Spatial *In Situ* Structural Health Monitoring for Fiber-Reinforced Polymer Composites

SAND2012-4688P

UNIVERSITY OF CALIFORNIA, DAVIS

Bryan R. Loyola
Department of Mechanical & Aerospace Engineering

Advisors:
Valeria La Saponara
Advanced Composites Research, Engineering, and Science (ACRES) Laboratory
Department of Mechanical and Aerospace Engineering
Kenneth J. Loh
Nano-Engineering & Smart Structures Technologies (NESST) Laboratory
Department of Civil and Environmental Engineering

Doctoral Exit Seminar
Department of Mechanical and Aerospace Engineering, UC Davis
June 7, 2012

Presentation Outline

- **Introduction**
  - Why does structural health monitoring (SHM) for fiber-reinforced polymer (FRP) composites matter?
- **Implementation of carbon nanotubes**
  - Utilizing their impressive properties for structural monitoring
- **Characterizing nanocomposite sensors**
  - What are their mechanical sensing capabilities?
- **Changing the SHM paradigm to spatially distributed sensing**
  - From discrete to distributed sensing using electrical impedance tomography
- **Validating spatial sensing for common FRP damage modes**
  - How well does multi-modal spatial sensing perform?

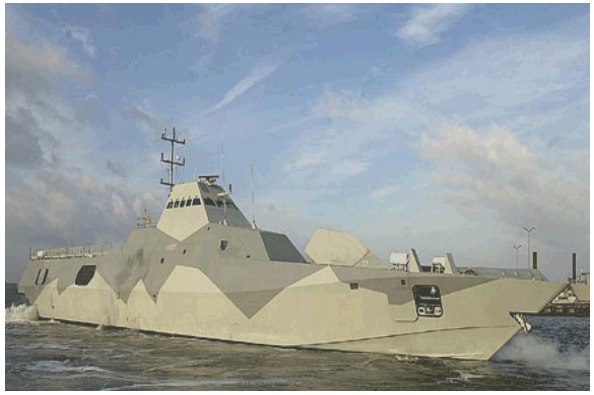
Usage of Fiber-Reinforced Composites

- **Over the past 50 years, increased usage of composite materials**

Commercial aircraft systems

Space shuttle and space structures

Military aircraft



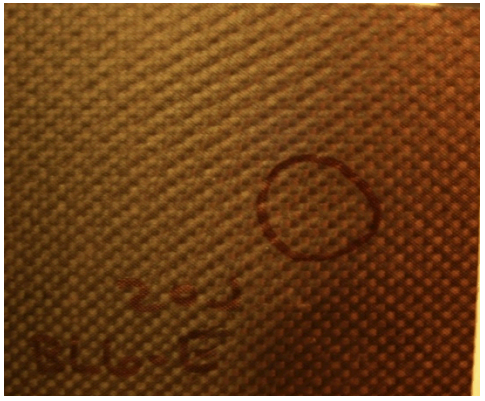
Naval structures

Wind turbine blades

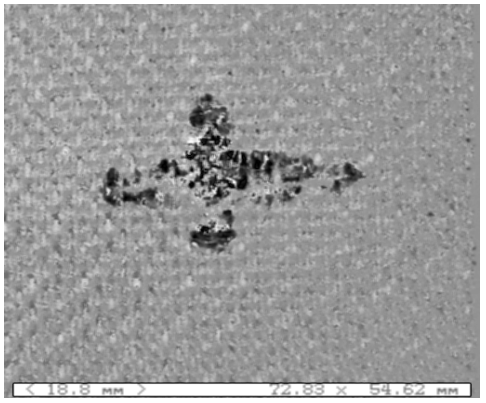
CFRP cable stay bridge

Composite Damage Modes

- **Susceptible to damage due to:**
  - Strain, impact, chemical penetrants, multi-axial fatigue
- **Damage modes:**
  - Matrix cracking
  - Fiber-breakage
  - Delamination
  - Transverse cracking
  - Fiber-matrix debonding
  - Matrix degradation
  - Blistering
- **Difficult to detect**
  - Internal to laminate structure
  - Nearly invisible to naked eye

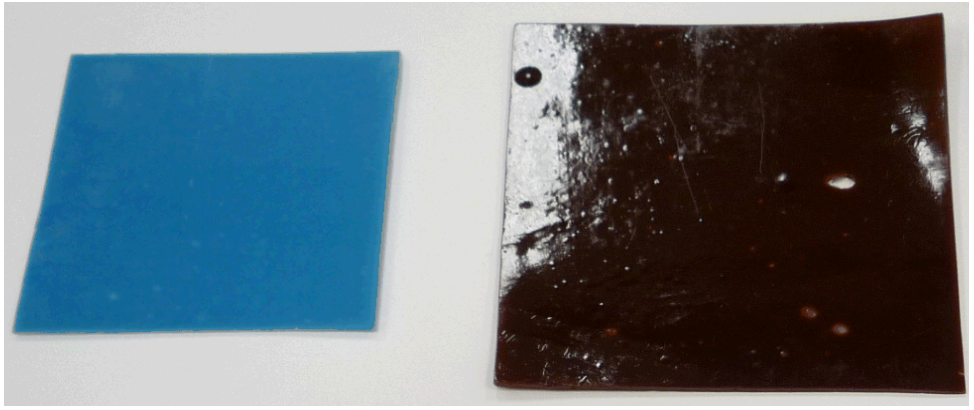


Visual inspection



C-SCAN ultrasound image

CFRP panel after 20 Joule impact

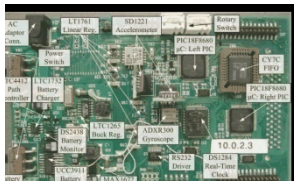


Adhesive exposed to hydraulic fluid at 70°C
Sugita et al, (2010)

Emerging Sensing Technologies

Wireless Sensors and Sensor Networks

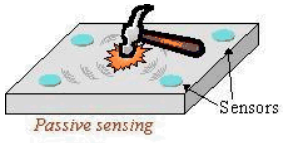
WiMMS
Wang, *et al.* (2008)

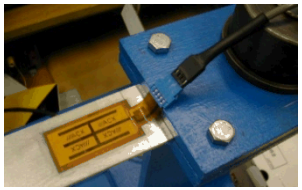


UCI DuraNode
Chung, *et al.* (2005)

- **Advantages:**
  - Low cost
  - Dense instrumentation
  - Reconfigurable
- **Disadvantages:**
  - Point sensors
  - Indirect damage detection
  - Physics-based models

Ultrasonics and Guided-Waves

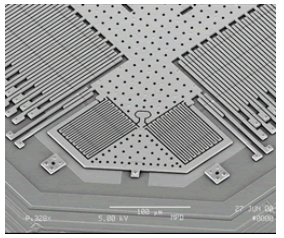




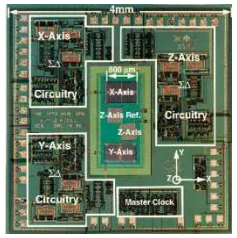
Array of piezoelectric ceramic sensors and actuators

- **Advantages:**
  - Sensors and actuators
  - Spatial damage detection
- **Disadvantages:**
  - Indirect damage detection
  - Wave propagation models or pattern recognition
  - Thin metallic structures
  - Expensive data acquisition

Micro-electromechanical Systems (MEMS)



AD *i*MEMS
Weinberg (1999)



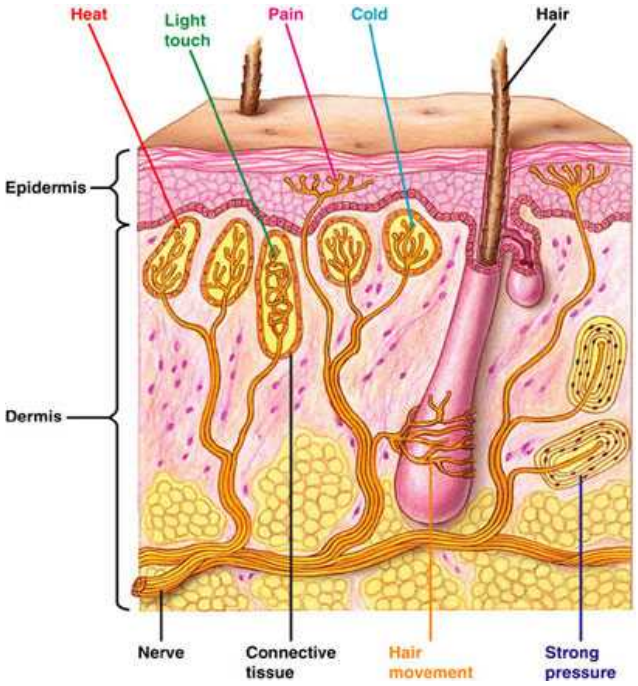
3-axis accelerometer
Lemkin (1997)

- **Advantages:**
  - Miniaturized sensor designs
  - Complex sensors/actuators
- **Disadvantages:**
  - "Top-down" design
  - Expensive fabrication equipment
  - High costs
  - Sensor sensitivity on par with macro-scale counterpart

SHM Design Considerations

Current SHM limitations

- Indirect sensing approaches
- Point-based sensing
- Tethered sensors
- Lack of system scalability



Overview of the human dermatologic system (Mallery 2008)

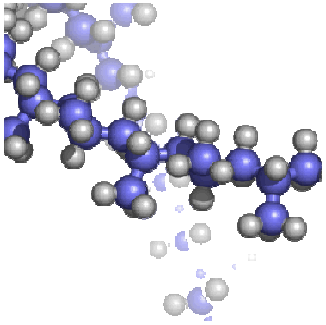
Successful SHM system

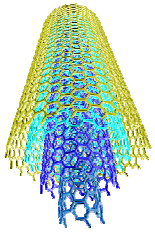
1. Directly detect and measure damage
2. Determine the damage location
3. Ascertain the size of the damage
4. Quantify the severity of the damage
5. Achieve multi-modal sensing capabilities (i.e., delamination, cracking, and chemical penetration)

Presentation Outline

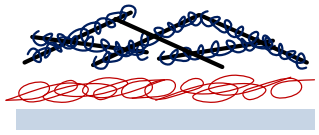
PART I

Development of carbon nanotube-based nanocomposites for multi-modal sensing





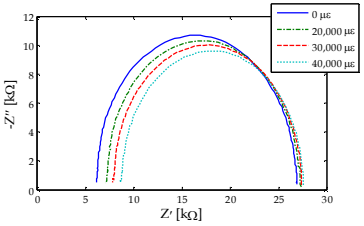
1. Harness unique material properties of carbon nanotubes



2. Layer-by-layer "bottom-up" thin film multi-modal sensor design

PART II

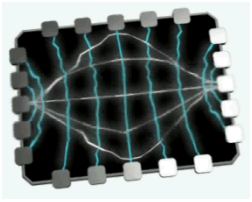
Embedded nanocomposite strain sensors for glass fiber-reinforced polymer composites



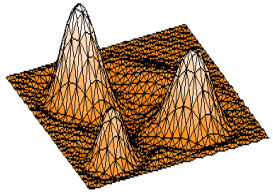
3. Deposited thin films on FRP for strain sensing

PART III

From point-sensing to distributed sensing using bio-inspired sensing skins



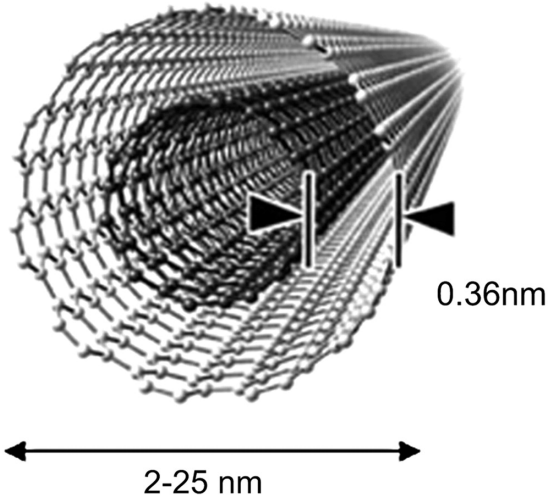
4. Electrical impedance tomography for spatial conductivity mapping

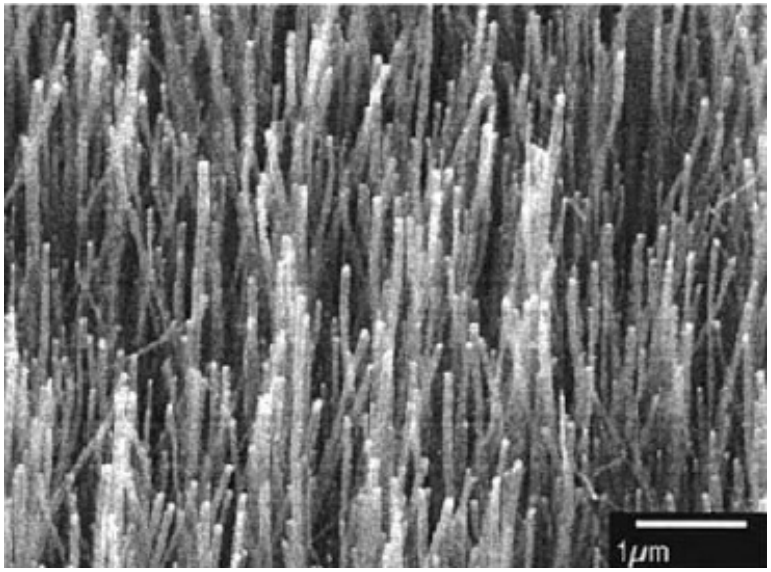


5. Distributed spatial damage sensing based on sensing skins

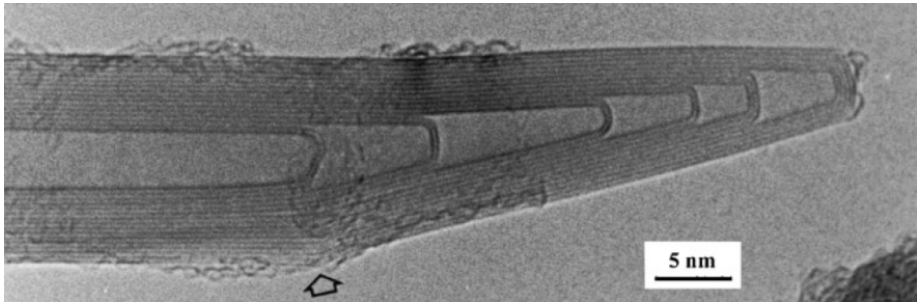
Carbon Nanotubes

- **Multi-walled carbon nanotubes (MWNT):**
  - Rolled concentric cylindrical structures constructed of graphene sheets
  - Diameter: 6 ~ 100 nm
  - High-aspect ratios: ~10^3 to 10^7
  - Metallic conductivity
  - Five times stiffer and ten times stronger than steel





Aligned carbon nanotube forest
Thostenson, et al. (2001)



TEM imagery of an end cap of a MWNT
Harris (2004)

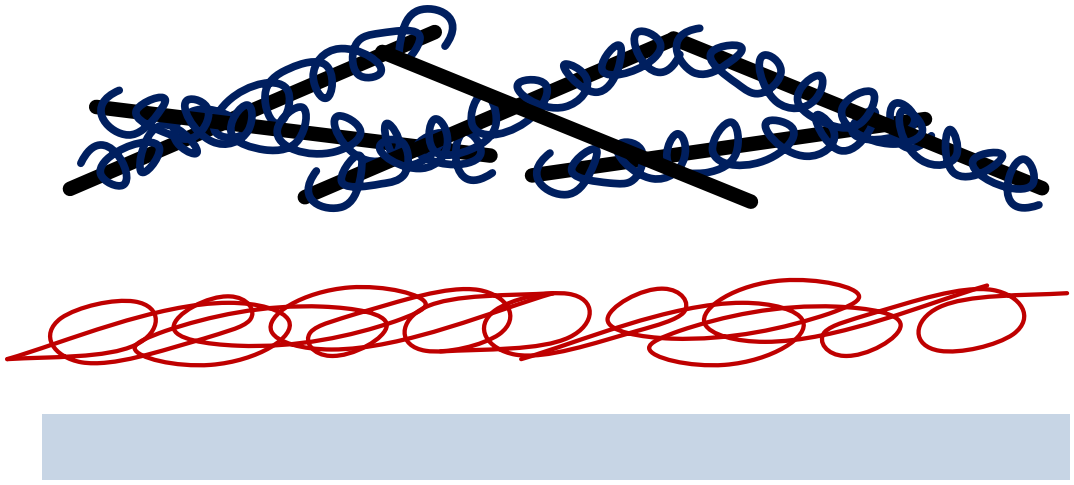
Layer-by-Layer (LbL) Method

- **Sequential assembly of oppositely-charged nanomaterials onto a charged substrate**
  - Bottom-up fabrication methodology
  - Incorporation of a wide variety of nanomaterials
  - 2.5-dimensional nano-structuring to design multifunctional composites
- **Excellent physical, mechanical, and electrical properties:**
  - Physical: homogeneous percolated nano-scale morphology
  - Mechanical: high strength, stiffness, and ductility

2. Negatively-charged monolayer
MWNT-PSS

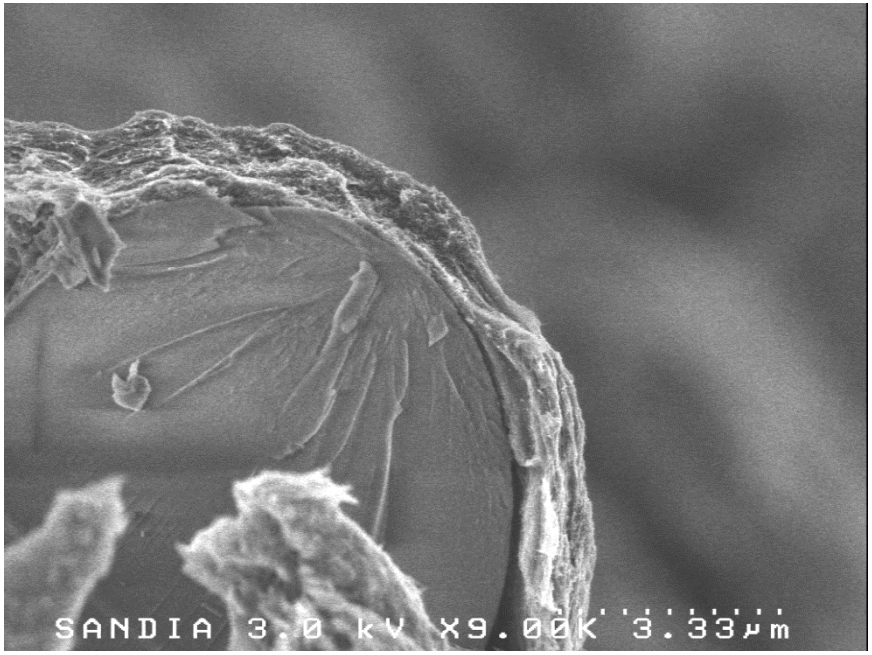
1. Positively-charged monolayer
PVA, PANI, etc.

0. Negatively-charged substrate
GFRP composite

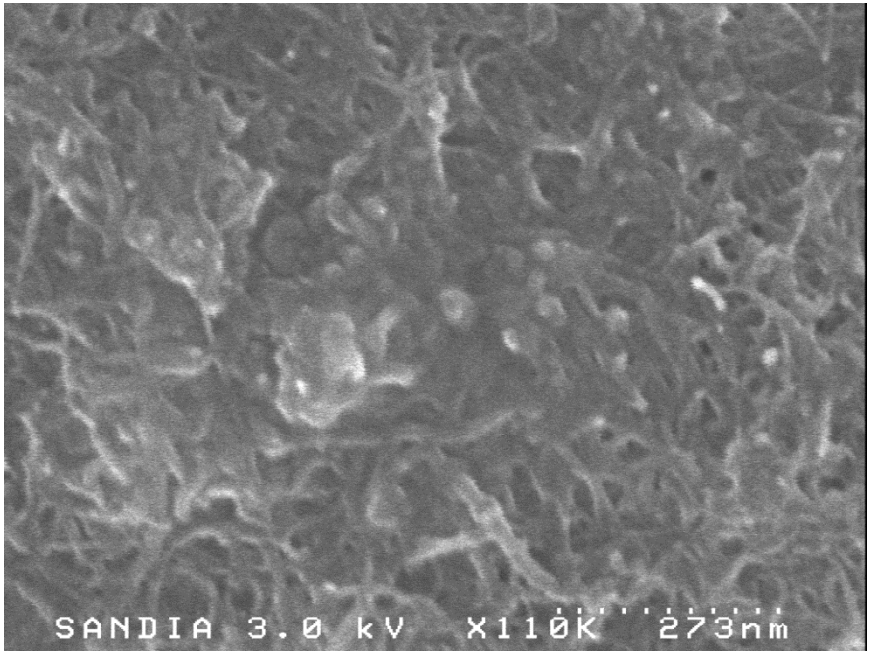


Nanocomposite Morphology

- **Mechanical strength and electrical conductivity/sensing derived from percolated thin film morphology**
  - Homogeneous composite with similar properties across entire film
  - Scanning electron microscopy (SEM) imagery to evaluate percolation and uniformity



Scanning electron microscopic (SEM) cross-section view of a 150 bilayer MWNT-PSS/PVA thin film on GFRP

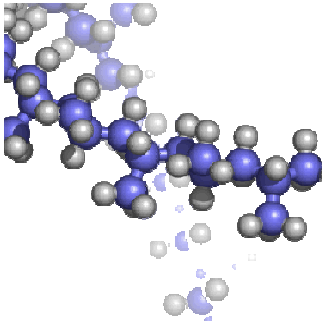


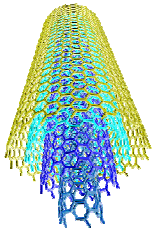
Surface SEM image of a 100 bilayer MWNT-PSS/PVA thin film

Presentation Outline

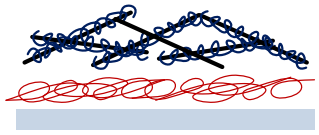
PART I

Development of carbon nanotube-based nanocomposites for multi-modal sensing





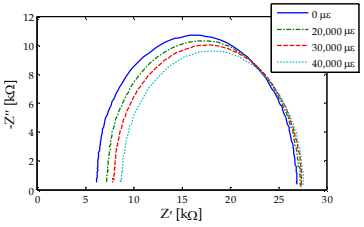
1. Harness unique material properties of carbon nanotubes



2. Layer-by-layer "bottom-up" thin film multi-modal sensor design

PART II

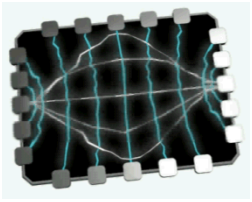
Embedded nanocomposite strain sensors for glass fiber-reinforced polymer composites



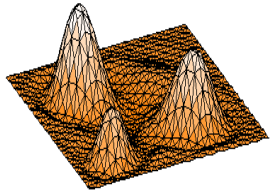
3. Deposited thin films on FRP for strain sensing

PART III

From point-sensing to distributed sensing using bio-inspired sensing skins



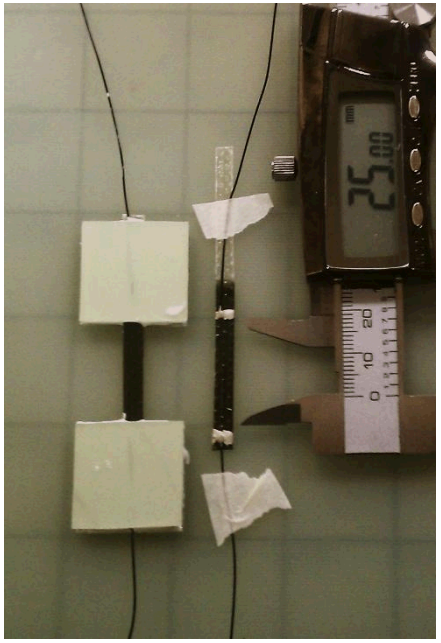
4. Electrical impedance tomography for spatial conductivity mapping



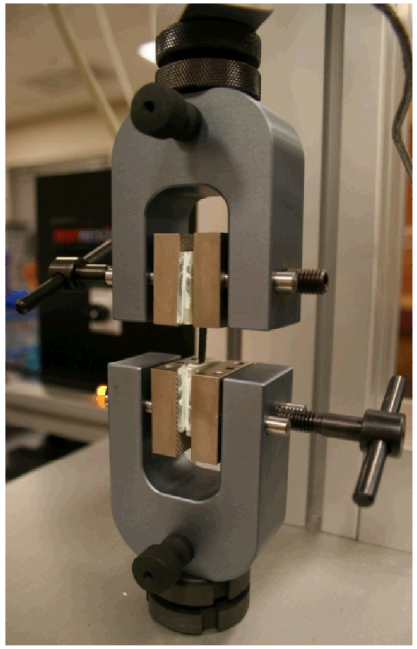
5. Distributed spatial damage sensing based on sensing skins

Piezoresistivity Validation

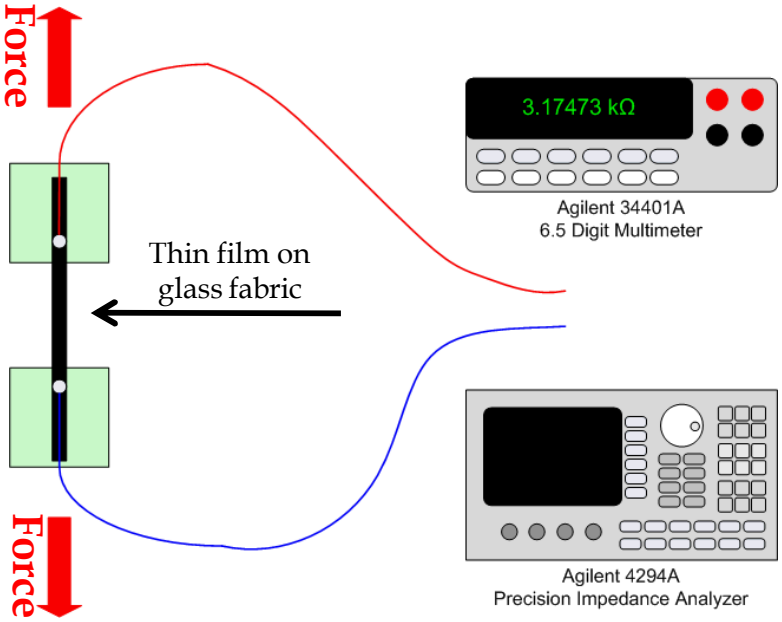
- **Objective:**
  - Validate thin film electromechanical performance deposited on GFRP
- **Specimen preparation:**
  - Attach two conductive electrodes and composite tabs
- **Nanocomposite electromechanical performance characterization:**
  - Apply monotonic and dynamic uni-axial tensile loading to specimens



Fiber-coated specimen



Thin film mounted in load frame



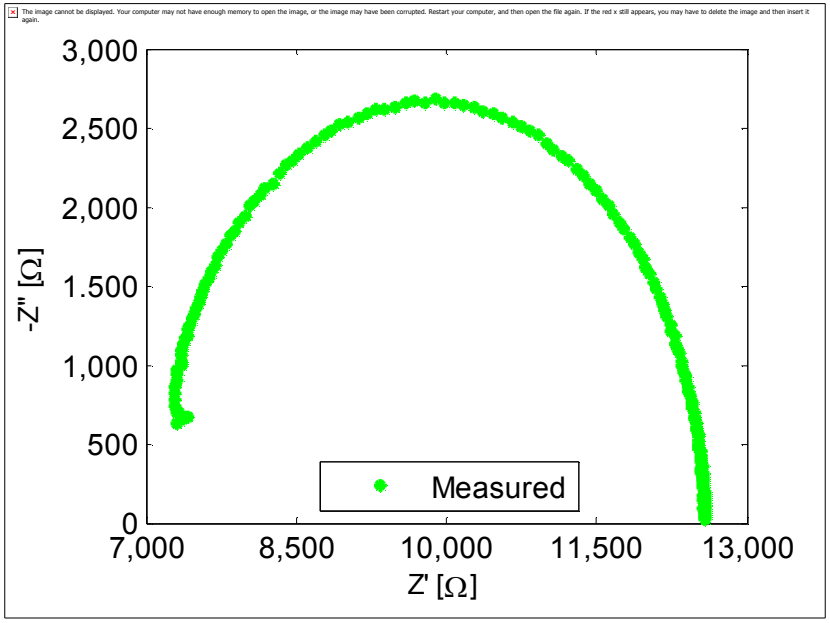
Time- and frequency-domain strain sensing

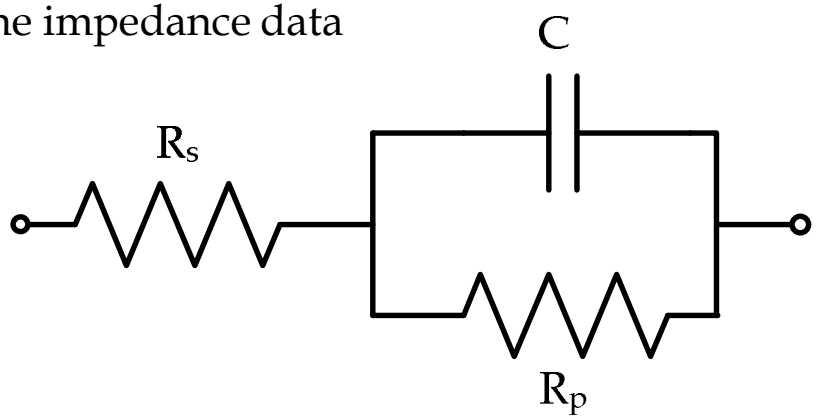
Electrical Impedance Spectroscopy (EIS)

- **Electrical impedance spectroscopy:**
  - Provides greater insight as compared to bulk resistivity measurements
  - Measurement of complex electrical impedance across spectrum of frequencies (40 Hz – 110 MHz)

$$Z(\omega) = \frac{V(j\omega)}{I(j\omega)} = |Z(\omega)|\angle\phi(\omega) = Z'(\omega) + jZ''(\omega)$$

  - Physically-based equivalent circuits are used to fit to the impedance data

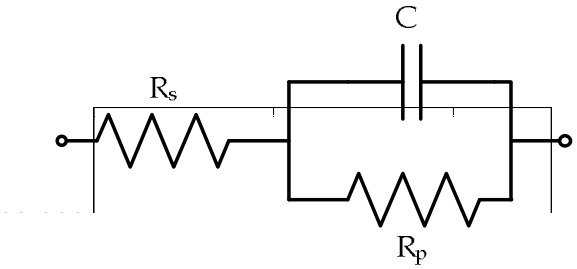


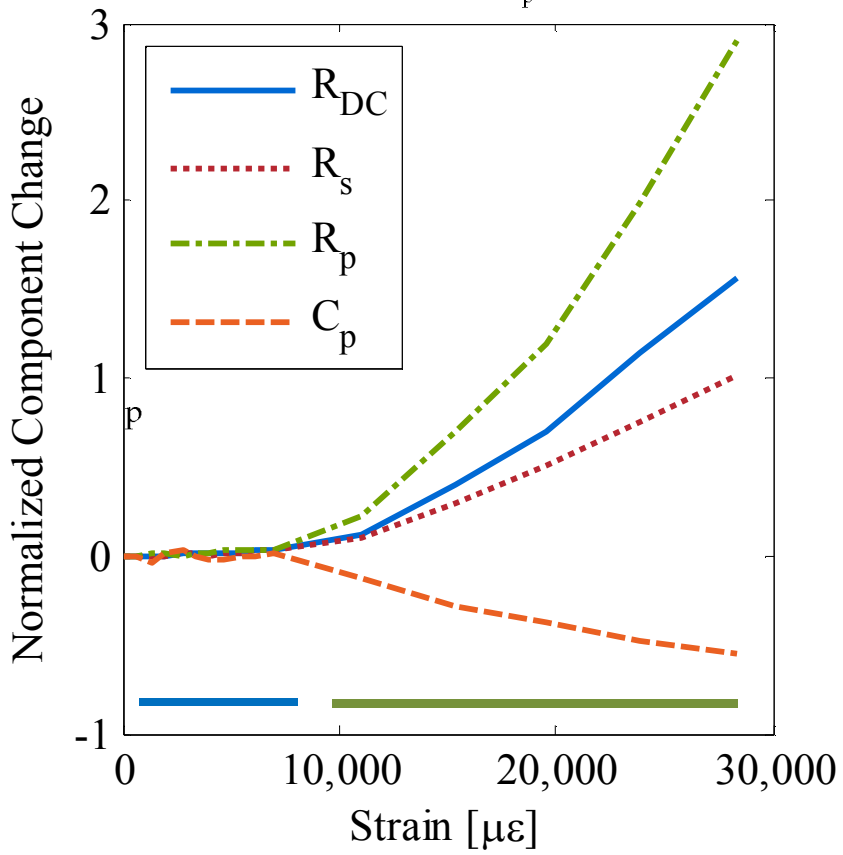


Proposed equivalent circuit model for LbL thin films

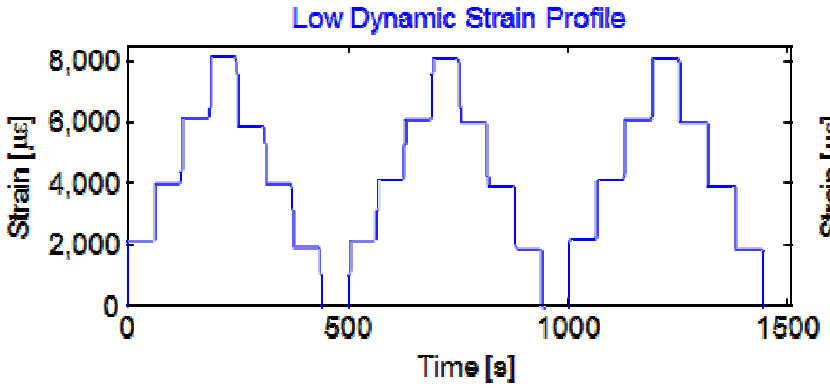
Monotonic Sensor Characterization

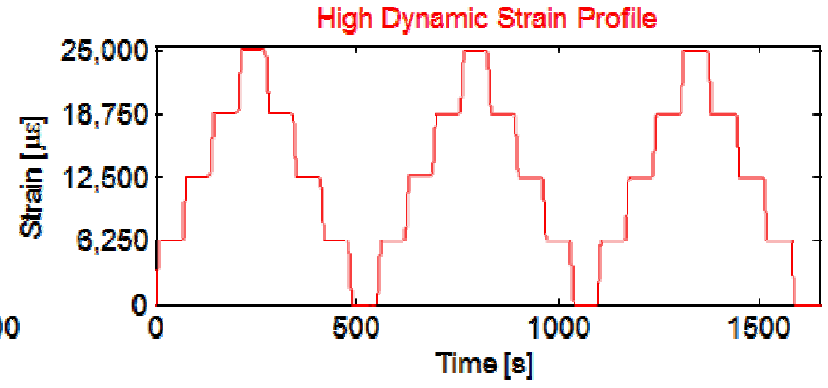
- **Load frame applies stepped-tensile displacement profile:**
  - Monotonic increasing strain to failure
  - Capture full sensors response
- **Equivalent circuit model-updating:**
  - Fitting with nonlinear least squares
  - Extract fitted circuit parameters as a function of applied strain
- **Bi-functional strain sensitivity:**
  - Low strain region:
    - Linear response (elastic)
  - High strain region:
    - Quadratic Response
      - Damage to GFRP/thin film



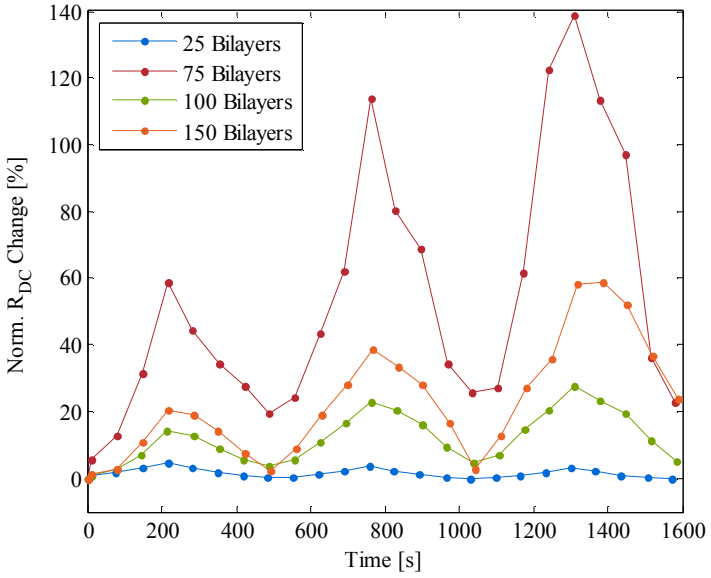


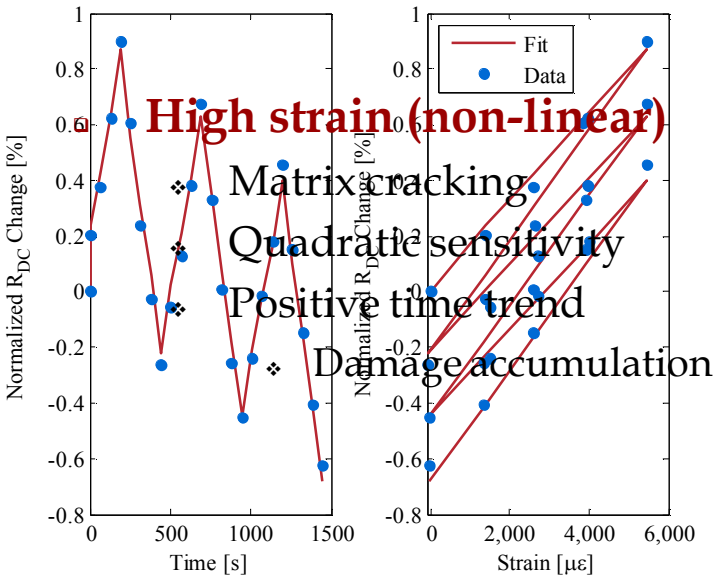
Dynamic Sensor Characterization





- **Lo**
  - ❖
  - ❖





High strain (non-linear)

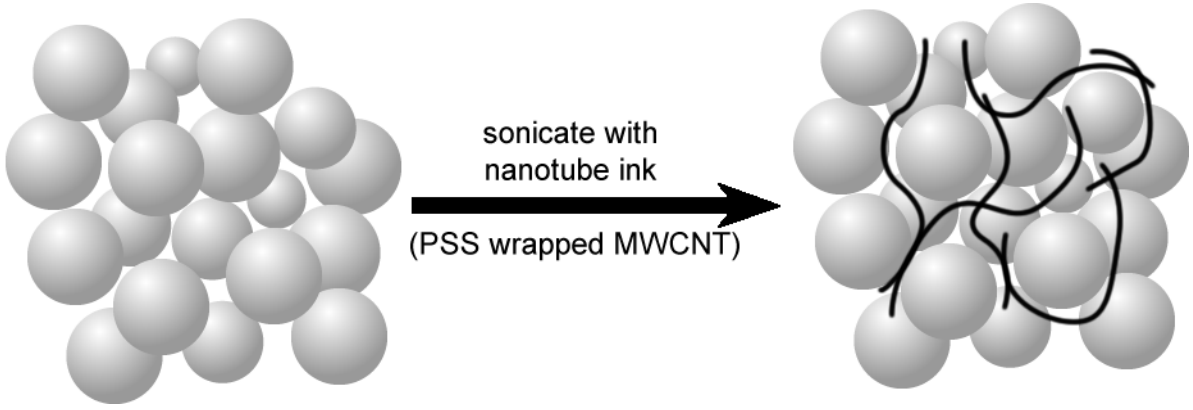
- ❖ Matrix cracking
- ❖ Quadratic sensitivity
- ❖ Positive time trend
- ❖ Damage accumulation

Preliminary Results

- **Application of a strain sensitive carbon nanotube thin film:**
  - Layer-by-layer deposition process
  - Direct deposition on GFRP
  - Demonstrated piezoresistivity
- **Bi-function strain sensitivity:**
  - Time and frequency-domain characterization
  - Demonstrated in monotonic and dynamic loading
  - Low strain region:
    - Linear strain sensitivity
  - High strain region:
    - Quadratic sensitivity
    - Damage accumulation
- **Deposition limitations:**
  - Substrates required to be less than a few square inches in size

Sprayable MWNT-Latex Thin Film

- **Rapid large-scale deposition**
  - Required for mass deployment of methodology
- **MWNT-PSS/Latex paint formulation**
  - Collaborated to improve initial Sandia formulation
  - Sub-micron PVDF creates mold for MWNT organization
  - Off-the-shelf deposition method

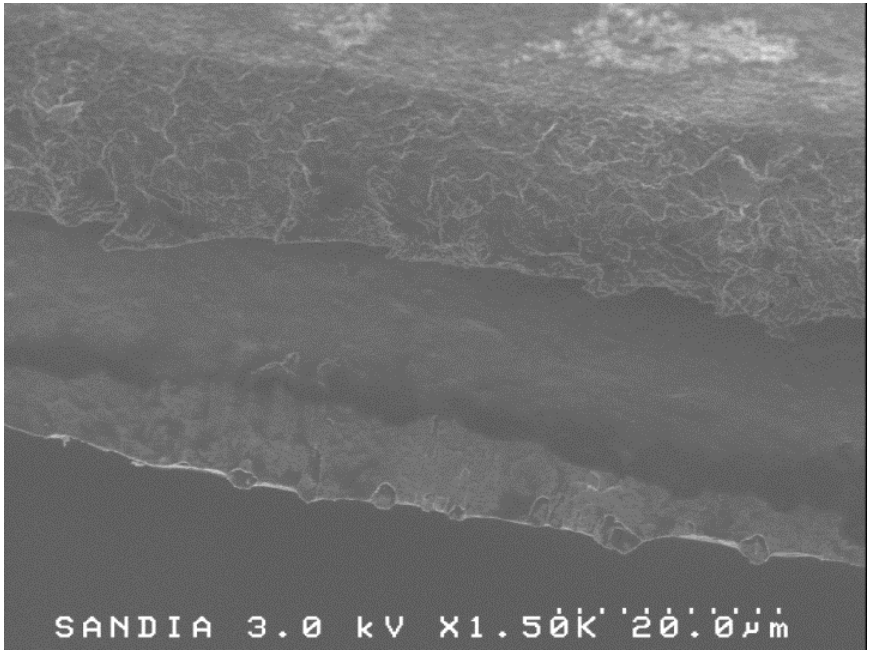


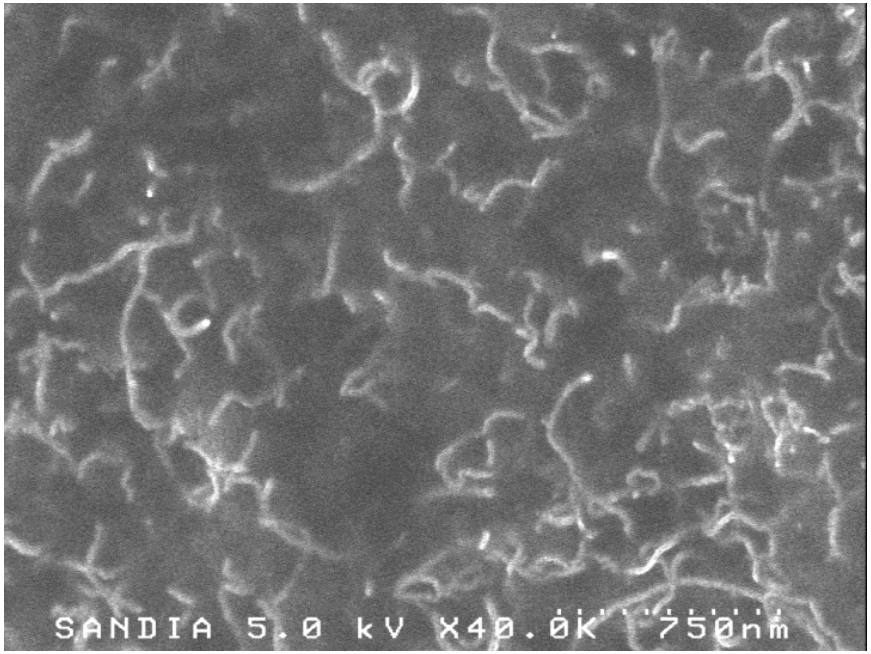
Kynar Aquatec™ latex solution
(avg. particle size 150nm)

Forms segregated
MWCNT network

MWNT-Latex Morphology

- **Creation of MWNT networks**
  - Electrical percolation above 1 wt% MWNTs
- **Fiber-reinforced polymer deployment**
  - Surface applied to post-cured composites
  - Applied to fiber weaves for embedded sensing

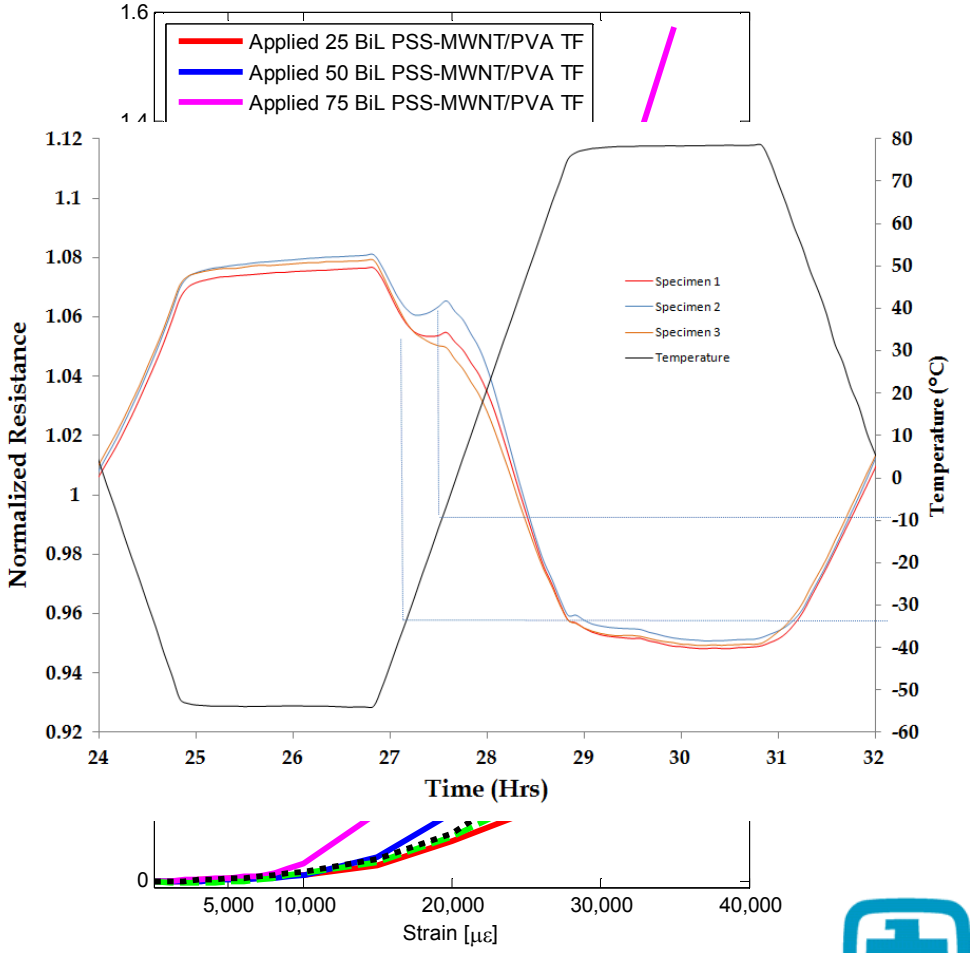




Cross-section and MWNT network SEM images of 3wt% MWNT-Latex film

MWNT-Latex Characterization

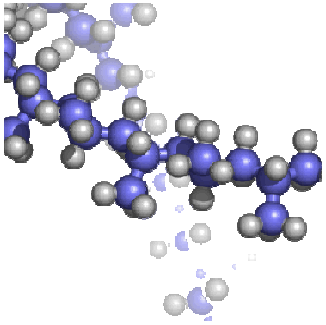
- **Electromechanical characteristics**
  - Quasi-static testing
    - Nearly same sensitivity as LbL
  - Bi-functional strain response
    - Linear
    - Quadratic
      - Cracking of film
- **Thermo-resistance coupling**
  - -50°C to 80°C over 2 hours
  - 2 hour holds
  - Inversely linear relationship
  - Non-linear response @ -30°C
    - ~ T_g of PVDF
    - Restructuring of MWNTs

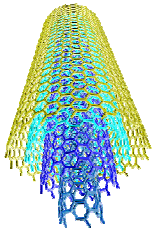


Presentation Outline

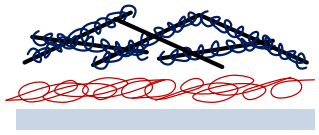
PART I

Development of carbon nanotube-based nanocomposites for multi-modal sensing





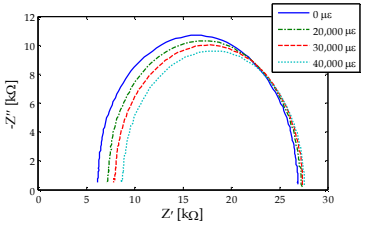
1. Harness unique material properties of carbon nanotubes



2. Layer-by-layer "bottom-up" thin film multi-modal sensor design

PART II

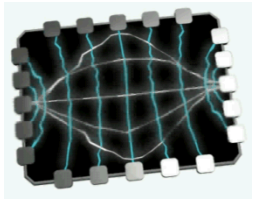
Embedded nanocomposite strain sensors for glass fiber-reinforced polymer composites



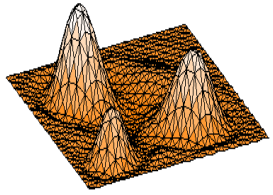
3. Deposited thin films on FRP for strain sensing

PART III

From point-sensing to distributed sensing using bio-inspired sensing skins



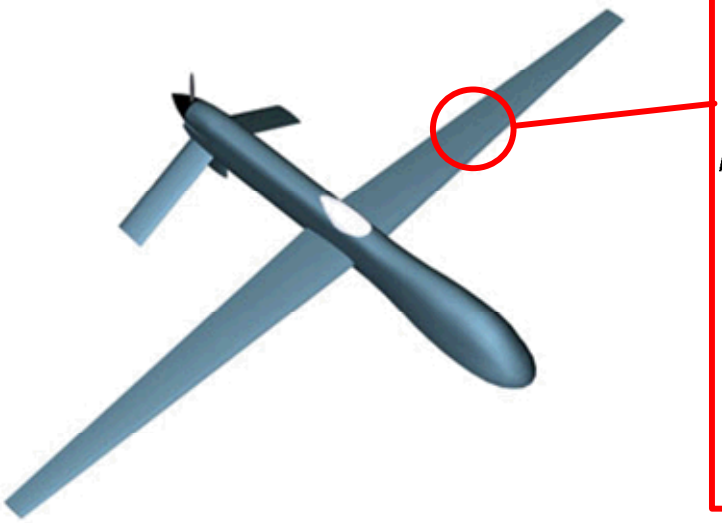
4. Electrical impedance tomography for spatial conductivity mapping



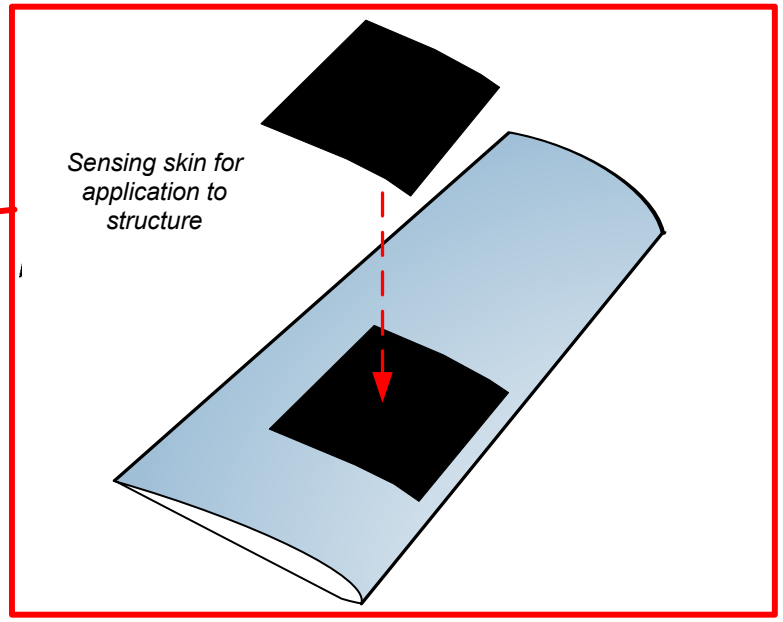
5. Distributed spatial damage sensing based on sensing skins

Spatially Distributed SHM Paradigm

- **Current state-of-art in structural health monitoring:**
  - Passive SHM using acoustic emissions
  - Active SHM using piezoelectric sensor/actuator pairs
- **"Sensing skins" for spatial damage detection:**
  - Objective is to identify the location and severity of damage
  - Monitor and detect damage over two- (or even three) dimensions
  - Direct damage detection

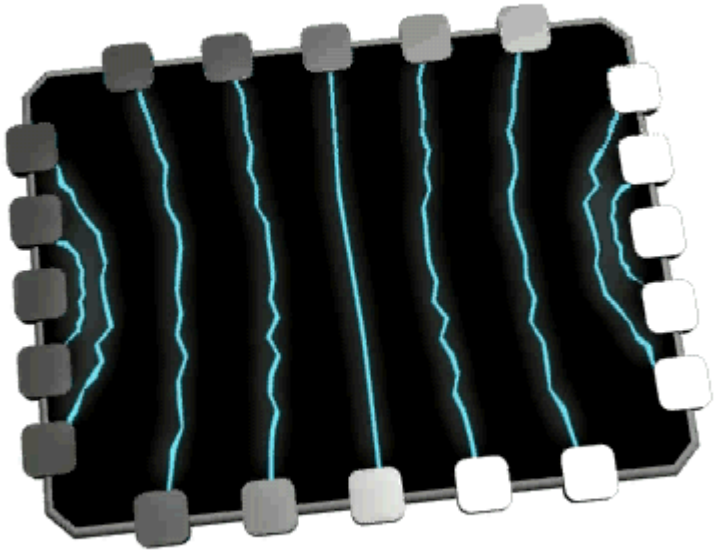


Composite Predator UAV Drone



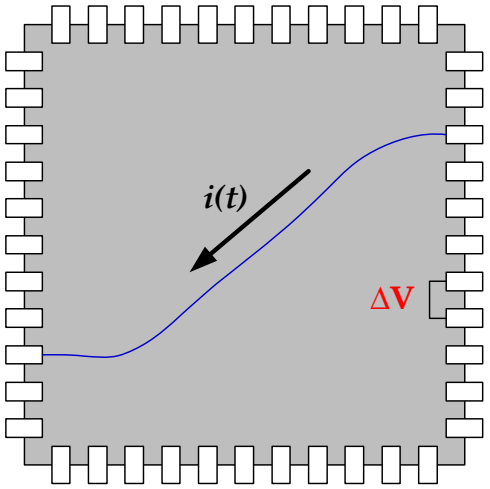
Electrical Impedance Tomography

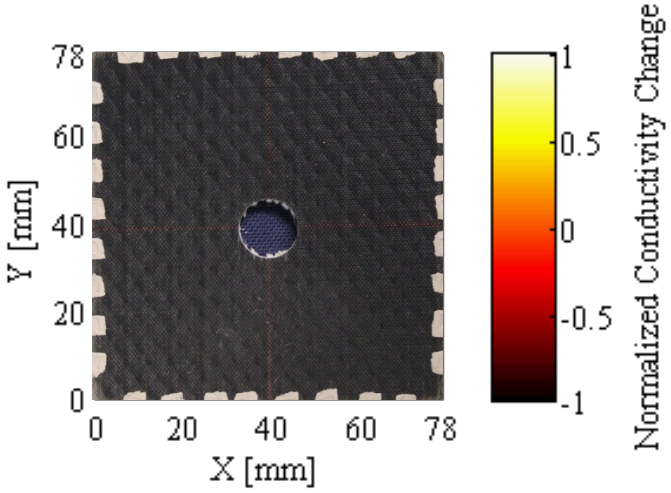
- **Overview of spatial conductivity mapping**
  - Since film impedance calibrated to strain, conductivity maps can correspond to 2-D strain distribution maps



Electrical Impedance Tomography

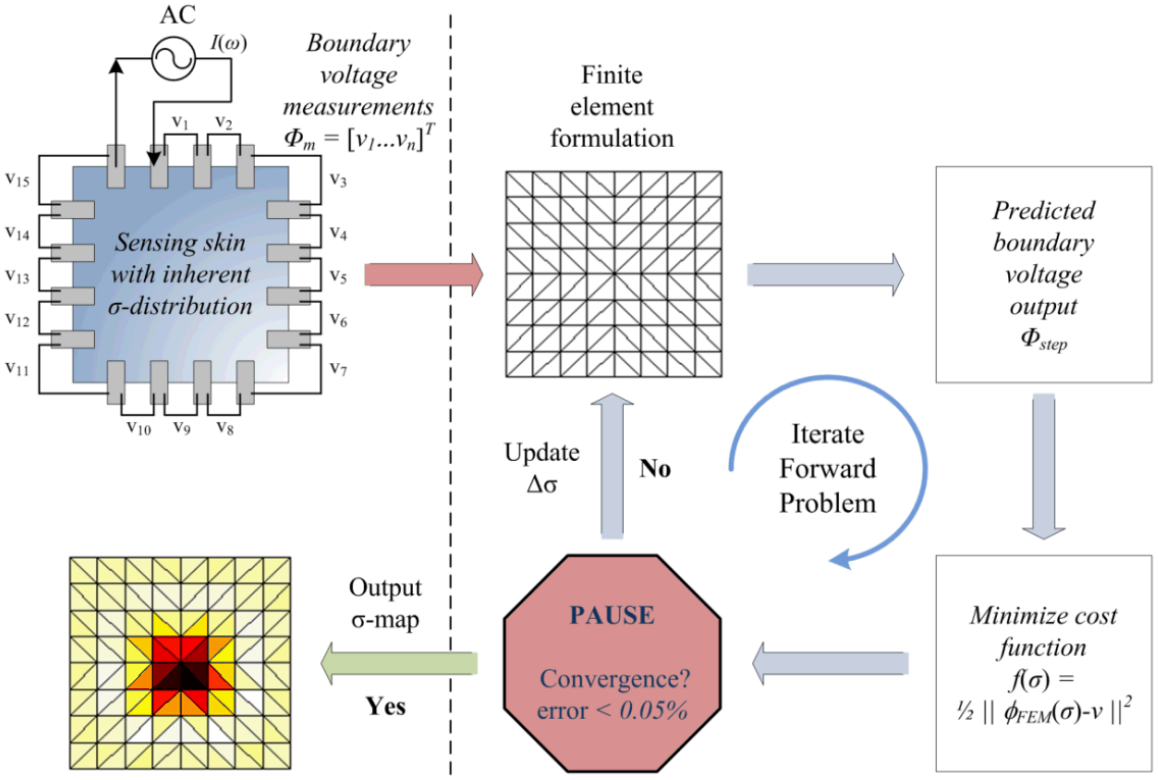
- **Electromagnetic imaging technique**
  - Compute $\tilde{\gamma}(\omega) = \sigma + j\omega\varepsilon$
- **Measure voltage response of injected current**
- **Solve conductivity**
  - Inverse problem:
    - $\min\left\{\left\|V^{meas} - V^{calc}(\tilde{\gamma})\right\| + C(\tilde{\gamma})\right\}$
- **Inverse problem methods**
  - Statistical-probabilistic
  - Linear Methods
    - Direct / Iterative
  - Non-linear Methods
    - Iterative





Iterative EIT Reconstruction

- **Laplace's equation:**
  - $\nabla \cdot (\sigma \nabla \phi) = 0$, where σ can vary by orders of magnitude
  - Governs potential and conductivity relationship
- **Forward problem: conductivity known, solve voltage**
- **Inverse problem: voltage known, solve conductivity**



Linear EIT Reconstruction

- **Reconstructs small σ changes**
  - Typically difference imaging
    - $\sigma_1 - \sigma_2 << \sigma_2$
- **Maximum a posteriori (MAP)**
  - H: sensitivity matrix

$$H(\sigma_{bkgd})_{ij} = \frac{\partial V_i}{\partial \sigma_j}$$

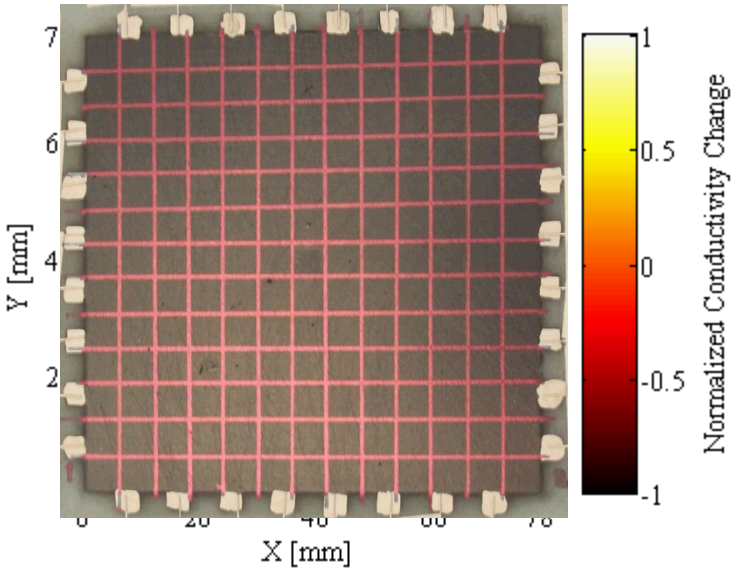
  - Regularization hyperparameter: λ
    - Noise figure

$$NF(\lambda) = \frac{SNR_{in}}{SNR_{out}} \approx 1$$

    - Use representative σ distribution
  - W: Noise model
  - R: Regularization matrix
- **Advantages**
  - Can pre-calculate H
  - Many damage modes lead to small changes in σ

$$\frac{\Delta\sigma}{\sigma_0} = \left(H^T W H + \lambda R\right)^{-1}\left(H^T W\right)\frac{\Delta V}{V_0}$$

$$\frac{\Delta\sigma}{\sigma_0} = B\Delta\frac{\Delta V}{V_0}$$

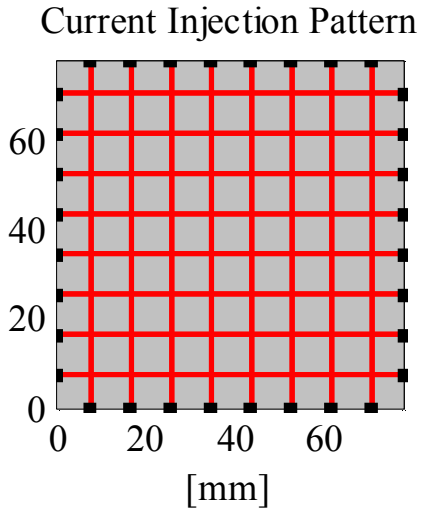


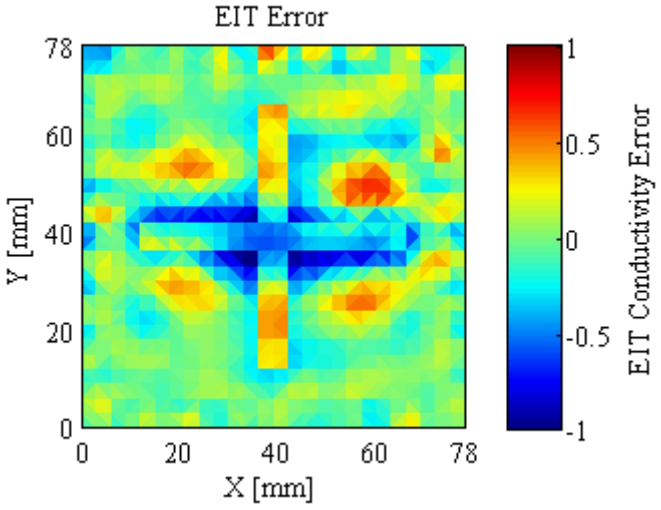
Validation EIT

- **Applied sensing measurements**
  - MWNT-Latex deposited upon cured GFRP composites
  - 78 mm x 78 mm sensing region
  - 8x8 electrodes scheme = 32 electrodes
    - 3 mm electrodes
    - 6 mm spacing

- **Investigate stability and efficiency:**
  - Computational demand
    - ~ 1 s reconstruction time

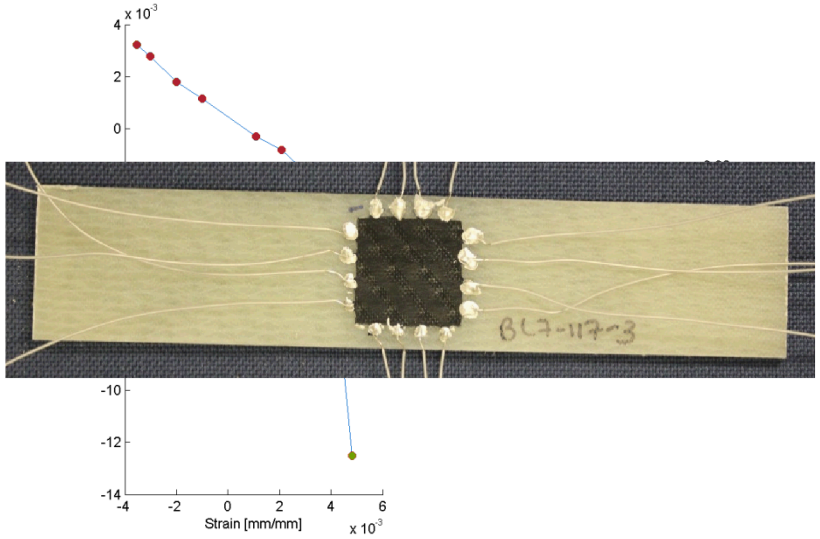
- **Accuracy characterization:**
  - Conductivity:
    - Point-to-point resistance map via 4-pt probe
  - Spatial feature ID sensing resolution
    - ~ 6 mm square at center with -50% $\Delta\sigma$

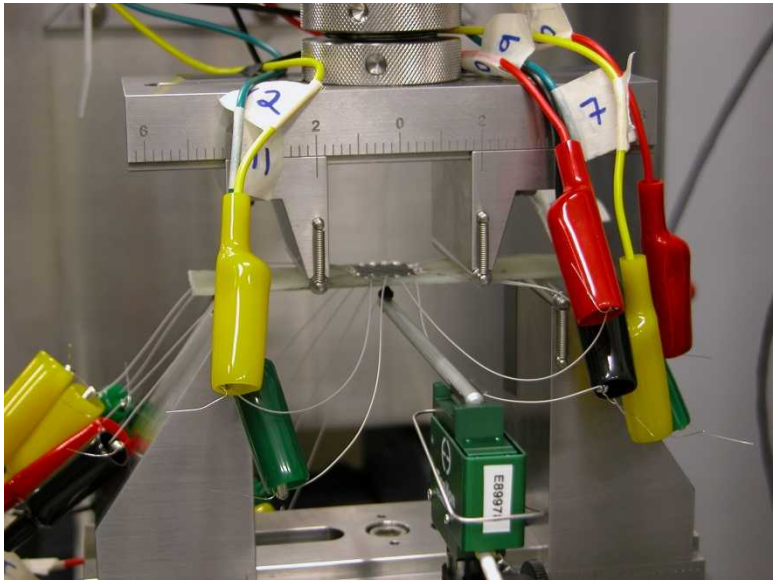




Spatial Strain Sensing

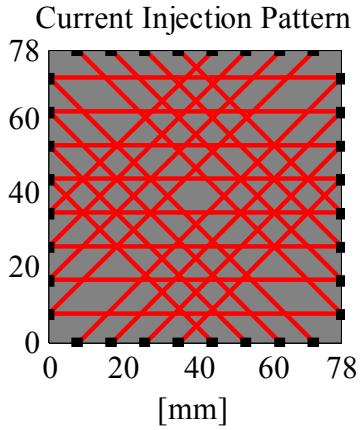
- **4-pt bending**
  - **ASTM D7264**
  - MWNT-Latex on GFRP
  - Stepped displacement profile
  - Tensile/compressive strains
- **Strain sensitivity**
  - Nearly linear

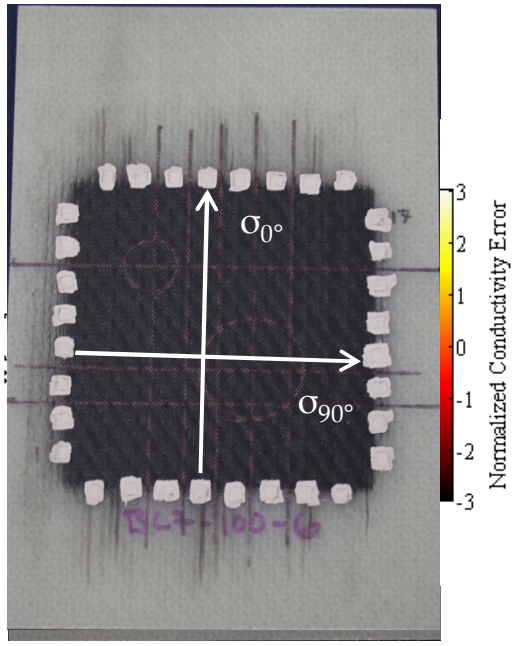




Embedded Spatial Sensing

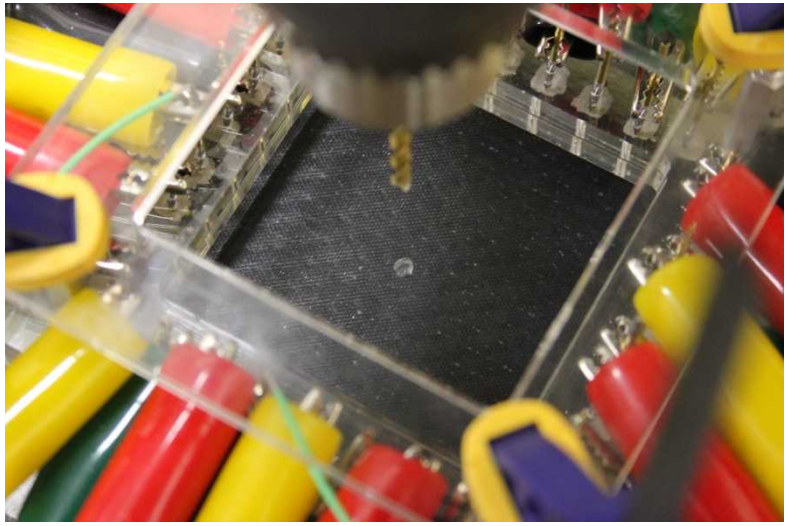
- **Embedded sensing architecture**
  - MWNT-latex on GF fiber weave
  - Embedded within epoxy matrix
- **Specimens**
  - $[0°/+45°/90°/-45°]_{2s}$
  - Unidirectional GF
  - 150 mm x 100 mm
    - ASTM D7146 Standard
- **Anisotropic EIT**
  - Isotropic ► Anisotropic
  - Scalar ► Matrix: σ
  - $\sigma_{0°} > \sigma_{90°}$ by ~2:1
  - $\nabla \cdot (\sigma \nabla \phi) = 0$

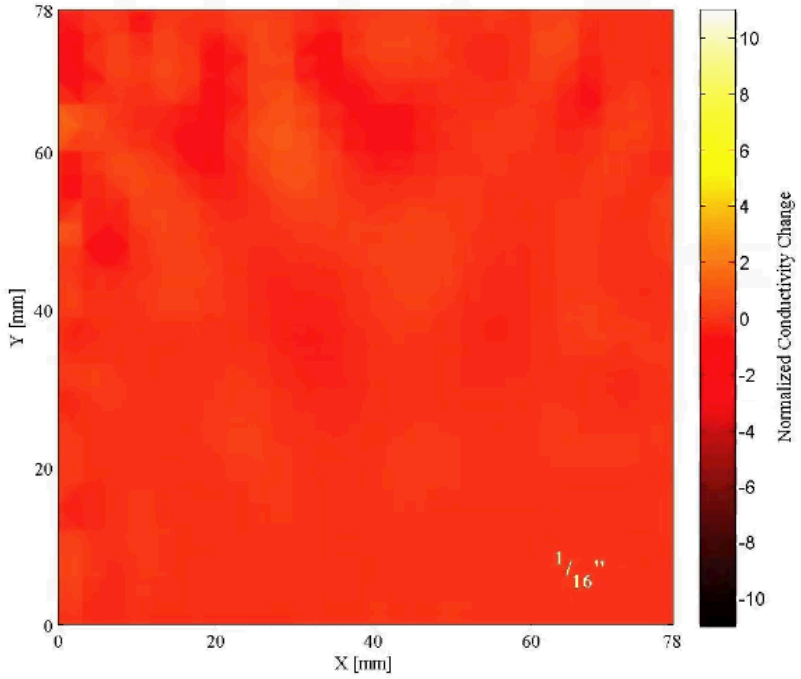




Embedded Spatial Sensitivity

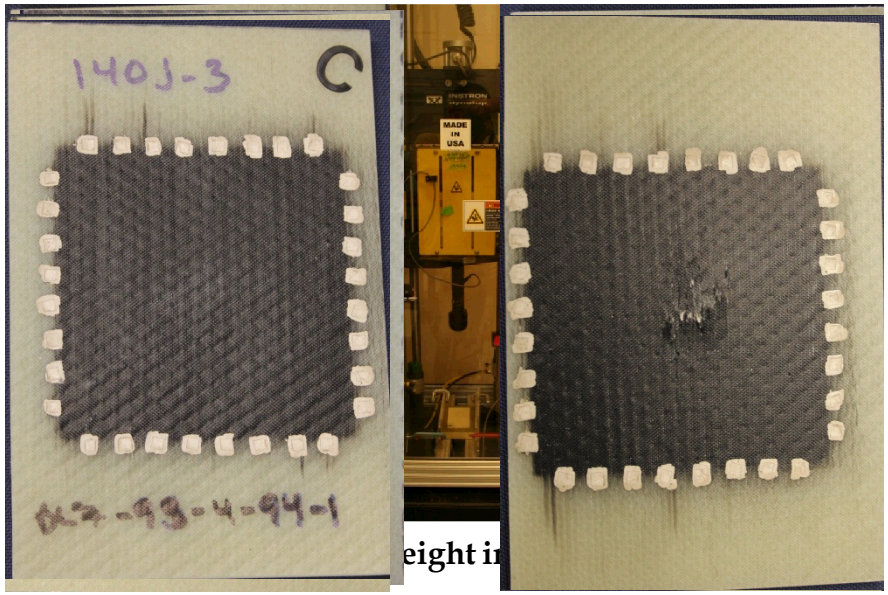
- **Embedded sensing validation:**
  - Determine conductivity change sensitivity
  - Process:
    - Progressively larger drilled holes:
    - $^{1}/_{16}$", $^{1}/_{8}$", $^{3}/_{16}$", $^{1}/_{4}$", $^{5}/_{16}$", $^{3}/_{8}$", $^{1}/_{2}$"
  - Anisotropic EIT performed
    - Conductivity change from pristine sample

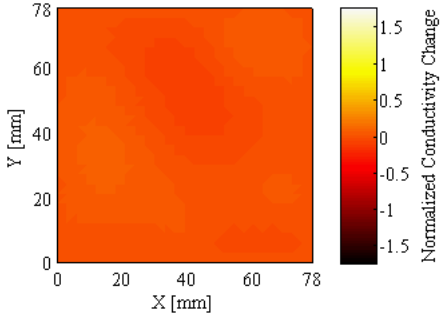


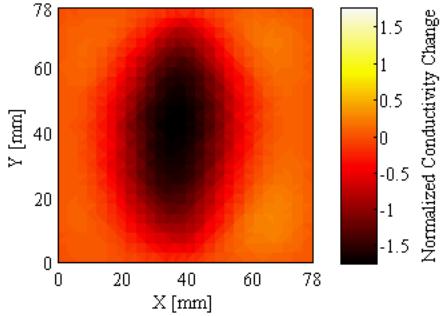


Impact Damage Detection

- **Drop-weight impact tests**
  - **ASTM D7146**
  - 78 mm by 78 mm sensing region
  - MWNT-latex on glass fiber weave
  - Impact energy: 20, 60, 100, 140 J
  - Before/after EIT measurements
- **Verification:**
  - Thermography
    - Matrix Cracking
    - Delamination
  - Photographic Imaging
    - Surface damage







Summary

- **Propose a next-generation SHM system**
  - Direct in situ damage detection
  - Monitor location and severity of damage
- **Embedding multi-modal sensing capabilities**
  - Development of MWNT-nanocomposites for SHM
  - Characterized electromechanical response to monotonic and dynamic strain
  - Response to temperature swings
- **Outline validation of EIT for damage detection**
  - Strain sensitivity
  - Damage sensitivity
  - Impact damage

Thank You!
Questions?

UNIVERSITY OF CALIFORNIA, DAVIS

Acknowledgements:

UC Davis Dissertation Year Fellowship

NINE @ Sandia National Laboratories

National Science Foundation

Center for Information Technology Research for the Interest of Society

College of Engineering, University of California, Davis

CFRP Sensing

- **Carbon Fiber Reinforced Polymers**
  - Highly anisotropic conductivity
  - Inhomogeneous
- **EIT Model**
  - Isotropic
  - Homogeneous
  - Gives reasonable results within bounds

Future Research Interests

- **Basic science**
  - Continue improving EIT reconstruction algorithms
  - Investigate sensitivity mechanisms
    - Mechanical
    - Thermal
    - Chemical
  - Development of new sensors
    - Nanoparticle-based
    - Electroactive polymers

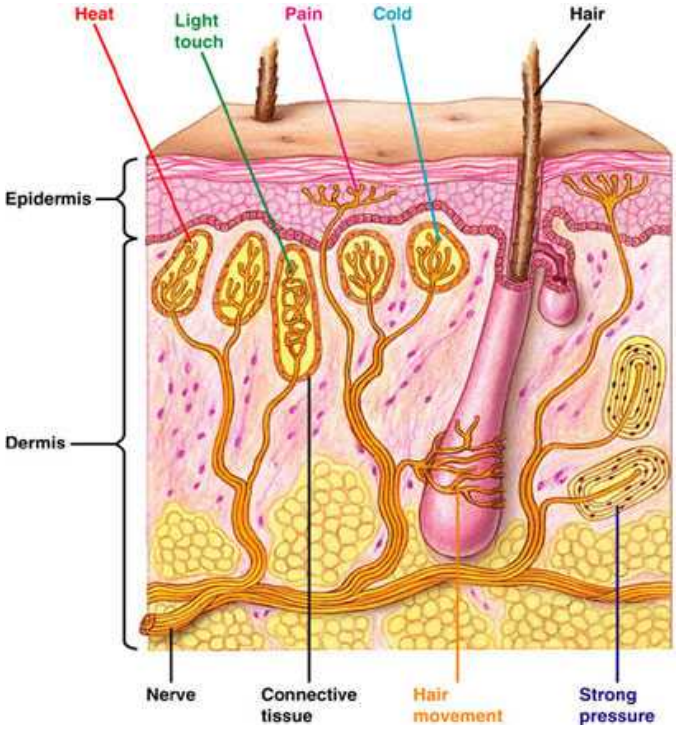
- **Application**
  - Extend EIT to wireless monitoring
  - Implementing new EIT methods specifically designed for SHM
  - Grid-based EIT

Bio-Inspired Sensing

- **Two important fundamental limitations of SHM technology:**
  1. *Indirect sensing approaches*: Sensors do not sense damage directly
  2. *Point-based sensing*: "point" sensors do not detect spatial structural behavior

- **Human dermatological system:**
  - Multifunctional material:
    - Strong to keep germs out
    - Temperature regulation
    - Absorption of nutrients
    - Sensing

- **Sensing with spatial recognition**
  - Stimulus localization
  - Multi-modal sensing:
    - Multiple receptor types
    - Intricate network of nerves

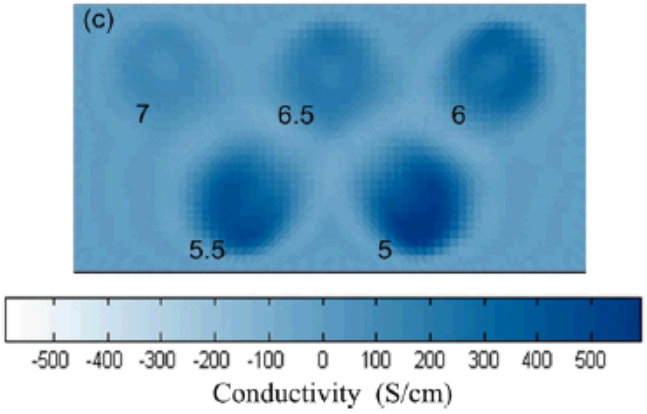


Overview of the human dermatologic system (Mallery 2008)

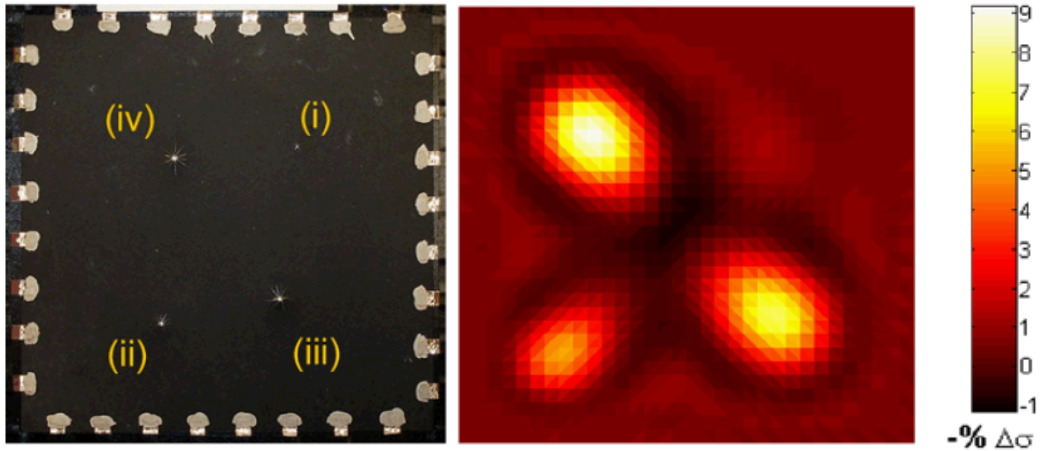
Previous Research on Spatial Sensing

- **SWNT-PE thin films**
  - Homogeneous substrates
    - Aluminum
    - Glass
- **Previous SHM EIT work has shown:**
  - Linear strain sensitivity
  - Impact sensitivity
  - pH sensitivity

- **Limitation**
  - DC currents only
  - Single current pattern
  - Slow converging inverse algorithm
  - Desire in situ sensing



pH sensitivity
Hou et al. (2009)



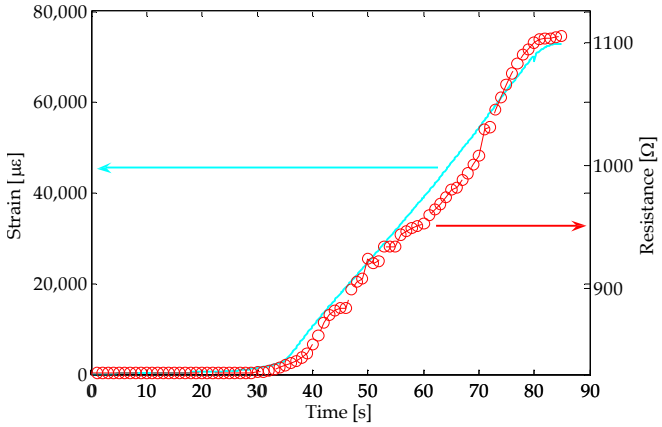
Impact damage sensitivity
Loh et al. (2009)

Encoding Piezoresistivity for Strain Sensing

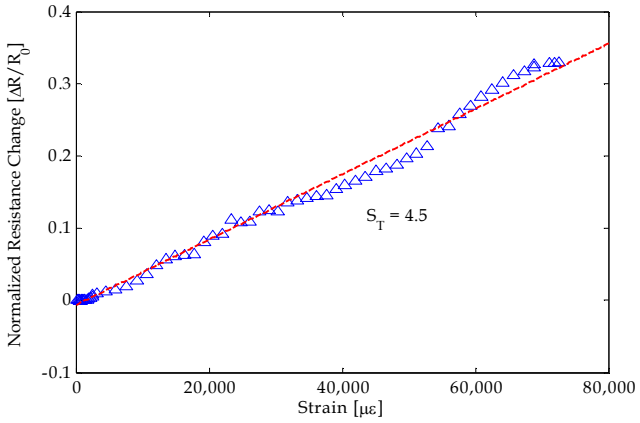
- **Piezoresistivity based on percolated SWNT nanostructure**
  - Bulk electrical conductivity influenced by number of nanotube-to-nanotube junctions
  - Applied strain modifies the number of conductive junctions

- **Monotonic tensile testing to explore thin film piezoresistivity:**

Nanocomposite monotonically loaded in tension



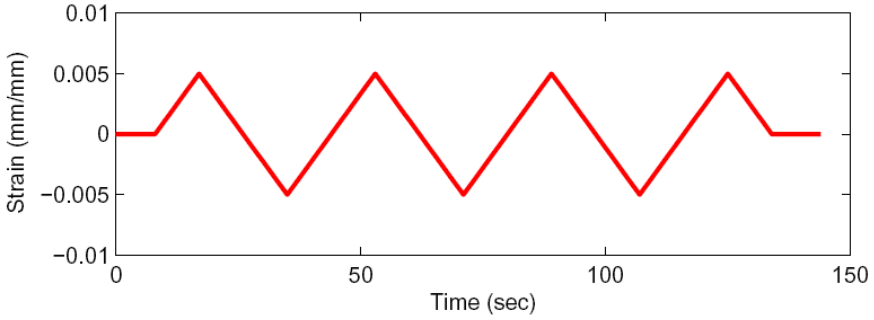
Resistance time history due to applied tensile strain

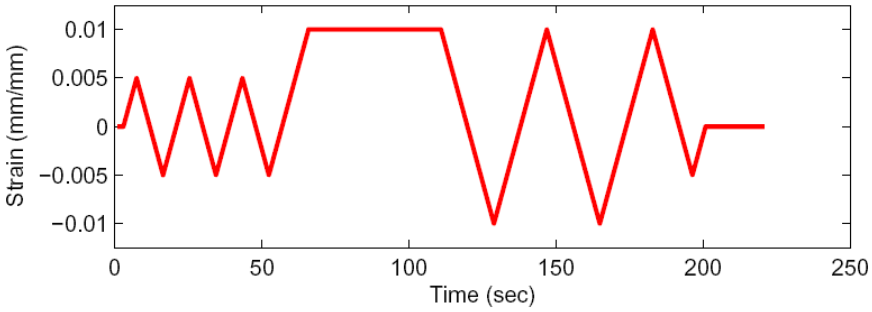


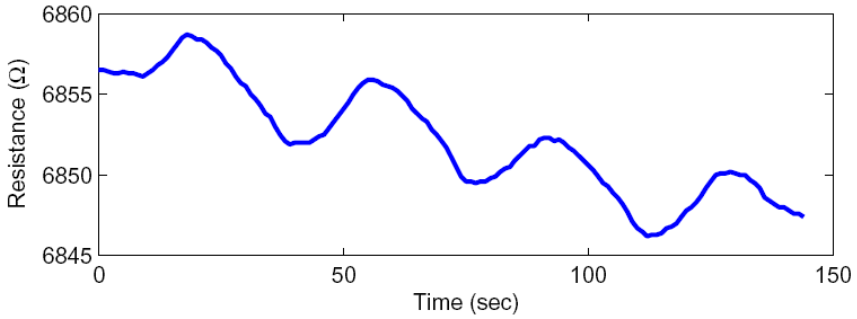
Nanocomposite piezoresistive linearity

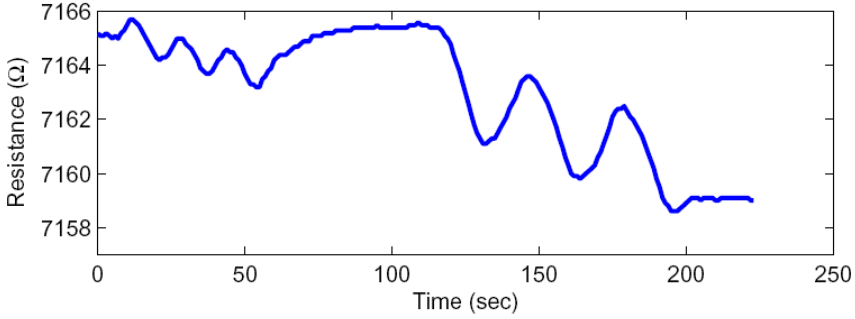
Nanocomposite Strain Sensor Response

- **Applied cyclic tensile-compressive strains (±10,000 με)**
  - Detect both tensile and compressive strains
  - Linear response beyond 10,000 με and without film failure
  - Load-pattern and load-rate independent
- **Drawback: undesirable nominal resistivity drift**



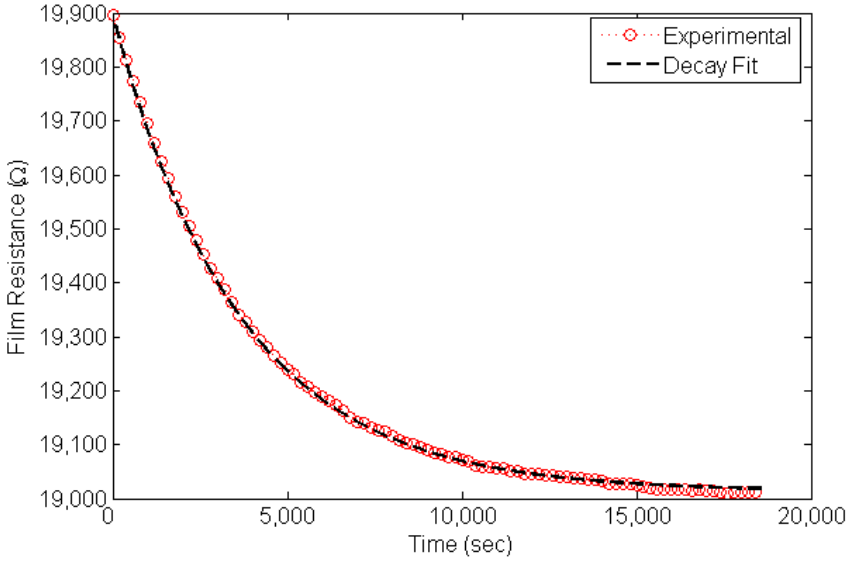


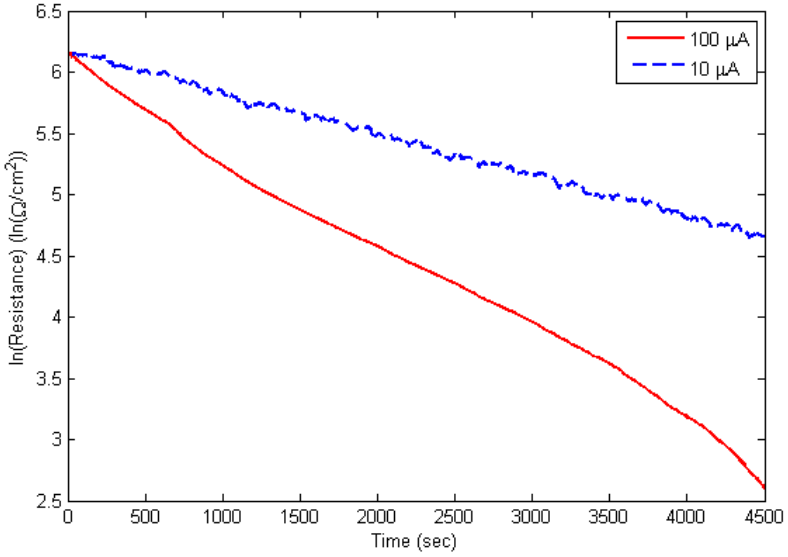




Inherent Electrical Properties

- **Observe decay in nominal film resistivity**
  - Resistance drift not due to contact effects
  - Decay rate dependent on applied current

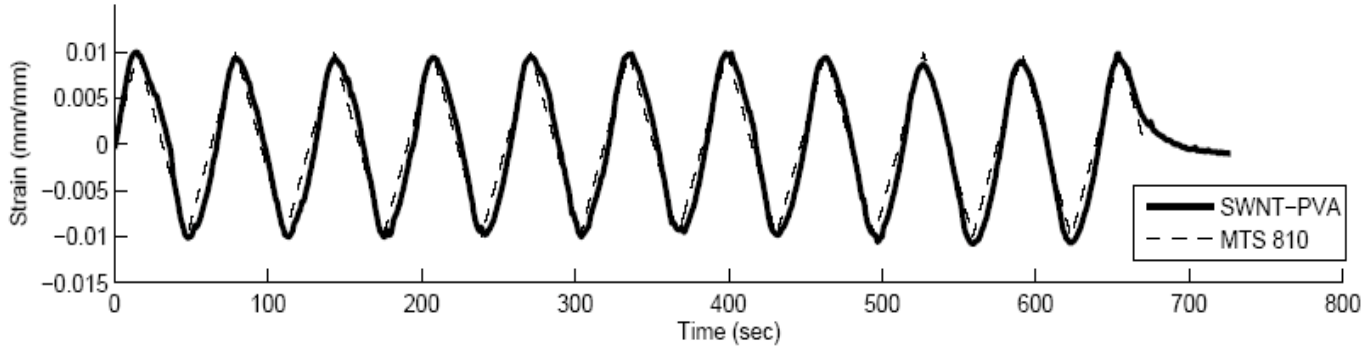




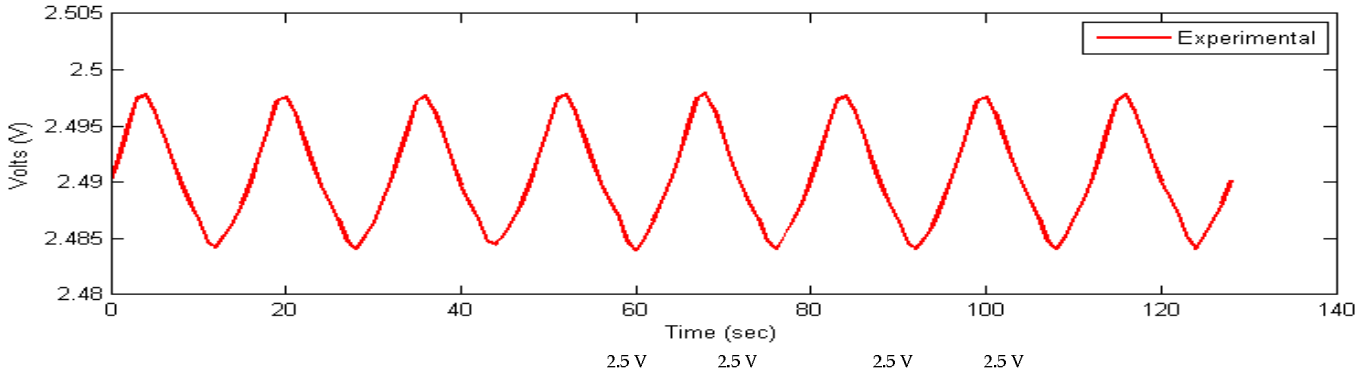
  - Nominal resistivity decay may be due to localized heating and physical/chemical changes in nanotube composite
  - Decay can be modeled accurately → $R = A\, e^{-Bt} + C$

Drift-free Strain Sensing Response

- **Exponential drift can be numerically removed to obtain drift-free response:**



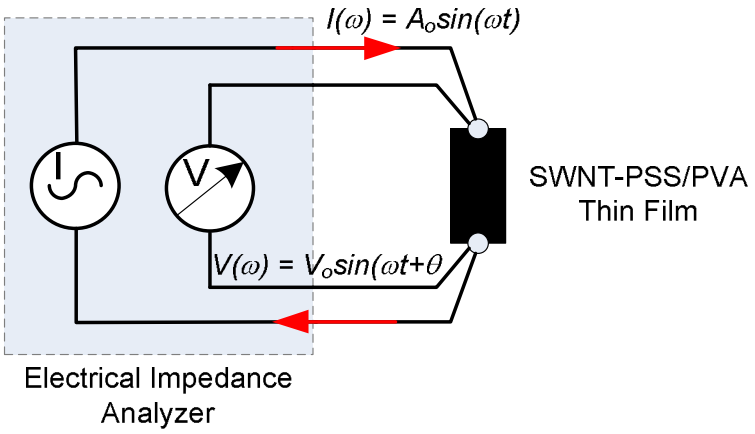
- **High-pass filtering can be employed for dynamic strain measurements:**



- **Disadvantageous for structural health monitoring in field environments**

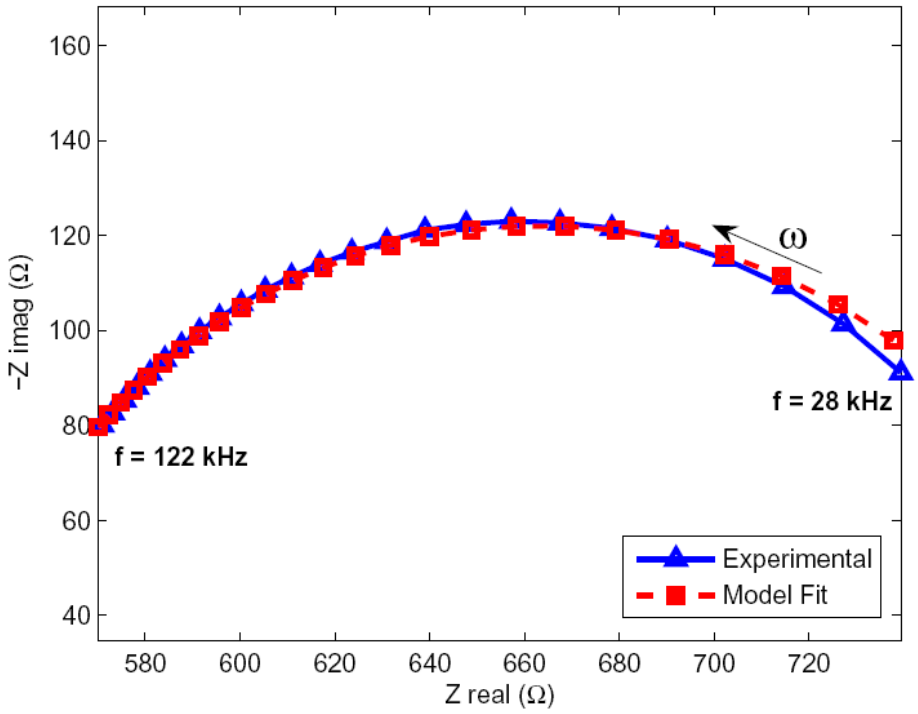
Passive and Active SHM Strategy

Electrical Impedance Spectroscopy (EIS)



$$Z = \mathrm{Re}(Z) + \mathrm{Im}(Z)\,j$$

$$\mathrm{Re}(Z) = \left|\frac{V_o}{I_o}\right| \qquad \mathrm{Im}(Z) = \theta$$



- **Characterize SWNT-PSS/PVA thin film electrical properties:**
  - Measured impedance using regulated electrical current signals (AC: 25 – 125 kHz)
  - Cole-Cole (or Nyquist) plots of complex impedance reveal thin film electrical properties
  - Formulate equivalent circuit model to describe strain and nominal resistance drift

Enhanced Thin Film Mechanical Properties

- **As-fabricated LbL films show good mechanical performance compared to other composites**
  - Mechanical properties important for long-term SHM applications
  - Significant mechanical performance improvements compared to buckypaper

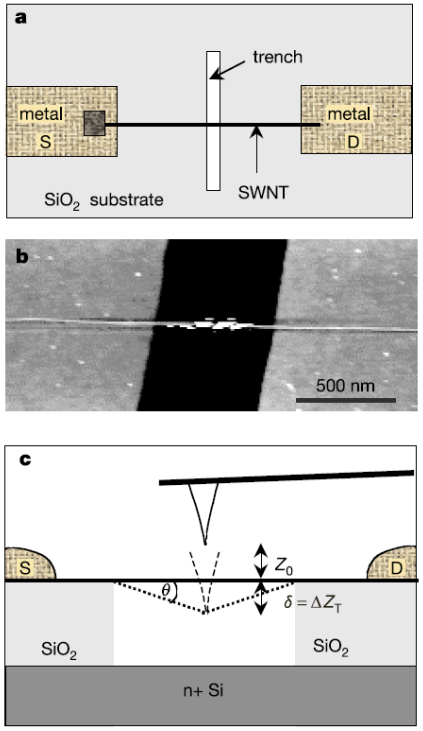
	Buckypaper[1] (Blighe, *et al.* 2008)	Epoxy-Resin[2] (Gojny, *et al.*, 2004)	Layer-by-Layer[1] (Loh, *et al.* 2010)
Young's modulus, E	1.3 GPa	3.3 GPa	13.0 GPa
Ultimate tensile strength, σ_f	7.5 MPa	63 MPa	215 MPa
Ultimate failure strain, ε_f	5,000 με	68,000 με	58,300 με

[1] Based on single-walled carbon nanotubes (SWNTs)
[2] Based on double-walled carbon nanotubes (DWNTs)

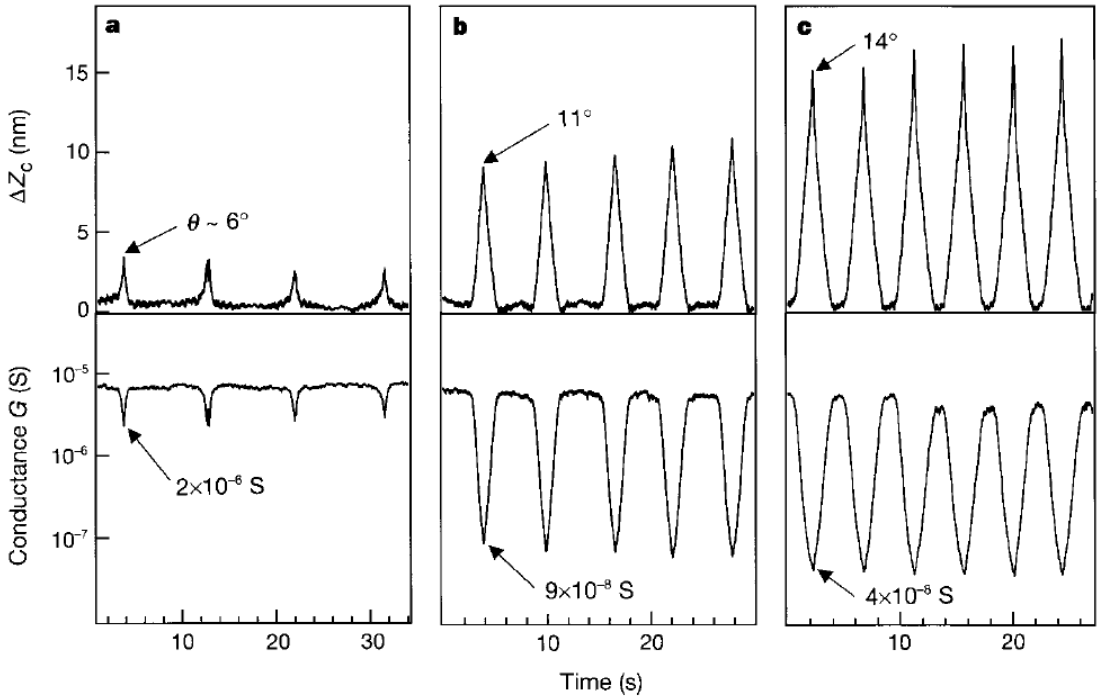
- **Seek to further enhance mechanical and fracture performance:**
  - Post-fabrication thermal annealing → polymer cross-linking
  - Optimize carbon nanotube weight content

Nano-Scale Sensing Performance

- **Early experimental studies on carbon nanotube strain sensing performance conducted with atomic force microscope (AFM)**
  - Use tip to bend individually-suspended SWNTs
  - At 3% strain, conductance decreased by more than two orders of magnitude



Individual SWNT suspended over trench

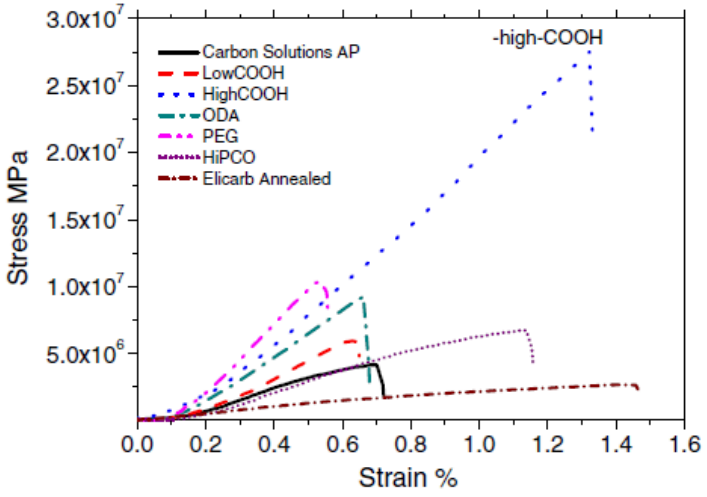


Applied AFM tip deflection and measured conductance

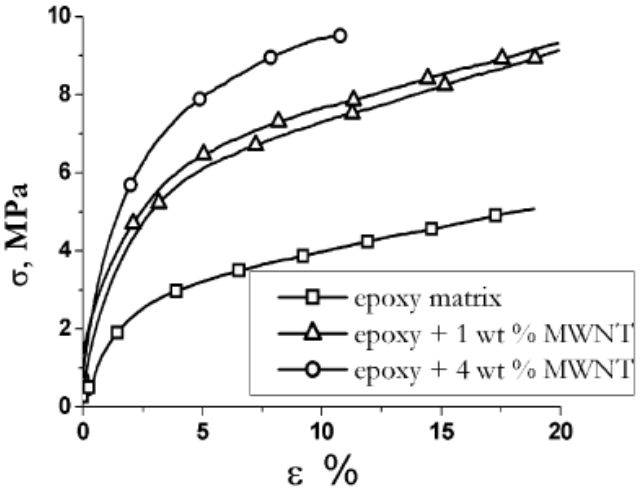
(Tombler, *et al.*, 2000) *Stanford University*

Limitations of Current Nanocomposites

- **Current-generation composites employ mixing of multiple ingredients:**
  - Carbon nanotubes with polystyrene
  - Carbon nanotubes in epoxy-resin
- **Employs traditional composite design methodology to optimize one material property**
  - Buckypaper – high stiffness, but low ductility and ultimate tensile strength



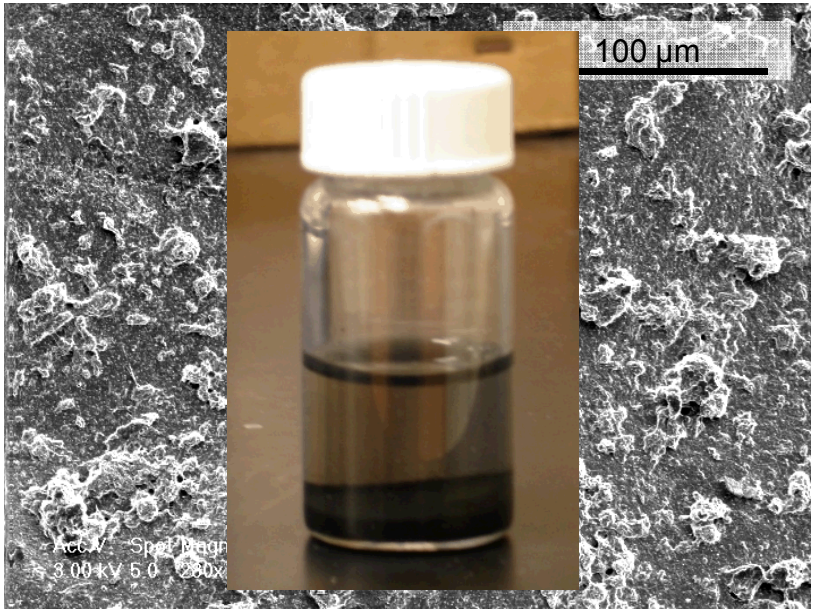
Buckypaper stress-strain responses
(Blighe, *et al.*, 2008) *Trinity College of Dublin*



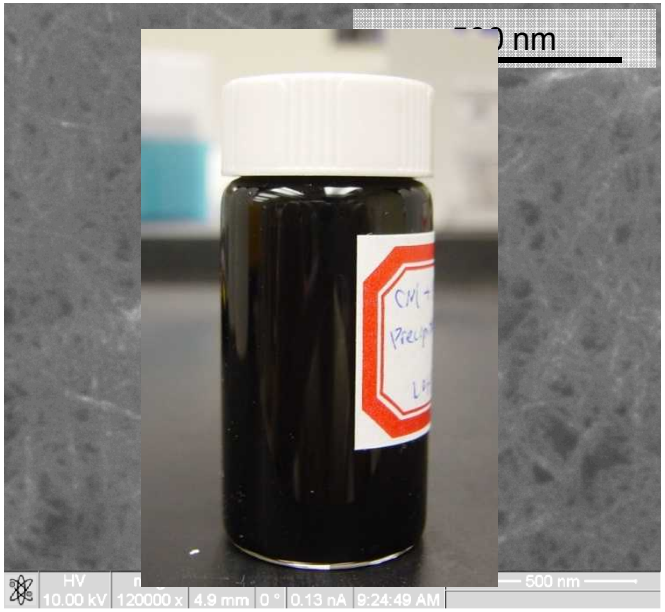
Epoxy-resin stress-strain responses
(Allaoui, *et al.*, 2002) *Shenyang National Lab*

Challenges with Using Carbon Nanotubes

- **Difficult to scale nanomaterial properties to the macro-scale:**
  - Tendency to agglomerate due to strong van der Waals interactions
  - Leads to poor material properties in buckypaper specimens



Poorly-dispersed SWNT solution

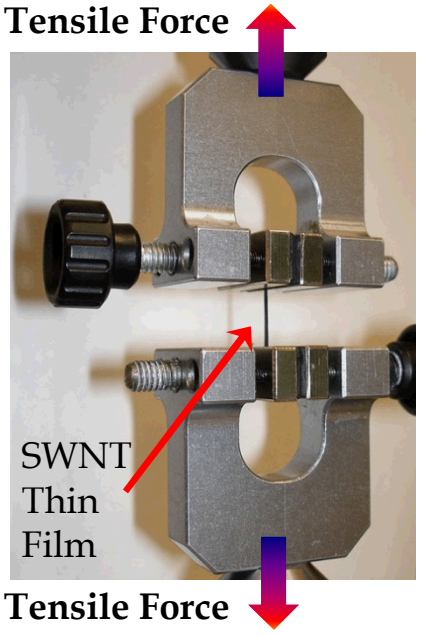


Well-dispersed SWNT-PSS solution

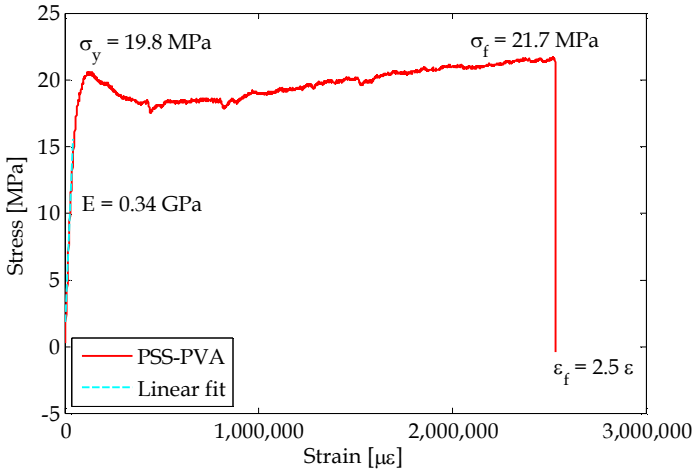
Scanning electron microscopic (SEM) views of carbon nanotube thin films

LbL Nanocomposite Mechanical Properties

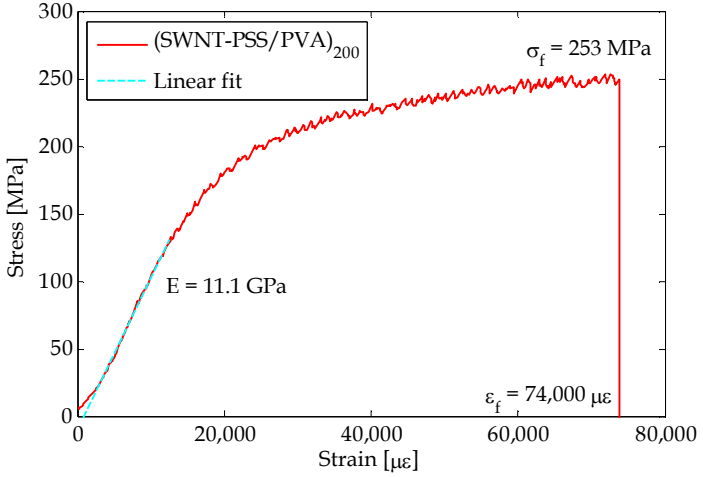
- **Morphology consists of mechanically-strong and –stiff nanotubes sitting in a highly compliant polymeric matrix**
  - Dramatic improvements in nanocomposite strength and stiffness
  - SWNT-tuned composites exhibit high ductility (> 10,000 με)



Nanocomposite strained



PSS/PVA polymeric nanocomposite



Carbon nanotube-reinforced SWNT-PSS/PVA LbL composite

Enhanced Thin Film Mechanical Properties

- **As-fabricated LbL films show good mechanical performance compared to other composites**
  - Mechanical properties important for long-term SHM applications
  - Significant mechanical performance improvements compared to buckypaper

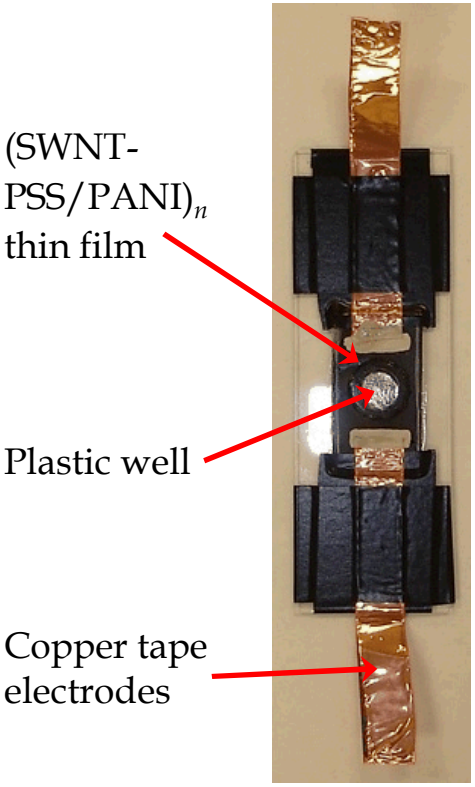
	Buckypaper[1] (Blighe, *et al.* 2008)	Epoxy-Resin[2] (Gojny, *et al.*, 2004)	Layer-by-Layer[1] (Loh, *et al.* 2008)
Young's modulus, E	1.3 GPa	3.3 GPa	11.1 GPa
Ultimate tensile strength, σ_f	7.5 MPa	63 MPa	253 MPa
Ultimate failure strain, ε_f	5,000 με	68,000 με	74,000 με

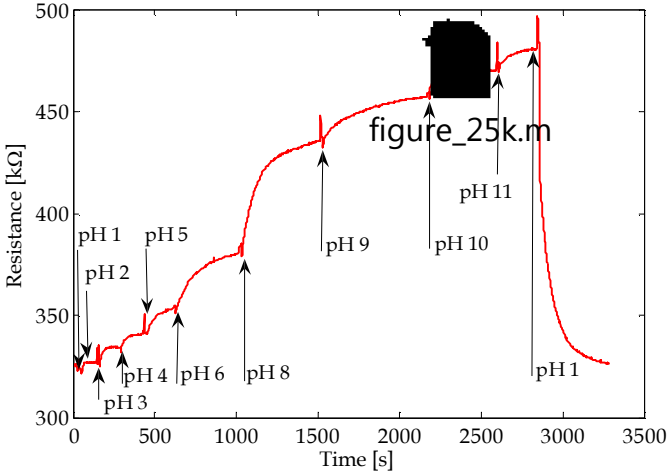
[1] Based on single-walled carbon nanotubes (SWNTs)
[2] Based on double-walled carbon nanotubes (DWNTs)

- **Quasi-static load tests only reveal time-independent mechanical response:**
  - Layer-by-layer films are polymer-based nanocomposites
  - It is likely that they exhibit time-dependent mechanical properties such as viscoelasticity

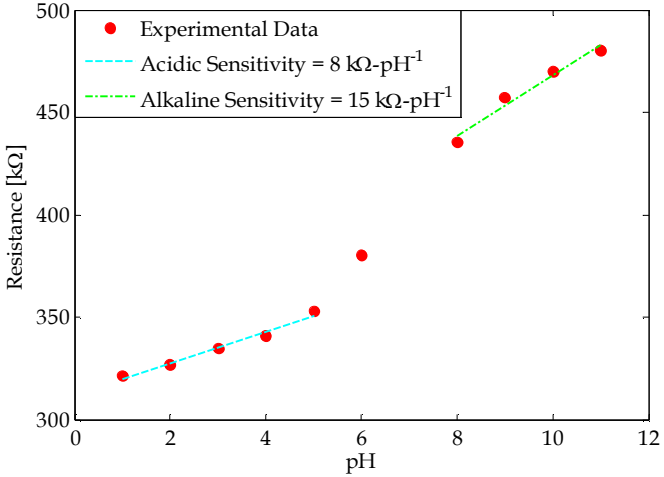
Nanocomposite pH Sensing

- **LbL versatility allows us to encode pH sensitivity within thin films:**
  - Can be used for monitoring corrosion or biological processes
  - Employ pH-sensitive polyelectrolyte: poly(aniline) emeraldine base (PANI)





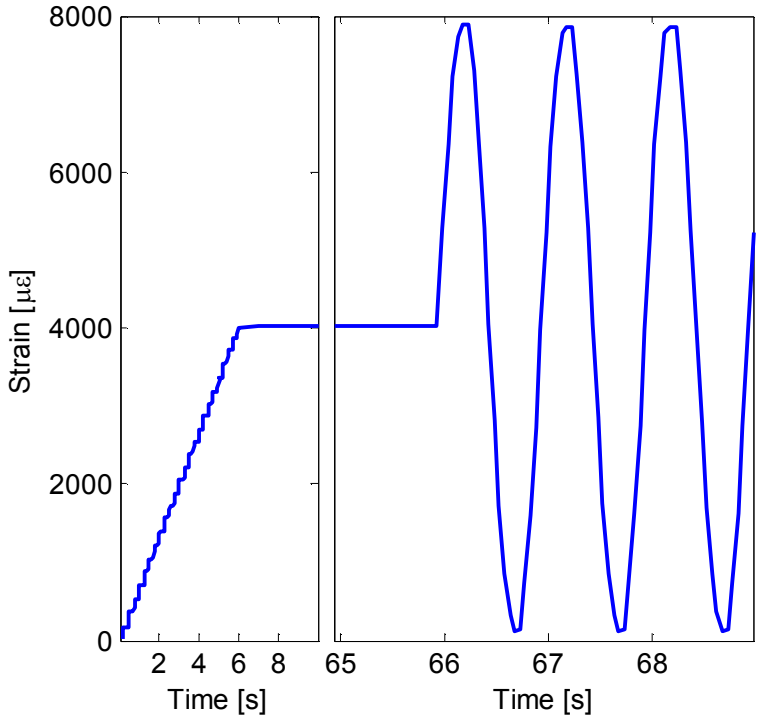
Resistance time history due to pH variations



Nanocomposite pH sensitivity

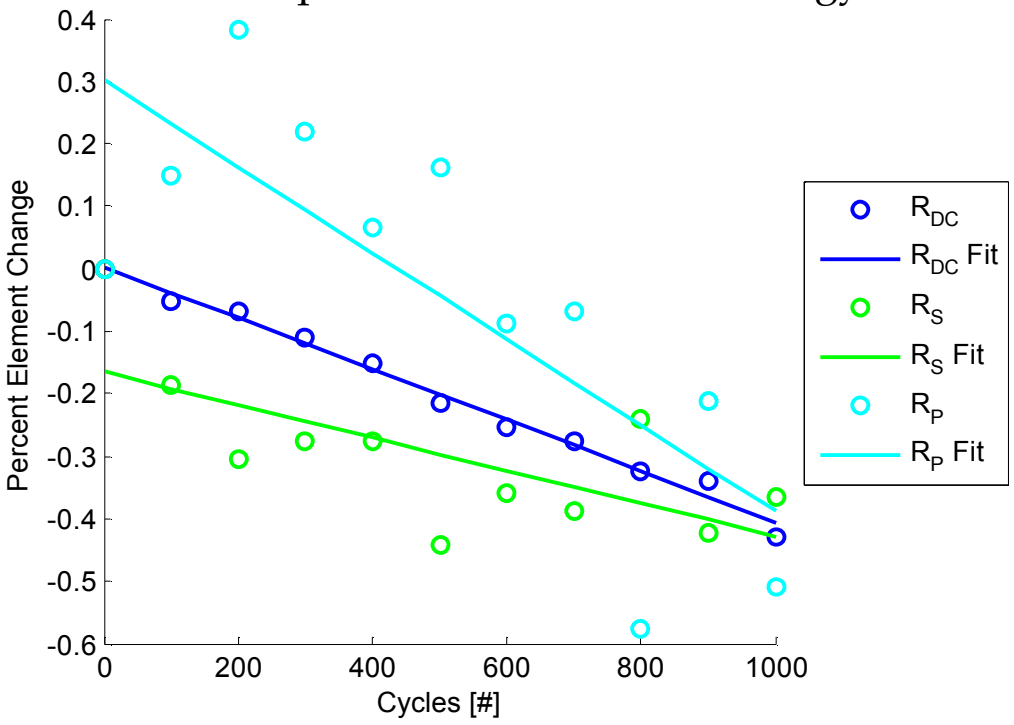
Fatigue Sensor Characterization

- **Long-term low strain dynamic response**
  - Off-set: +4,000 με
  - Amplitude: 4,000 με



Applied strain profile

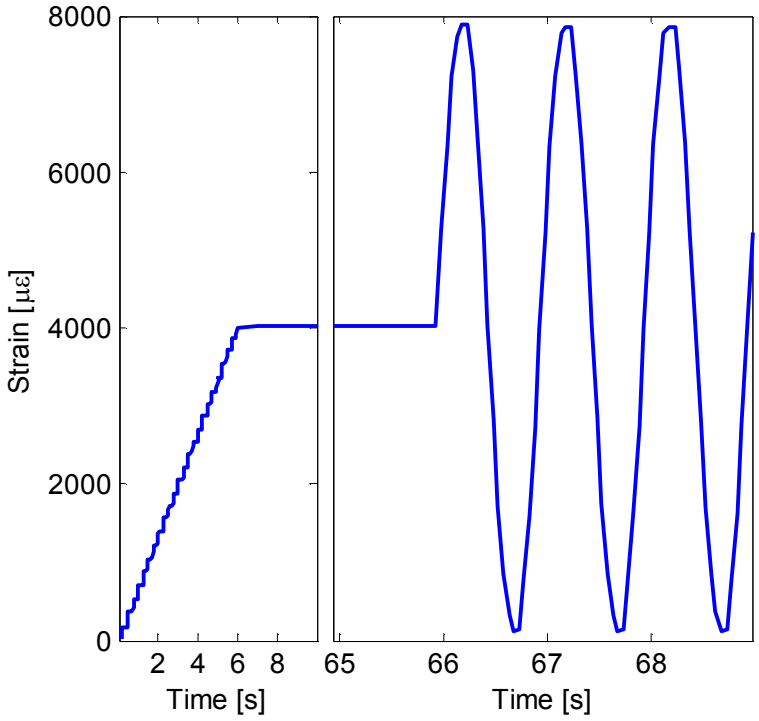
- **Long-term dynamic response:**
  - Slight linear trend in response
    - Less than 0.5% over 1,000 cycles
  - Demonstrates the robust sensing capabilities of this methodology



Applied strain profile

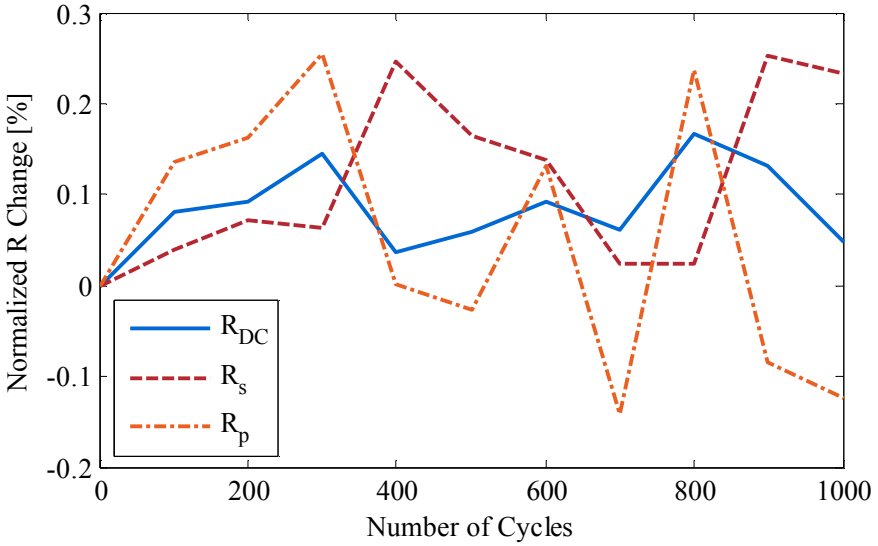
Fatigue Sensor Characterization

- **Long-term low strain dynamic response**
  - Off-set: +4,000 με
  - Amplitude: 4,000 με



Applied strain profile

- **Long-term dynamic response:**
  - Slight linear decrease in response
    - Less than 0.5% over 1,000 cycles
  - Demonstrates the robust sensing capabilities of this methodology



Applied strain profile