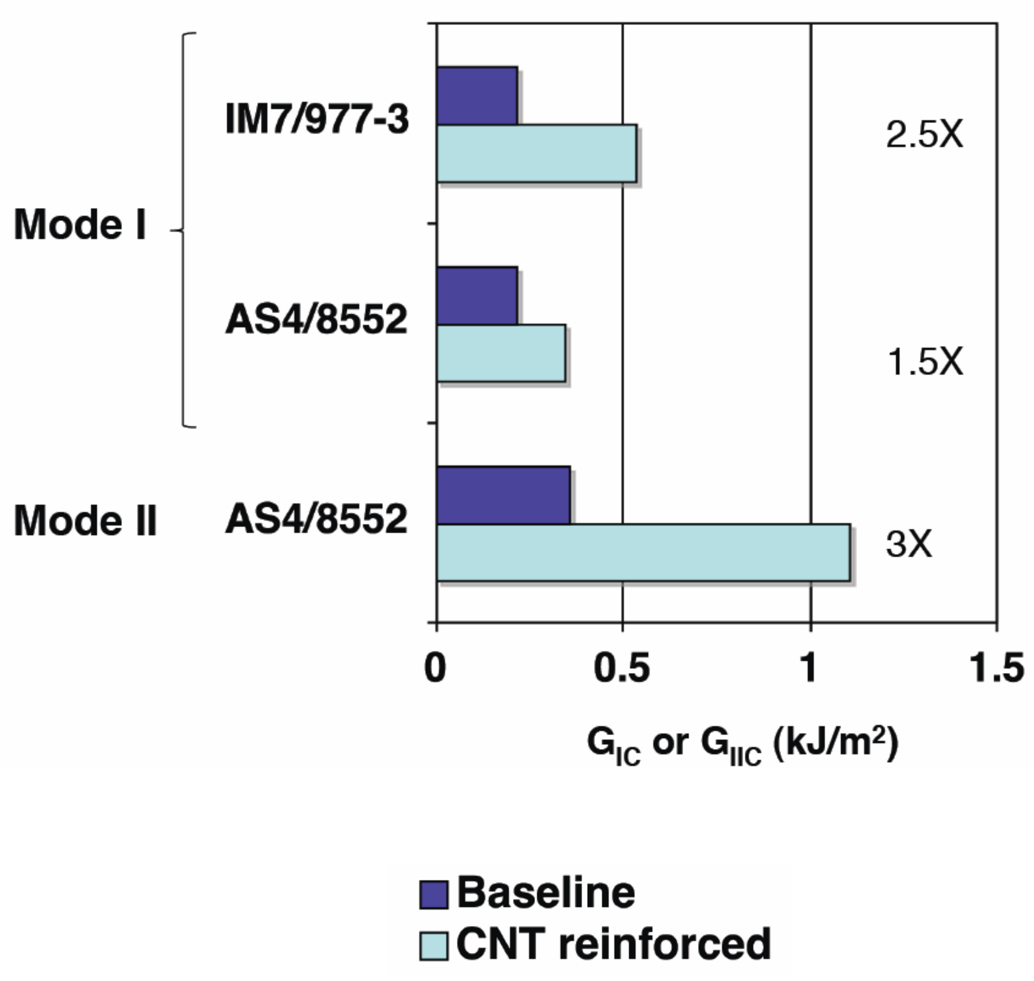
1. "Nanostitching"

2. "Fuzzy Fiber" Reinforced Plastic (FFRP)

Aligned CNTs

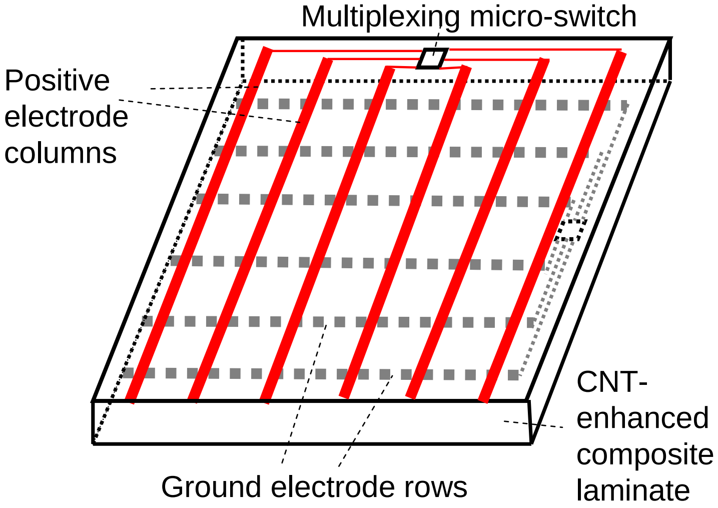
Measured CNT-Enhanced Properties





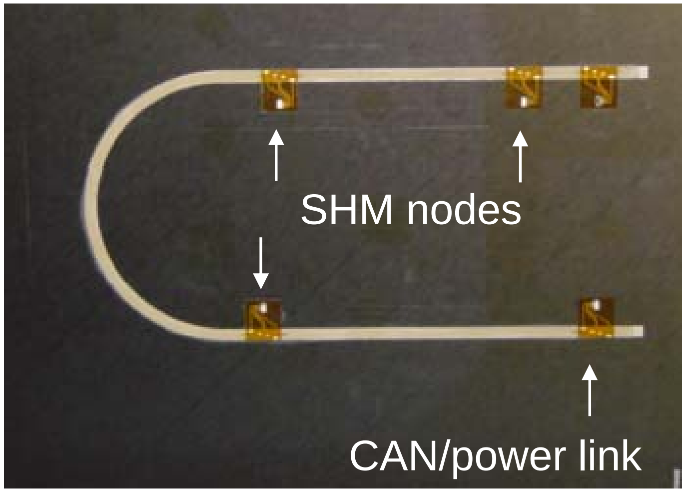
CNT-Enhanced Composites for SHM

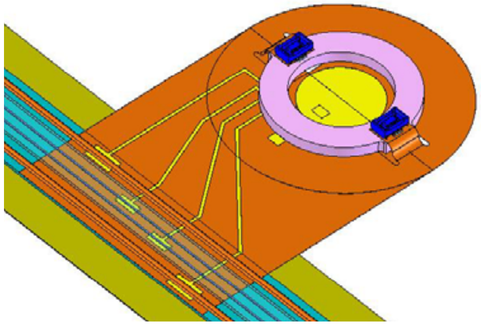
- Aligned CNTs greatly enhance composite laminate properties
  - mechanically improve impact, delamination & fatigue resistance
  - multifunctional capabilities introduced by conductivity & piezoresistivity
- Present research exploits CNTs for in-situ damage imaging
  - direct-write (DW) electrode grids applied similar to LCD technology
  - in-plane & through-thickness resistance measurements collected
  - surface & sub-surface damage images produced in post-processing



Direct-Write Technology

- Subject of recently completed Phase I NASA SBIR
  - Direct-Write (DW) technology can be used to replace traditional cables
  - silver inks & copper sintering patterned on structure for conductors
  - polymers & ceramic deposited on structure for insulators
- TRL for DW technologies is at least 8
  - DW implemented by Boeing on commercial aircraft production line
  - successful durability/longevity testing, FAA approved technology





Proof of Concept (POC) Approach

- Instrument FFRP laminates with DW silver-ink electrodes
  - painted electrode grid inspired by flat panel liquid crystal display (LCD)
  - “active” columns on one laminate surface as positive electrode
  - “passive” rows on opposite surface as ground electrode

- Select row/column(s) for resistance measurements
  - both in-plane and through-thickness measurements possible
  - manually selected with alligator clips for preliminary experiment
  - multiplexing micro-switches used to select pairs in further experiments

- High-resolution resistance change maps interpolated from data
  - damage breaks CNT links around affected zone, increases resistivity
  - in-plane results for grid-boxes of intersection row/column pairs
  - through-thickness results for grid-points of intersecting row/columns

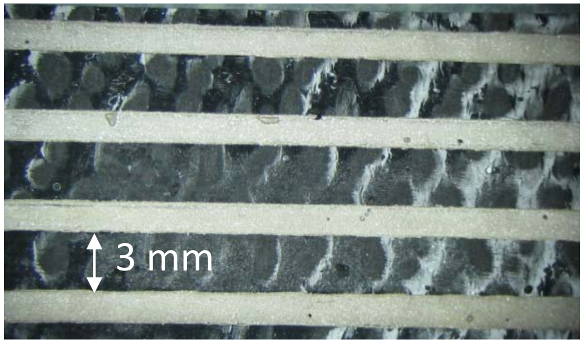
POC Specimen Preparation

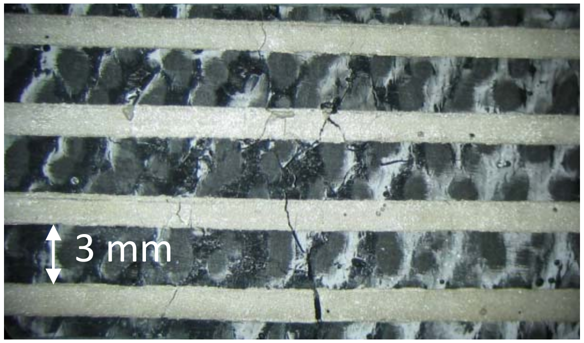
- FFRP laminate fabricated
  - ➢ alumina fiber satin-weave cloth dipped in solution of 50 mM iron nitrate
  - ➢ catalyst coats fibers with CNT “seeds” inside tows of ply
  - ➢ CNTs grow radially aligned 20-50 μm with modified thermal CVD method
  - ➢ 2 plies stacked by hand layup
  - ➢ West Systems™ Epoxy system infused for 12-hour RT cure
  - ➢ ~50% fiber volume fraction & < 2% void fraction (115 x 25 x 2 mm)

- Silver-ink electrodes applied w/masked silk-screening process
  - ➢ 14 parallel conductors patterned in short-dimension on top plate surface
  - ➢ 4 parallel conductors patterned in long dimension on opposite surface
  - ➢ traces were all 1.5 mm wide and spaced 3 mm edge-to-edge

POC Experimental Procedure

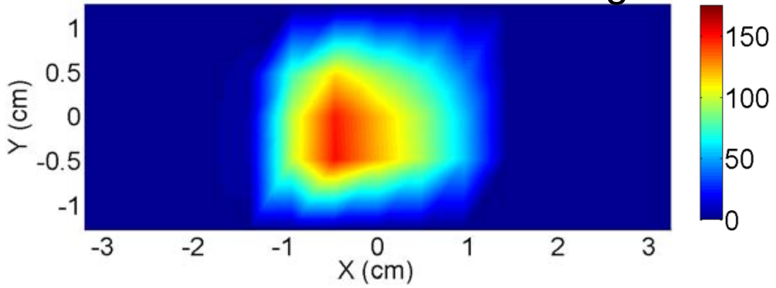
- Electrical resistance measured by multimeter
  - initial data showed significant variability due to contact resistance
  - subsequently thick wires were bonded to traces using silver epoxy
  - resulted in < 1% change (< 0.1 Ω for ~10 Ω trace) across 10 repeat trials
- Centered impacted with 13 mm diameter steel ball at 75 ft-lbs
  - calibrated to just initiate surface micro-cracking with trial impacts
  - no damage visible to unaided eye, but microscopy revealed cracking
  - post-damage resistance measured between pairs & through thickness

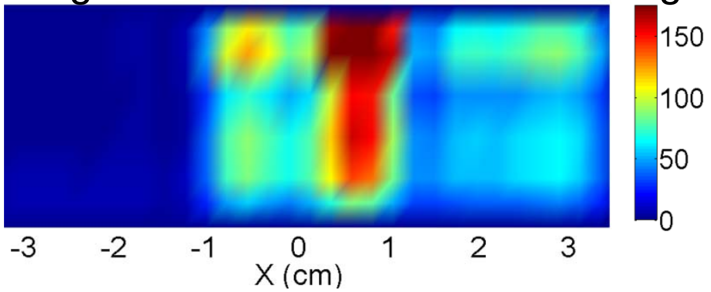




POC Results

- In-plane resistance between parallel pairs of adjacent traces
  - “short” traces averaged 9 Ω resistance pre-impact
  - > 100% change in middle traces, < 10% change for outermost trace pairs
  - minor changes < 1% measured between long trace pairs
  - appears to be more sensitive to surface cracking
- Through-thickness resistance at each virtual grid point
  - 56 through-thickness grid points averaged 20 Ω resistance pre-impact
  - > 100% change in middle points, < 10% change for “left” half points
  - resistance offset introduced by cracks across traces on “right” half points
  - appears to be more sensitive to delamination


In-Plane Resistance Change


Through-Thickness Resistance Change

Continuing Research

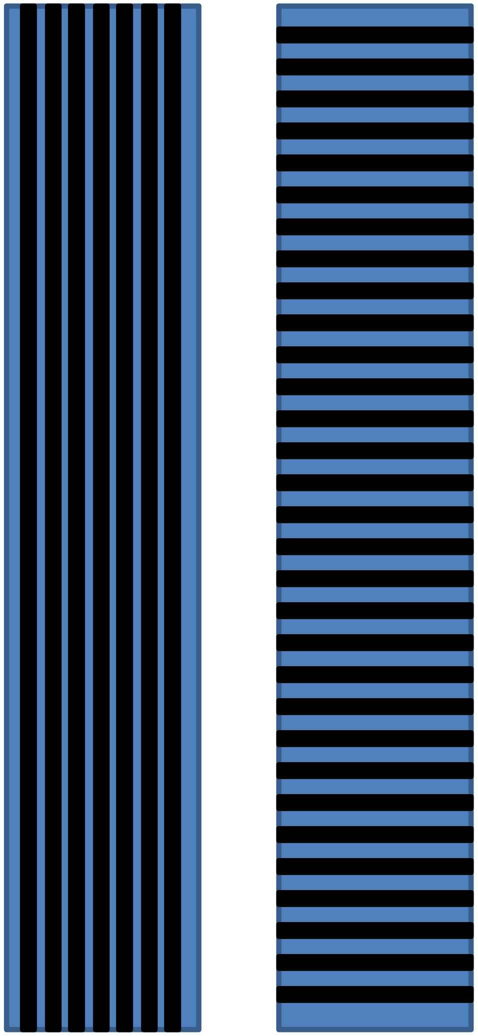
- Method validation with more comprehensive test matrix
  - ➢ 8 FFRP specimens (115 x 25 x 2 mm)
  - ➢ 3 baseline specimens (no CNT enhancements)
  - ➢ observe effects of multiple progressive impact events 25-100 ft-lbs

- Process improvements
  - ➢ refined silk-screening process to reduce trace resistance & variability
  - ➢ flexible circuit frame for connection with DW traces
  - ➢ dedicated hardware designed for expedited & consistent data collection

- Additional planned measurements
  - ➢ pre & post-damage tensile tests to evaluate residual strength & stiffness
  - ➢ baseline measurements to quantify effect of trace compression
  - ➢ data collected from both ends of traces to eliminate constant offsets

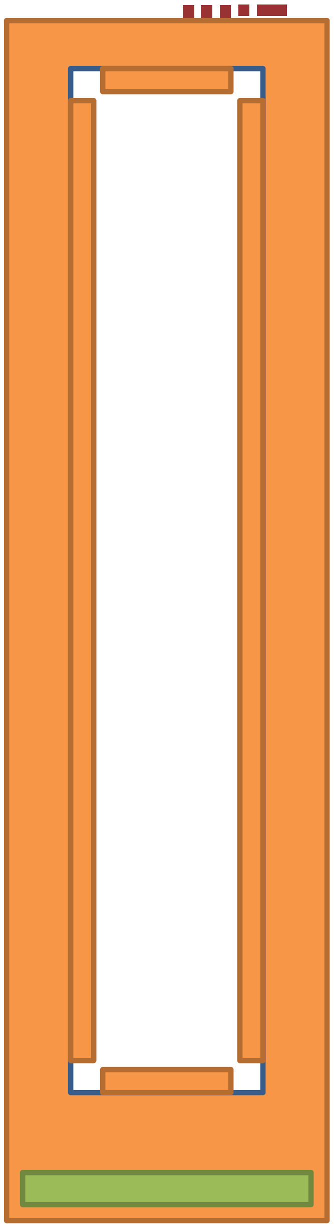
New Specimen Preparation

- Traces using refined DW process
  - ➢ 8 traces 1.5 mm wide on first surface
  - ➢ 32 traces 1.5 mm wide on opposite surface
  - ➢ all traces spaced by 1.5 mm
- Greatly enhanced resolution
  - ➢ 32 x 8 traces versus 14 x 4 traces
  - ➢ through-thickness proportional to intersections
  - ➢ in-plate proportion to top pairs x bottom pairs
  - ➢ both cases results in > 4x resolution



Flex-Frame

- Flexible circuit frame (flex-frame) designed
  - provides electrical continuity from traces to hardware
  - reliable & consistent, eliminates contact resistance
  - also incorporates marks for better DW alignment
- Simple construction
  - single double-sided copper-coated-Kapton w/coverlay
  - 80 pin SMT header connector (2 rows of 40-pins)
- Easy installation
  - flex-frame is bonded using AE-10 w/exposed pads
  - DW traces are drawn over pads
  - scalable process demonstrated in NASA SBIR



Multiplexing Hardware

- Original data collected by hand with multimeter
  - some variability introduced by manual connections & settling times
  - fewer trace combinations measured because of testing time (½ day)

- New multiplexing hardware designed dedicated to this research
  - connects directly to flex-frame via SMT header, PC via RS-232
  - dual multiplexer banks to select 2 traces for measurement
  - constant current applied through 2 traces, measure 16-bit voltage
  - resistance directly related to V/I

- Allows many more combinations to be measured quickly
  - 1140 total measurements (including both sides of traces)
  - test time dependant on determined settling time (1 second to 1 hour)

Alternative Approaches

- Alternative SHM schemes also being explored
  - exploiting dynamic piezoresistivity property of CNTs
  - acoustic emission (AE)
  - guided waves (GW)
- Same hardware & flex frame can be used to measure dynamic resistance changes induced by wave perturbations
  - initial "pencil-tap" experiments has verify that AE can be detected
  - enable AE-based SHM without additional external sensor network
  - static & dynamic monitoring could occur simultaneously in software

Future System Vision

- Integration
  - CNTs introduced at prepreg level
  - flex-frames built in standard sizes, installed at component level
  - automated DW methods apply electrodes over flex-frame/structure
  - hardware mounted locally to control each flex-frame, digitally networked
- Operation
  - dynamic measurements would indicate impact event occurrence
  - static measurements would localize & characterize damage
  - CNT-based NDE methods could provide more resolution on ground
- Further research areas
  - electrode spacing versus damage size for optimization table
  - compensation for mechanical load, hysteresis or thermal effects

Acknowledgments

- This research was sponsored by AFOSR
  - SBIR Phase I award FA9550-09-C-0165
  - Topic AF08-T023 “SHM of CNT-Enhanced Composites”
  - program manager: Dr. Charles Lee
- Massachusetts Institute of Technology
  - joint development of concept & supporting fabrication
  - principal investigator: Prof. Brian L. Wardle
  - fabrication support from: Derreck Barber & Sunny Wicks
- Metis Design Corporation
  - Dr. Ajay Raghavan, Dr. Chris Dunn & Michael Borgen
  - direct-write research funded by NASA/ARC award NNX09CC57P
  - SHM hardware funded by AFRL/VA award FA8650-08-C-3860