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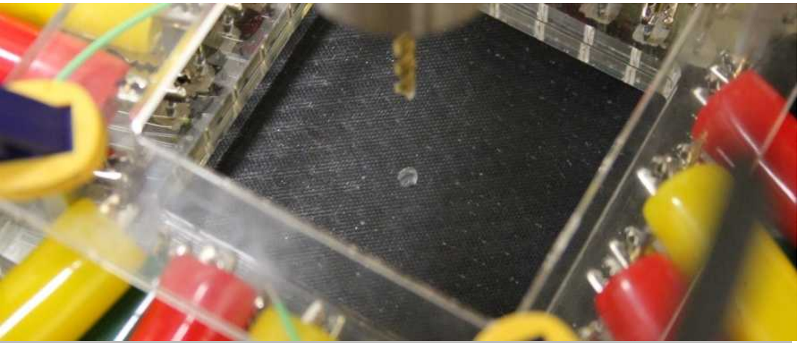

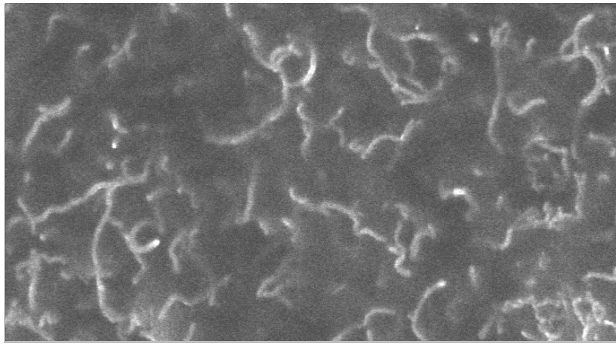

Electrically-based Structural Health Monitoring for Fiber-Reinforced Polymer Composites

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[1]Sandia National Laboratories, Livermore, CA, USA

U.S. DEPARTMENT OF ENERGY

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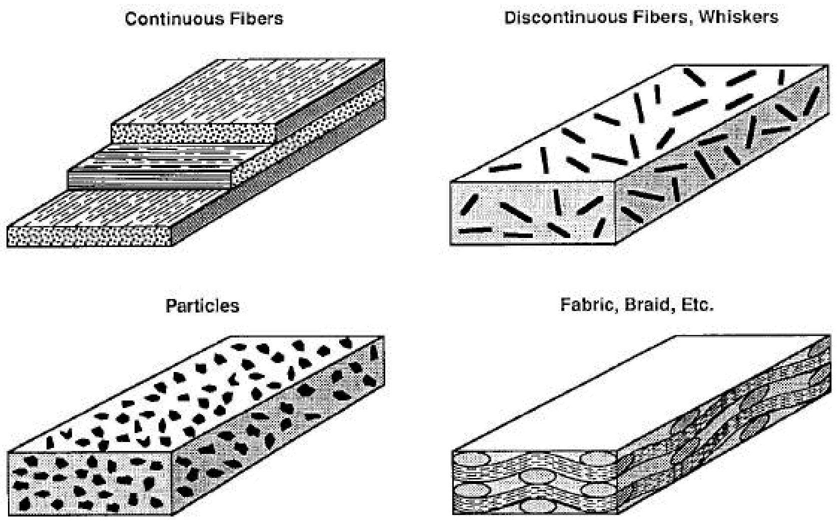
NNSA National Nuclear Security Administration

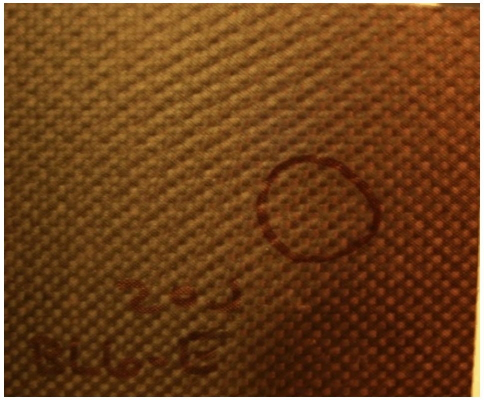
What Are FRP Composites?

- Composite material: "Composite materials are materials made from two or more constituent materials with significantly different physical or chemical properties, that when combined, produce a material with characteristics different from the individual components." (Wikipedia)
  - Matrix Material
    - Thermoplastics
    - Epoxies
    - Vinylesters
    - Carbon
    - Metals
    - Concrete
  - Reinforcement Material
    - Carbon
    - Glass
    - Aramids (Kevlar)
    - Polyethylene
    - Cellulose
    - Aluminum
    - Boron
  - Reinforcement Styles
    - Continuous Fiber
    - Woven Fibers
    - Chopped Fibers
    - Particulates

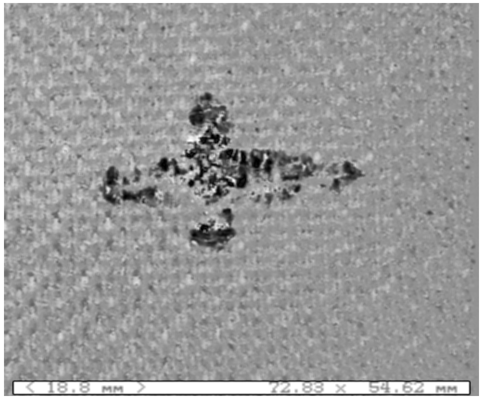


General Composite Properties

- Highly conformable during manufacturing process
- Composite materials do not yield
- Very fatigue resistant
- Age based one humidity conditions
  - Can absorb up to 2 wt% water
- Corrosion resistant, except for carbon and aluminum via galvanic corrosion
- Not sensitive to most standard chemicals
  - Solvents, oils, hydraulic fluids, grease
- Have low to medium impact resistance
- Better fire resistance than light alloys



Visual inspection



C-SCAN ultrasound image CFRP panel after 20 Joule impact

Material Performance Comparison

Material	Steels	Al 2024	Ti 6Al-4V	Carbon/ Epoxy[1]	Glass/ Epoxy[1]	Kevlar/ Epoxy[1]	Boron/ Epoxy[2]
Density [kg/m^3]	7800	2800	4400	1530	2080	1350	1950
Spec. Elastic Modulus [MPa]/ρ	26.3	26.8	23.9	87.6	21.6	63.0	107.7
Poisson Ratio	0.3	0.4	0.3	0.25	0.3	0.34	
Spec. Tensile Strength [kPa] /ρ	205	161	273	830	601	1044	718
Spec. Comp. Strength [kPa] /ρ	397		220	739	289	207	1333
C.T.E. [ppm^{o}C^{-1}]	13	22	8	-1.2	7	-4	5
Temp. Limit [^{o}C]	800	350	700	90	90	90	90

[1]Fiber Volume Fraction = 0.6
[2]Fiber Volume Fraction = 0.5

Usage of Fiber-Reinforced Composites

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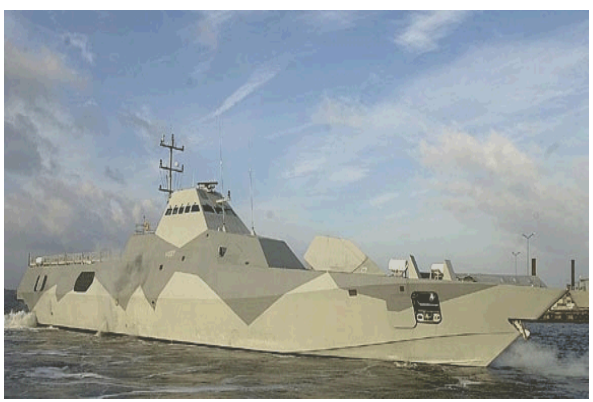
- Over the past 50 years, increased usage of composite materials

Commercial aircraft systems

Future and legacy spacecraft

Military aircraft



Naval structures

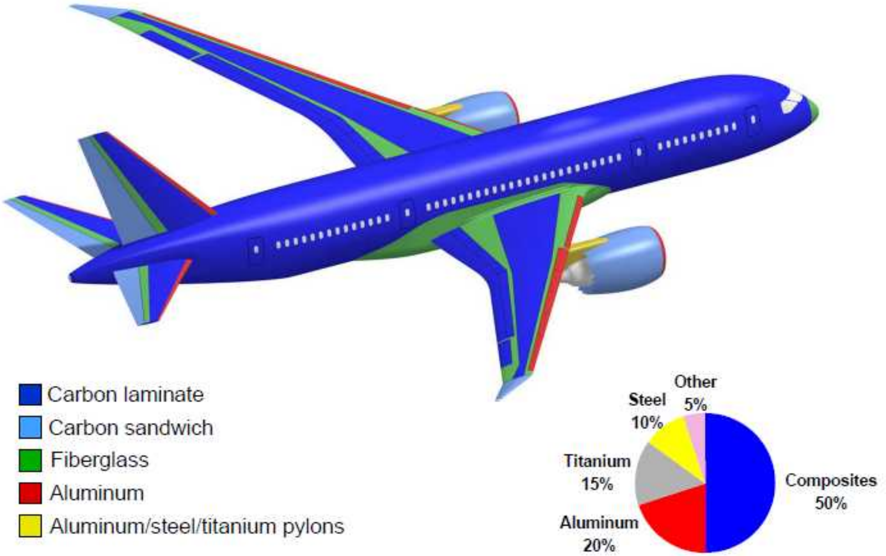
Wind turbine blades

CFRP cable stay bridge

Boeing 787

Sandia National Laboratories

- Composites
  - Predominantly CFRP
    - Fuselage
    - Wings
  - GFRP for certain lower-load bearing and impact resistant applications
- Benefits
  - Weight savings
    - Fuel savings
  - Higher fuselage hoop strength
    - Higher cabin pressure in-flight
  - Higher humidity
    - No corrosion, except Al to CFRP
  - Larger windows



Boeing 787 material composition (Boeing)

Boeing 787 Wing Flex

Sandia National Laboratories

Smith, 7-April-2011, ESASI-Lisbon | 7

Boeing 787 Wing Flex

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Boeing 787 wing on the ground

Boeing 787 wing at cruising altitude (~34,000 ft)

Boeing 737 Wing Flex

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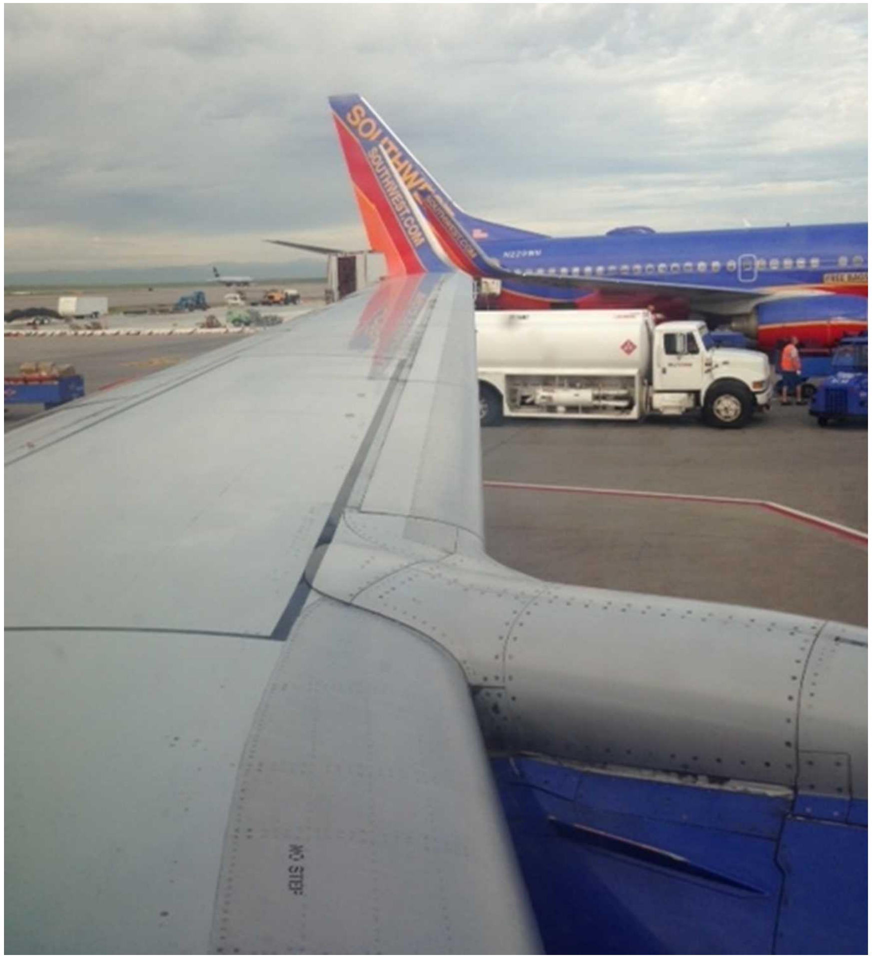


Boeing 737 wing on the ground

Boeing 737 wing on the ground

Space Structures

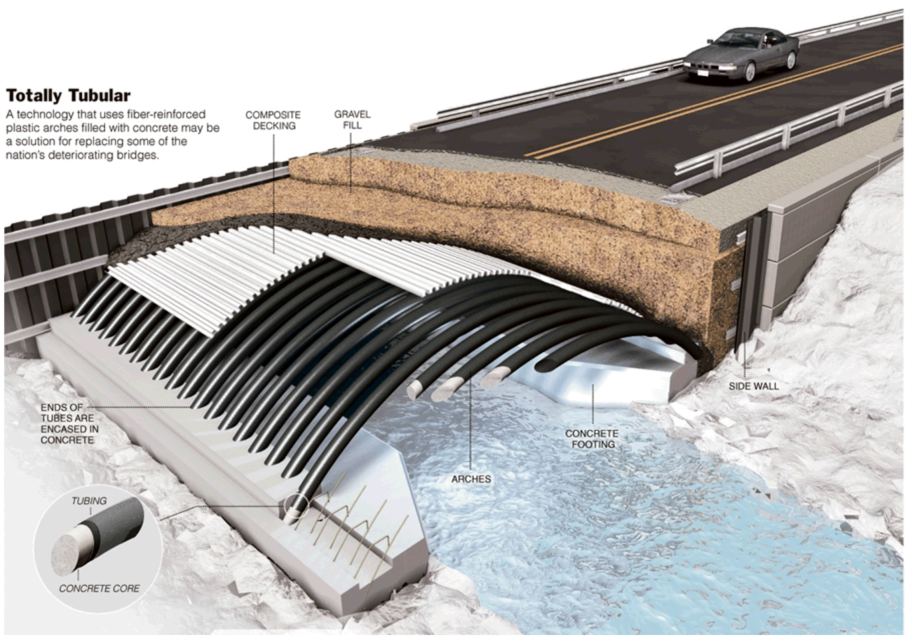
- Benefits
  - Low CTE
    - High temperature gradients in space
  - Weight reduction
    - Increased cargo capacity
  - Tailorable mechanical properties
  - Tailorable thermal properties
    - Conduct heat from hot to cold side of spacecraft
- Typical composite materials
  - Carbon fiber/epoxy
  - Carbon fiber/phenolic
  - Kevlar fiber/epoxy

Spaceship Two mounted on White Knight Two (Scaled Composites)

James Webb Space Telescope carbon fiber backplane (Hexcel)

Civil Structures

- Benefits
  - Corrosion resistance
  - Fatigue resistance
  - Conformable fabrication
- Typical composite materials
  - Glass fiber/epoxy
  - Carbon fiber/epoxy

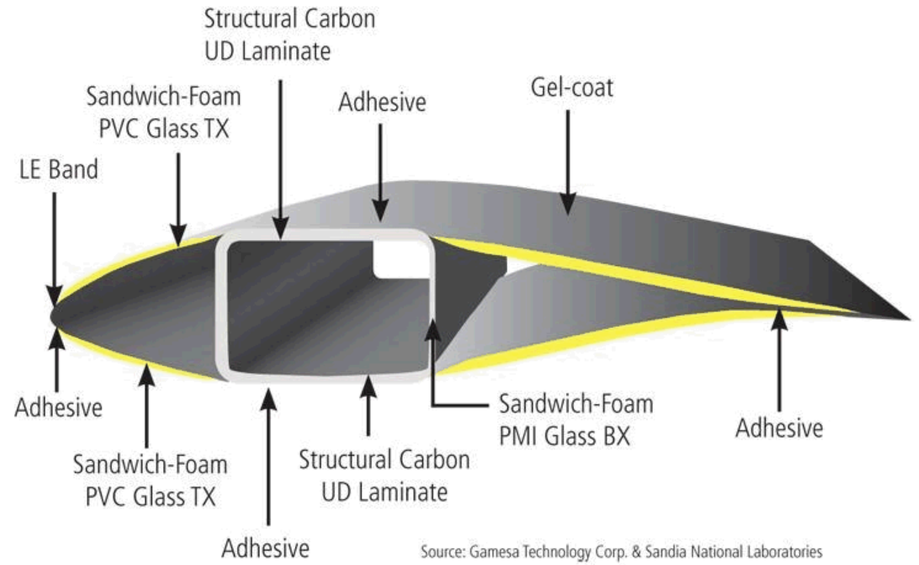


Carbon fiber/glass fiber bridge construction in Pittsfield, Maine (NY Times)

Workers applying GFRP warp to concrete column (Department of Transportation)

Wind Turbines

- Benefits
  - Tailorable laminate properties
  - Cheaper (E-glass)
  - No corrosion
  - Low maintenance



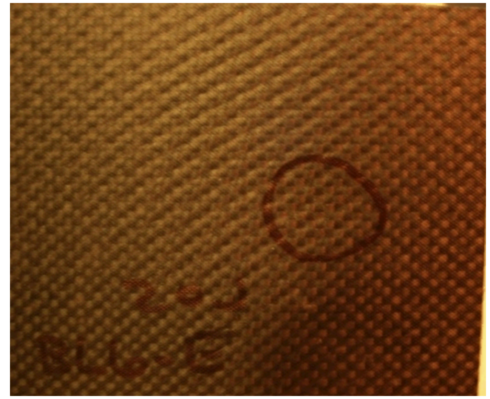
Cross-section of a Gamesa G87/G90 wind turbine blade (Gamesa / Sandia National Laboratories)

- Typical composite materials
  - Glass fiber/epoxy (current)
  - Carbon fiber/epoxy
    - Reinforcement for GFRP
    - Entire construction

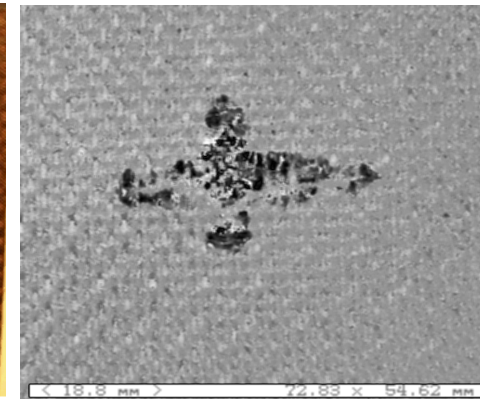
Vestas turbine blade mold (MIT Tech Review)

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
  - Current methods are laborious



Visual inspection



C-SCAN ultrasound image

CFRP panel after 20 Joule impact

Aircraft ultrasonic inspection (Composites World)

SHM Design Considerations

Current NDE limitations:

- Labor intensive
- Expensive equipment
- Structures must come out of service
- Experience technician required to interpret results

Boeing 787 (Boeing)

Successful SHM systems:

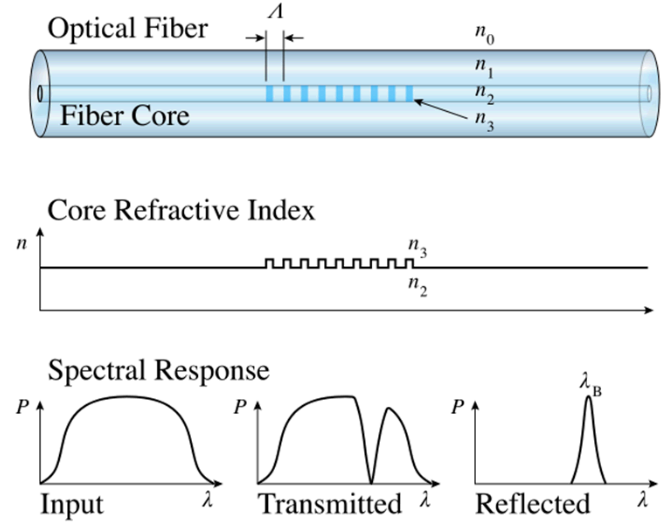
1. Directly detect and measure damage
2. Determine the damage location
3. Ascertain the size of the damage
4. Quantify the severity of the damage
5. Achieve multi-modal sensing capabilities (i.e., delamination, cracking, and chemical penetration)

Golden Gate Bridge (Wikipedia)

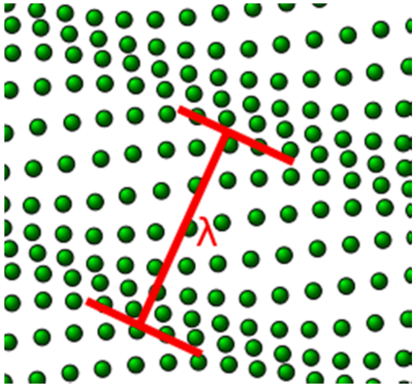
Fiber Optic Sensors

Sandia National Laboratories

- Light-based method
  - Reflection/refraction of light used for sensing
- Sensors
  - Fiber bragg gratings
    - Strain/temperature
  - Brouillon sensors
    - Strain/temperature
  - Plain
    - Crack detection
- Benefits
  - Embeddable
  - Radiation insensitive
  - High density of sensors along one fiber



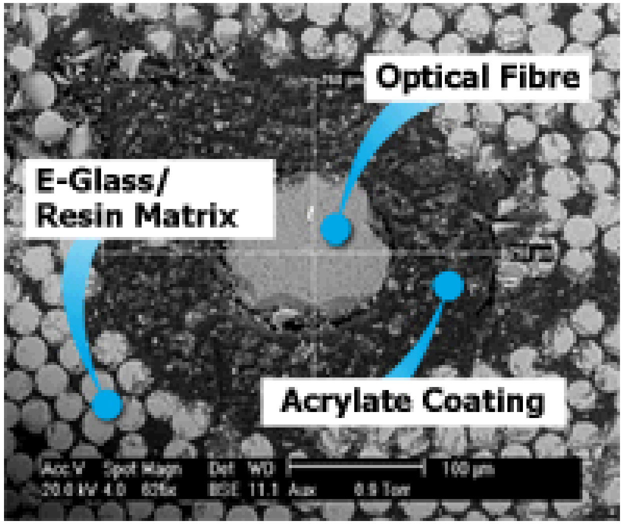
Explanation of a fiber bragg grating sensor (Wikipedia)



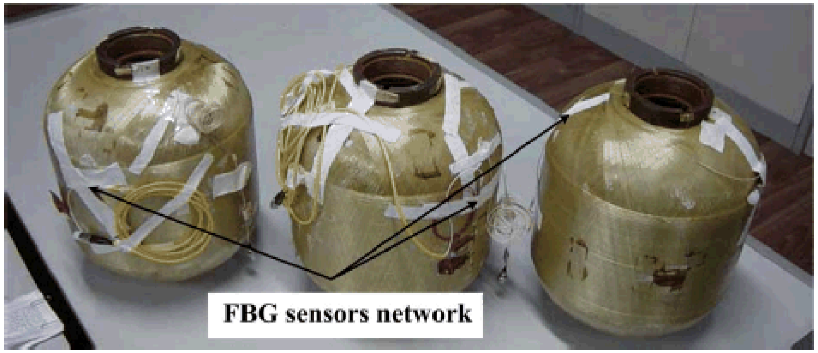
Density/refractive index changes that cause Brillouin scattering (Wikipedia)

Embedded Fiber Optics

- Layup composite with embedded optical fibers
- Positives
  - Sense damage/strain internal to composite
  - Resin cure monitoring
    - Temperature distribution
    - Residual stress field from cure
- Negatives
  - Fiber diameter <100 microns leads to decrease in fatigue performance
  - High stress concentration where fiber enters composite
    - Leads to easily fiber fracture



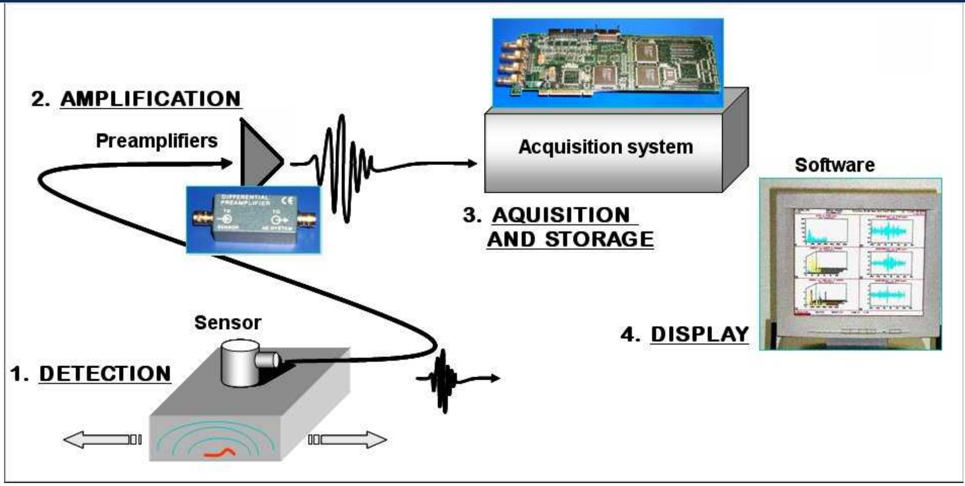
SEM image of embedded optical fiber in GFRP composite (Epsilon Optics)



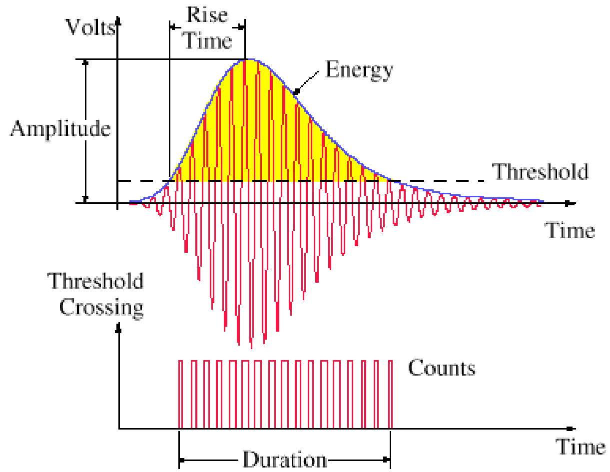
FBG optical fibers embedded in rocket motor GFRP structure (2008 X. Chang et al.)

Acoustic Emission

- Approach
  - Piezoelectric sensor applied/embedded to composite
  - Monitor for emission of sound from damage event
  - Characteristic of emission used to determine damage type
- Positives
  - Can localize and characterize damage event
- Negatives
  - Constant monitoring at high data rate to detect damage events
  - Equipment can be bulky and expensive
    - Getting a lot better



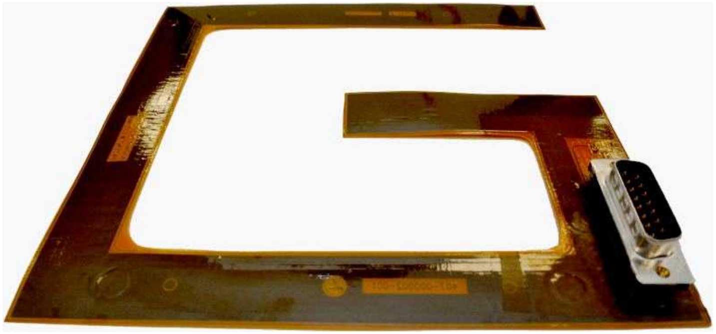
SEM image of embedded optical fiber in GFRP composite (Mistras Group)



SEM image of embedded optical fiber in GFRP composite (TMS)

Ultrasonic-based sensing

- Approach
  - Propagate a stress wave across the structure using piezoelectric
  - Wait for response at same or other sensor
  - Analyze for spatial and damage characteristics
- Positives
  - Rapidly maturing field
  - Sensitive to many damage modes
  - Can localize damage
- Negatives
  - Data acquisition and amplifiers can be bulky
    - Recent efforts have reduced hardware significantly



Acellent's Smart Layer ultrasonic sensors (Acellent Technologies)

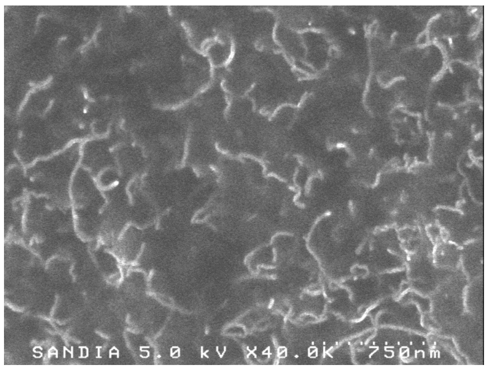
Metis Disk ultrasonic-based sensors (Metis Design)

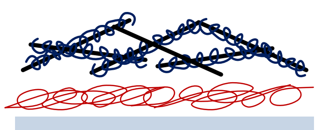
Embedded Sensing via CNT Thin Films

Sandia National Laboratories

PART I

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



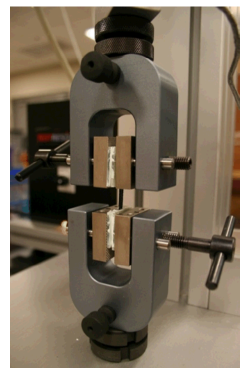


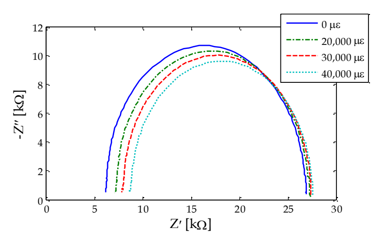
1. Harness unique material properties of carbon nanotubes

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

PART II

Embedded nanocomposite strain sensors for glass fiber-reinforced polymer composites



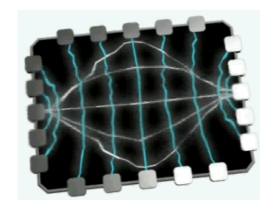


3. Deposited thin films on FRP for strain sensing

4. MWNT-latex multi-modal sensor via spray deposition

PART III

From point-sensing to distributed sensing using sensing skins

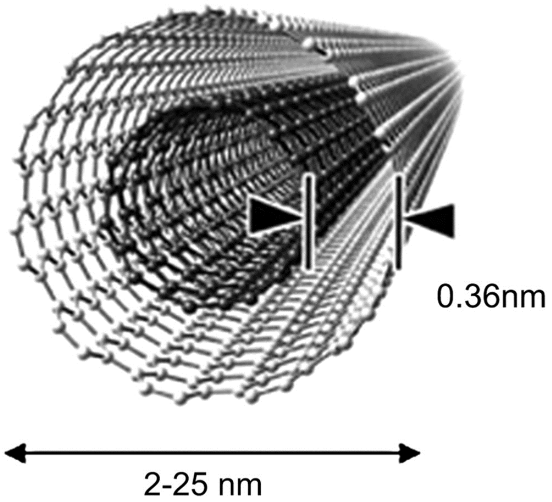


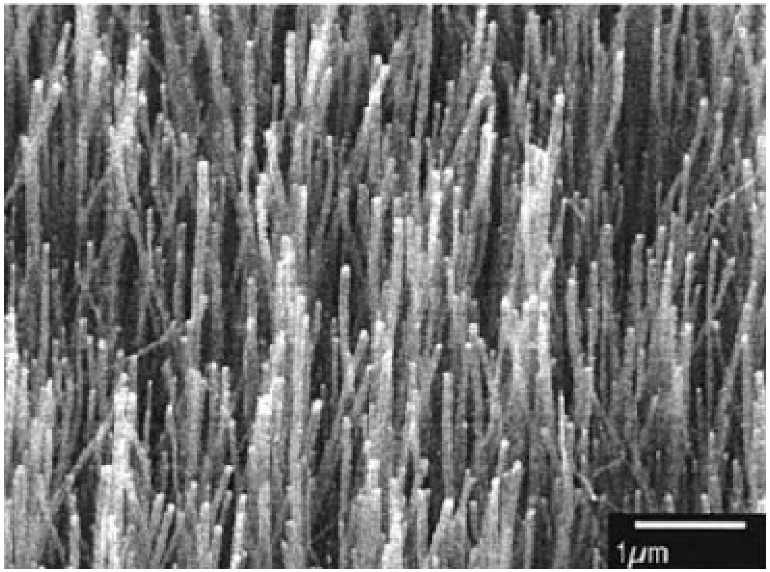
5. Electrical impedance tomography for spatial conductivity mapping

6. Distributed spatial damage sensing based on sensing skins

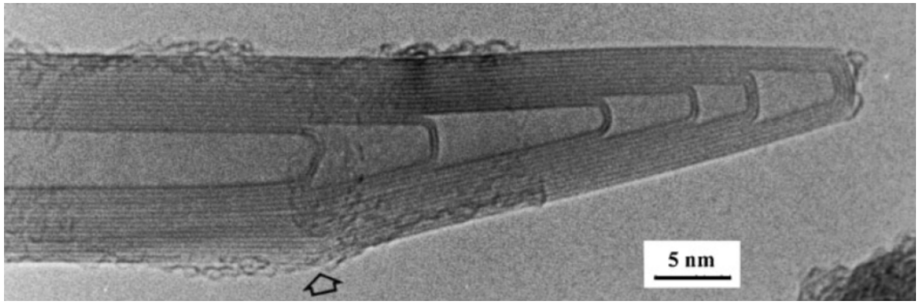
Carbon Nanotubes

- 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





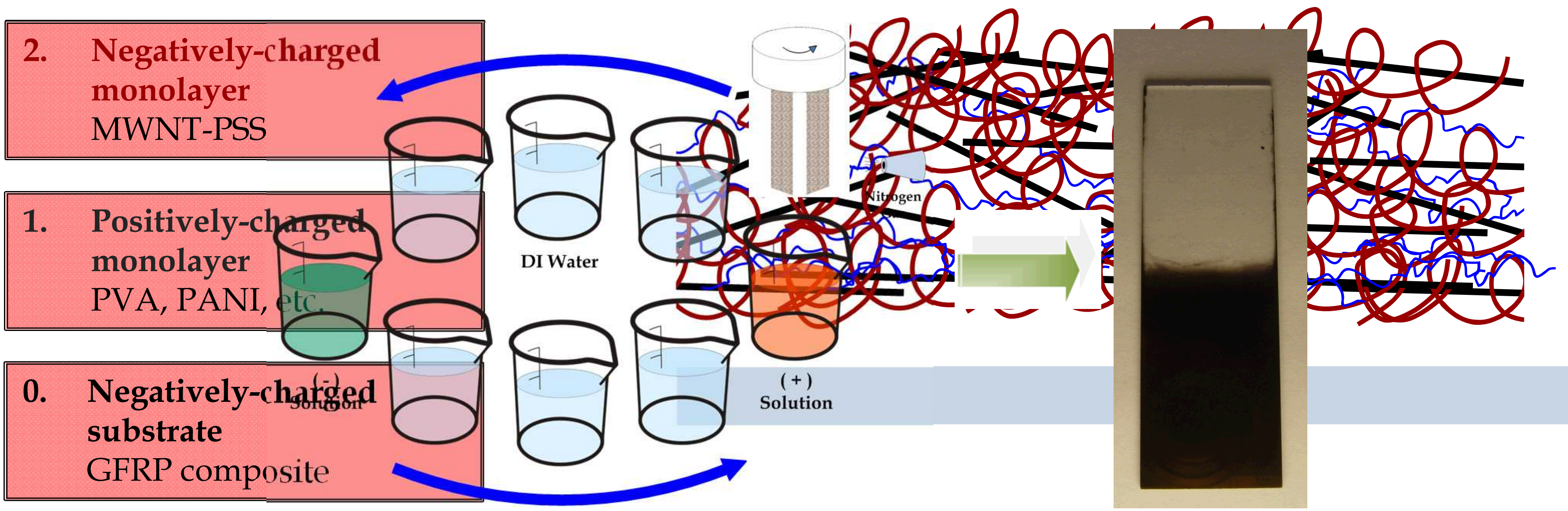
Aligned carbon nanotube forest
Thostenson, et al. (2001)



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

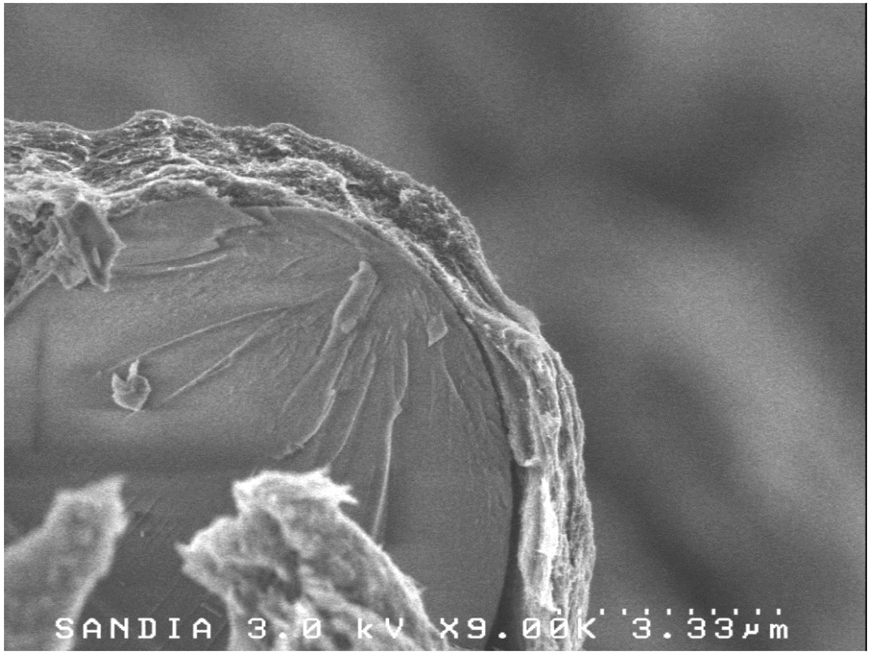
Layer-by-Layer (LbL) Method

- 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

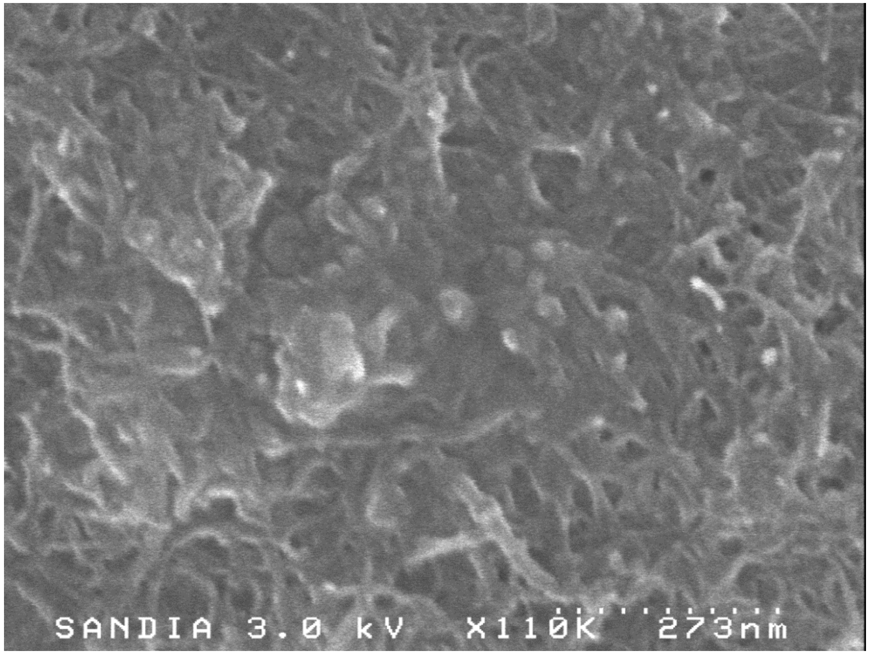


Nanocomposite Morphology

- 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 $[MWNT\text{-}PSS/PVA]_{150}$ thin film on GFRP



Surface SEM image of a $[MWNT\text{-}PSS/PVA]_{100}$ thin film

Presentation Outline

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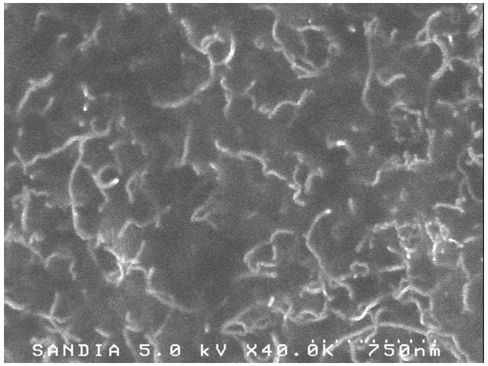
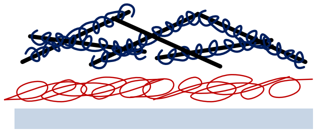
Development of carbon nanotube-based nanocomposites for multi-modal sensing





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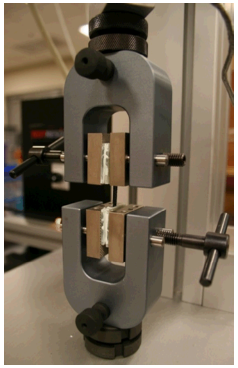

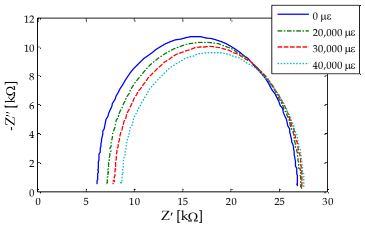

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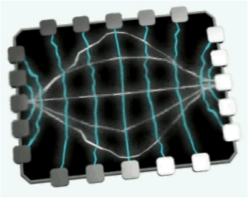
From point-sensing to distributed sensing using sensing skins

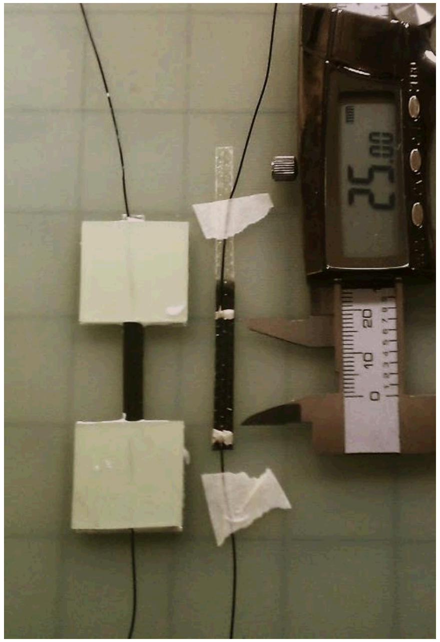


5. Electrical impedance tomography for spatial conductivity mapping

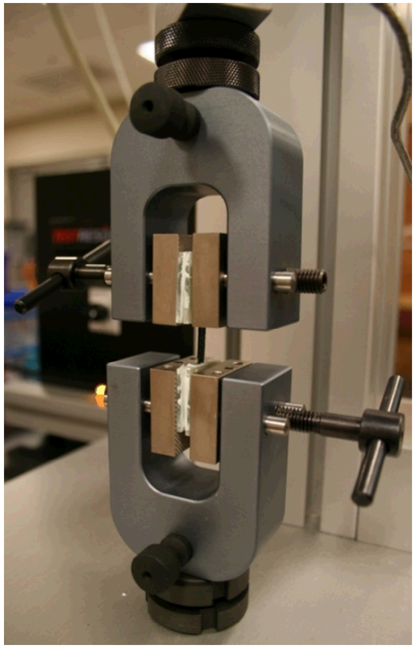
6. Distributed spatial damage sensing based on sensing skins

Strain Sensitivity Validation

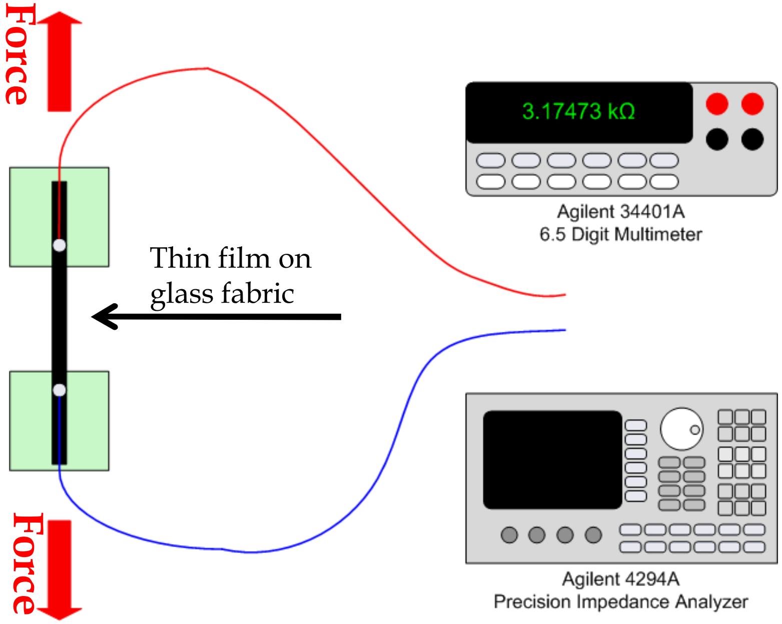
- Objective:
  - Validate thin film electromechanical performance deposited on GFRP
- Specimen preparation:
  - Attach two conductive electrodes and composite tabs
- Nanocomposite electromechanical performance characterization:
  - Apply monotonic and dynamic uni-axial tensile loading to specimens



Fiber-coated specimen



Thin film mounted in load frame



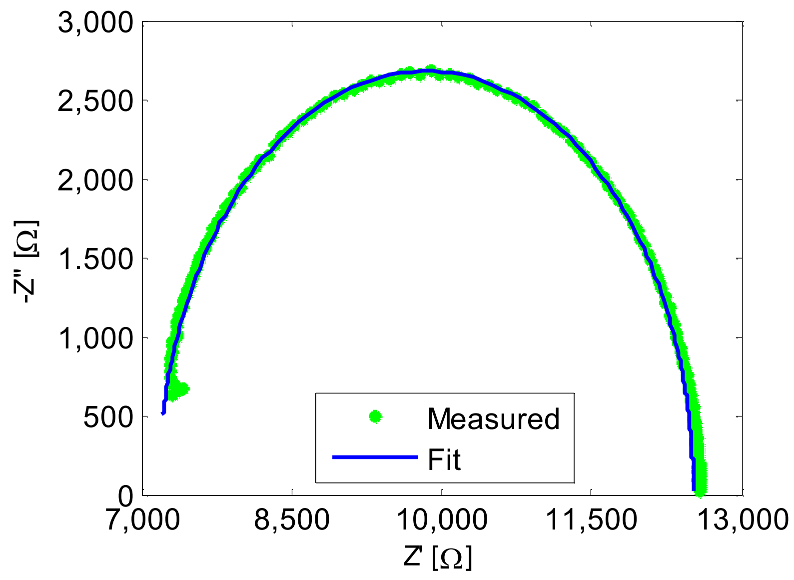
Time- and frequency-domain strain sensing

Electrical Impedance Spectroscopy (EIS)

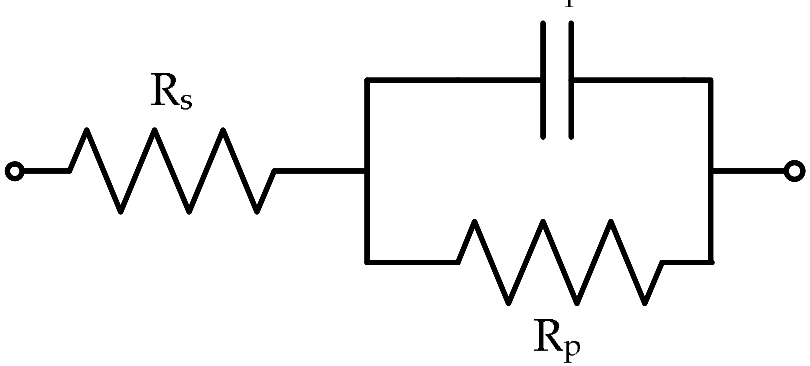
Sandia National Laboratories

- 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)

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



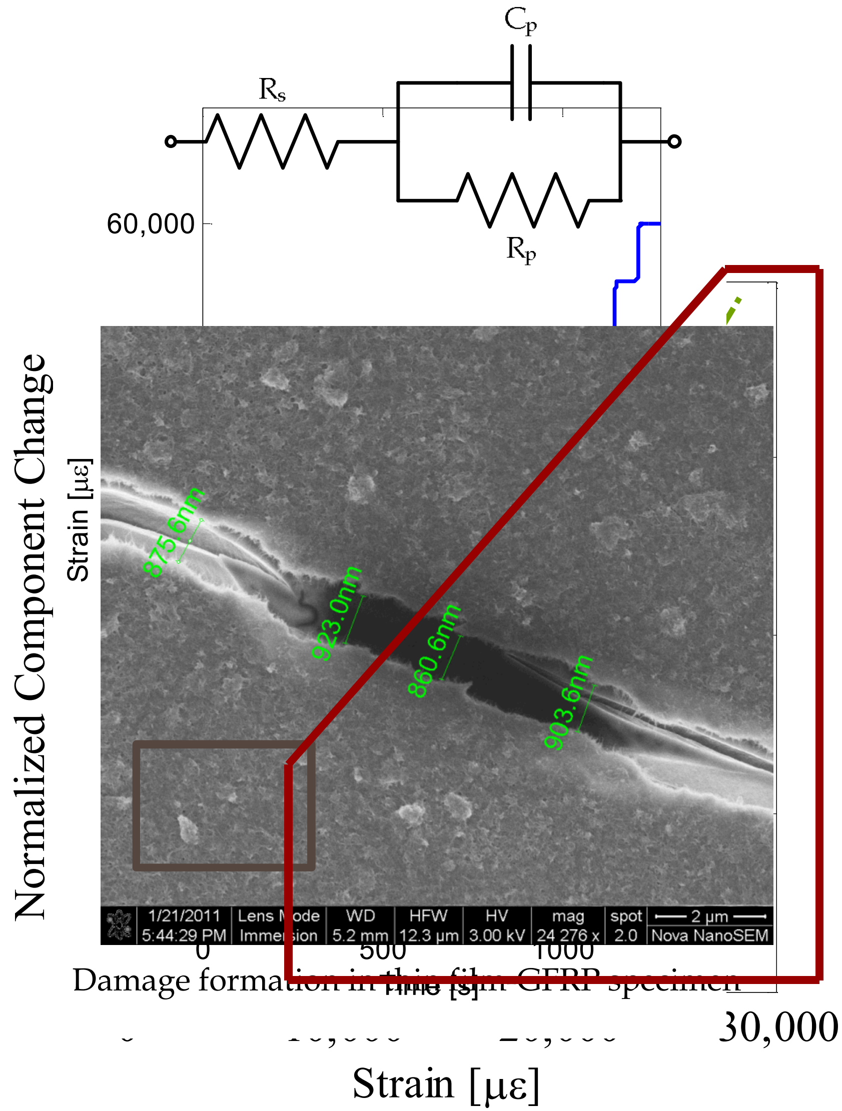
  - Physically-based equivalent circuits are used to fit to the impedance data



Proposed equivalent circuit model for LbL thin films

Monotonic Sensor Characterization

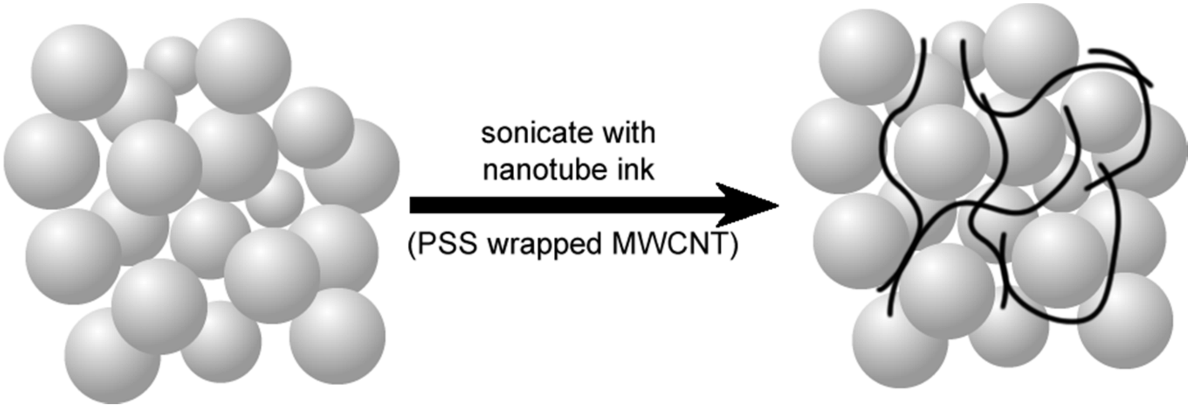
- Load frame applies stepped-tensile displacement profile:
  - Monotonic increasing strain to failure
  - Capture full sensors response
- Equivalent circuit model-updating:
  - Fitting with nonlinear least squares
  - Extract fitted circuit parameters as a function of applied strain
- Bi-functional strain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



Damage formation in thin film GFRP specimen

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



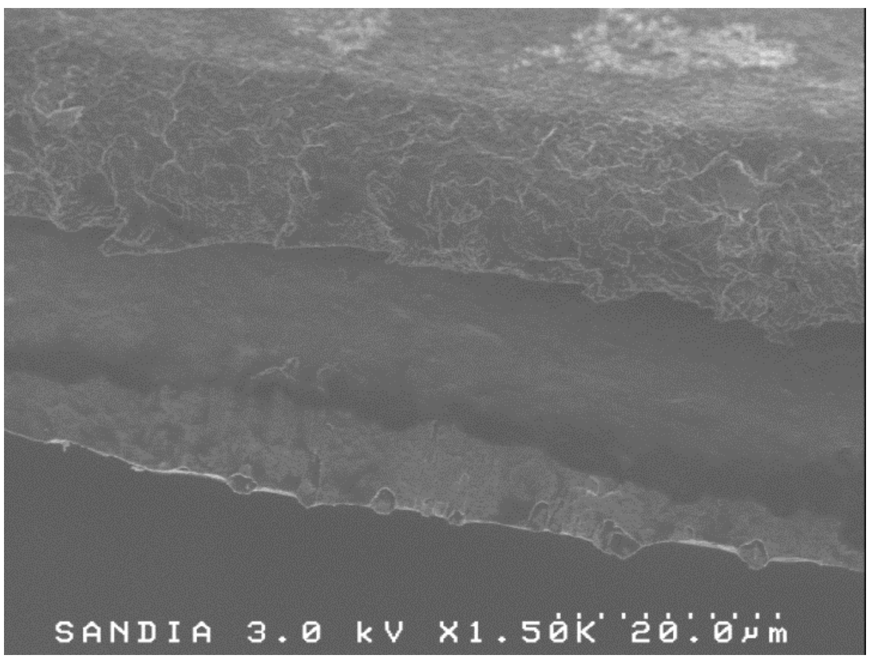
Kynar Aquatec™ latex solution (avg. particle size 150nm)

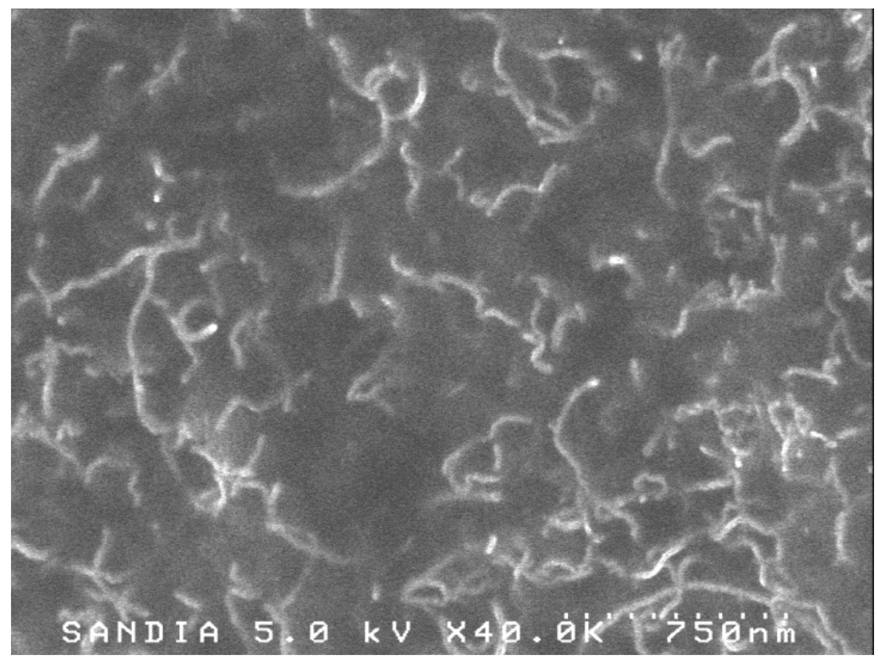
Forms segregated MWCNT network

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

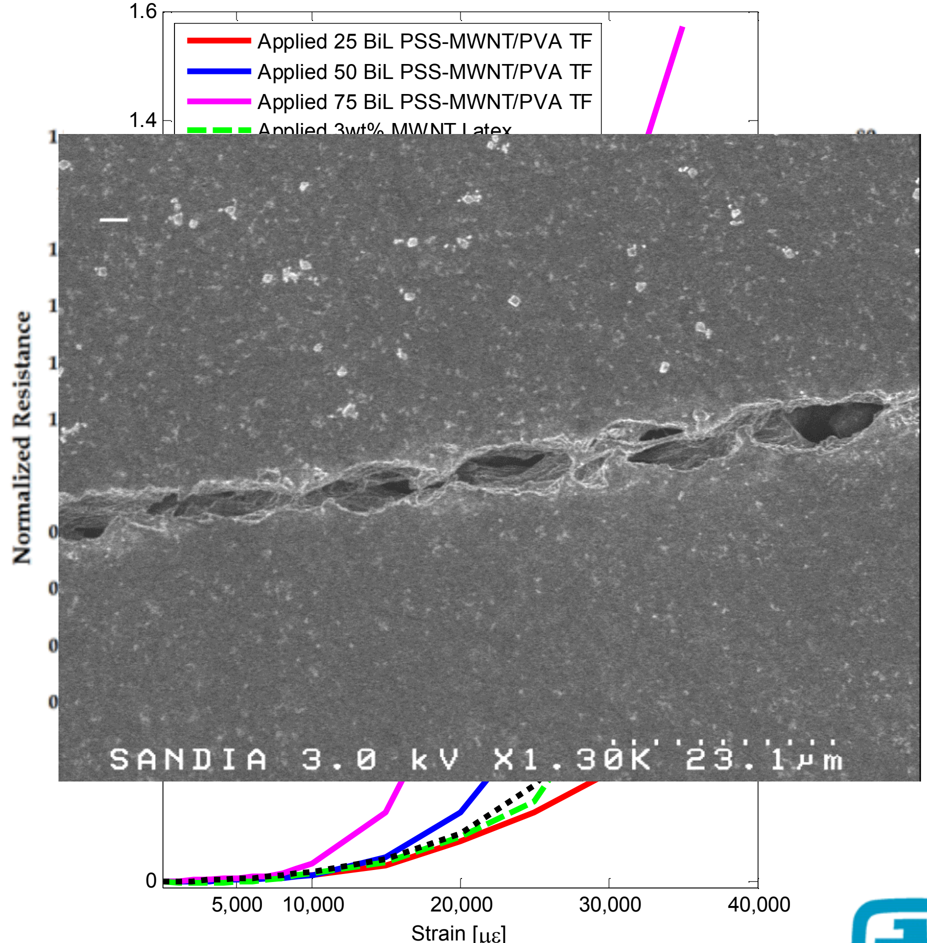




Cross-section and MWNT network SEM images of 3wt% MWNT-Latex film

MWNT-Latex Characterization

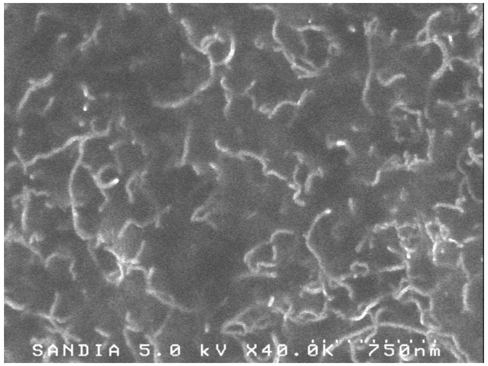
- Electromechanical characteristics:
  - Quasi-static testing
    - Nearly same sensitivity as LbL
  - Bi-functional strain response
    - Linear
    - Quadratic
      - Cracking of film
- Thermo-resistance coupling:
  - -50° C to 80° C over 2 hours
  - 2 hour holds
  - Inversely linear relationship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

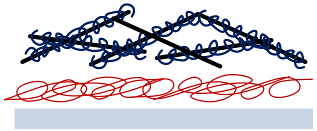


Presentation Outline

PART I

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



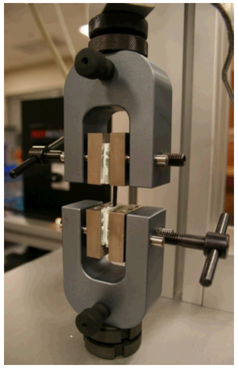


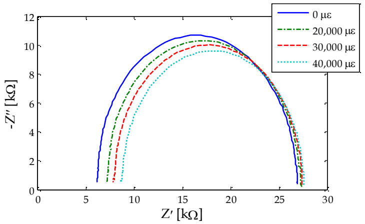
1. Harness unique material properties of carbon nanotubes

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

PART II

Embedded nanocomposite strain sensors for glass fiber-reinforced polymer composites



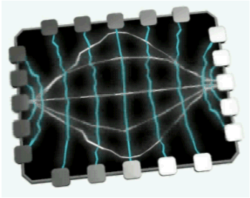


3. Deposited thin films on FRP for strain sensing

4. MWNT-latex multi-modal sensor via spray deposition

PART III

From point-sensing to distributed sensing using sensing skins



5. Electrical impedance tomography for spatial conductivity mapping

6. Distributed spatial damage sensing based on sensing skins

Spatially Distributed SHM Paradigm

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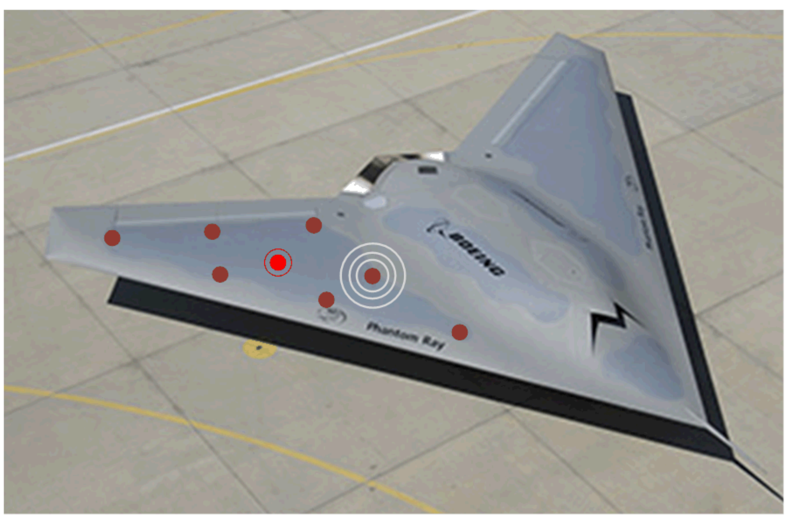
- Current state-of-art in structural health monitoring:
  - Passive SHM using acoustic emissions
  - Active SHM using piezoelectric sensor/actuator pairs
- "Sensing skins" for spatial damage detection:
  - Objective is to identify the location and severity of damage
  - Monitor and detect damage over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

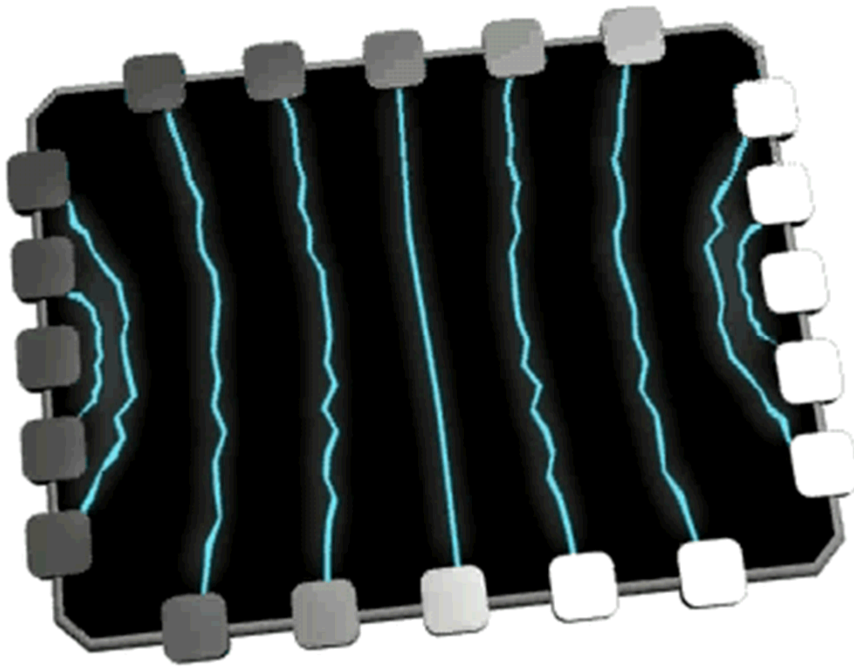


(Boeing)

(Boeing)

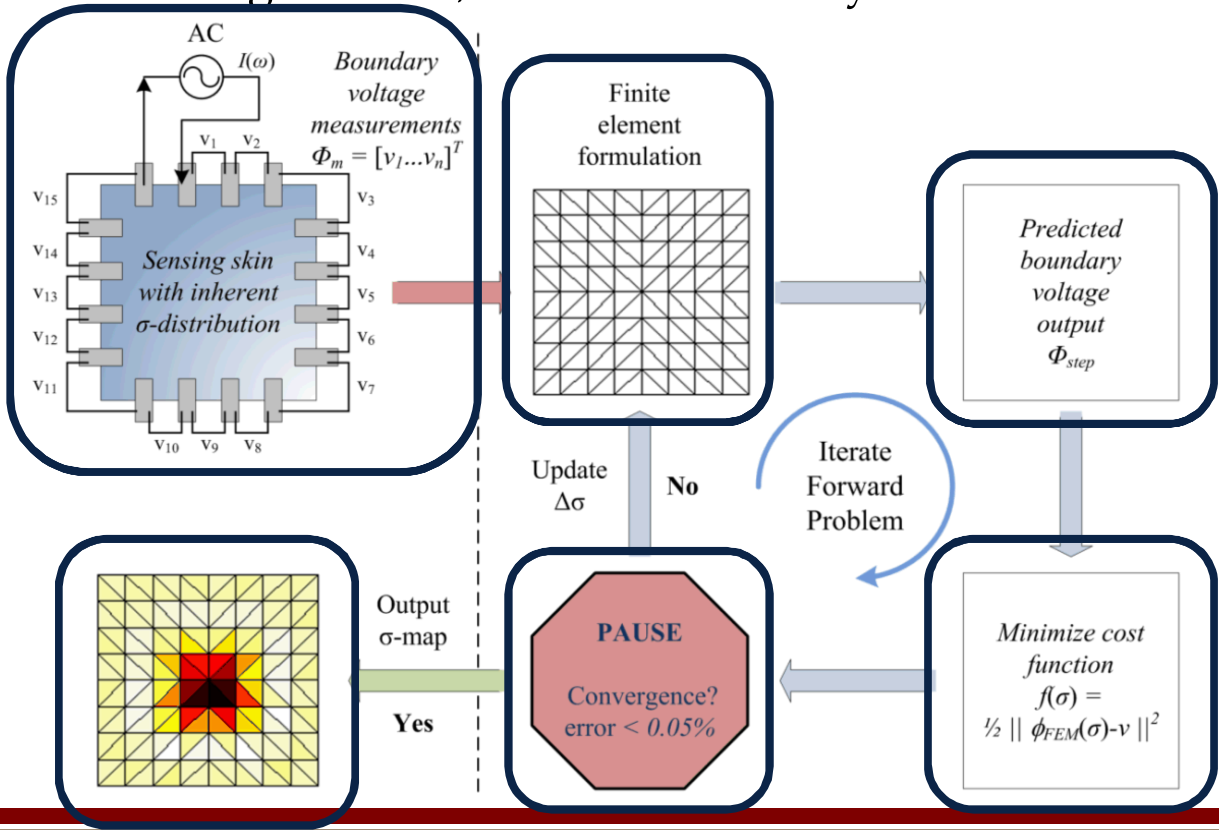
Electrical Impedance Tomography

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



Typical 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

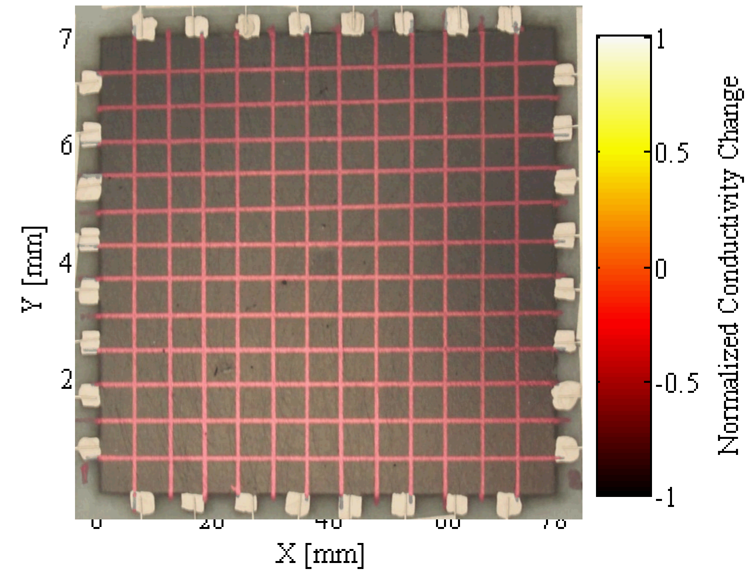
- Reconstructs small σ changes:
  - Typically difference imaging
    - $\sigma_1 - \sigma_2 << \sigma_2$
- Maximum a posteriori (MAP):
  - H: sensitivity matrix

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

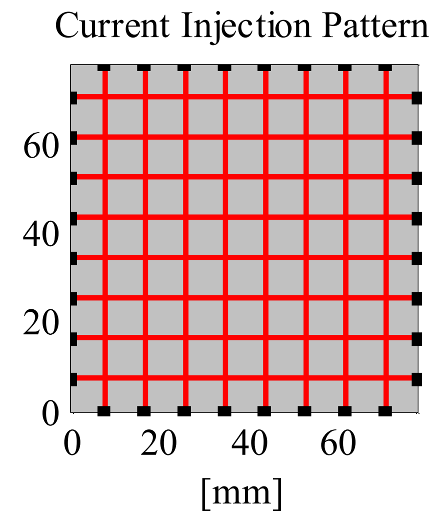
$$\frac{\Delta\sigma}{\sigma_0} = \left(H^T W H + \lambda R\right)^{-1}\left(H^T W\right)\frac{\Delta V}{V_0}$$

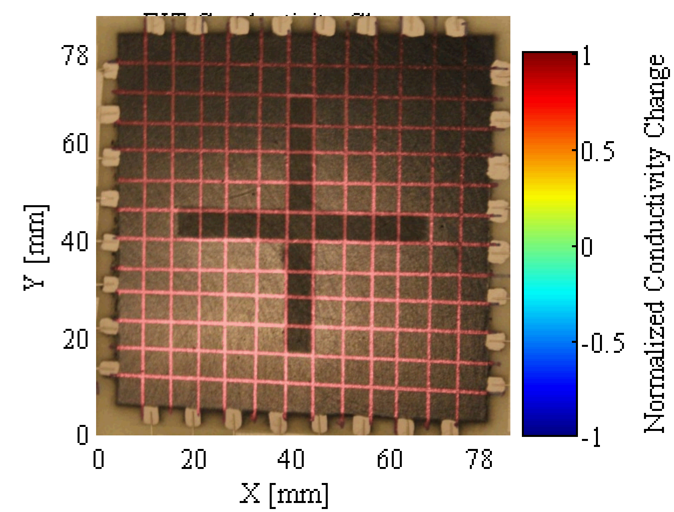
$$\frac{\Delta\sigma}{\sigma_0} = B\Delta\frac{\Delta V}{V_0}$$



Validation EIT

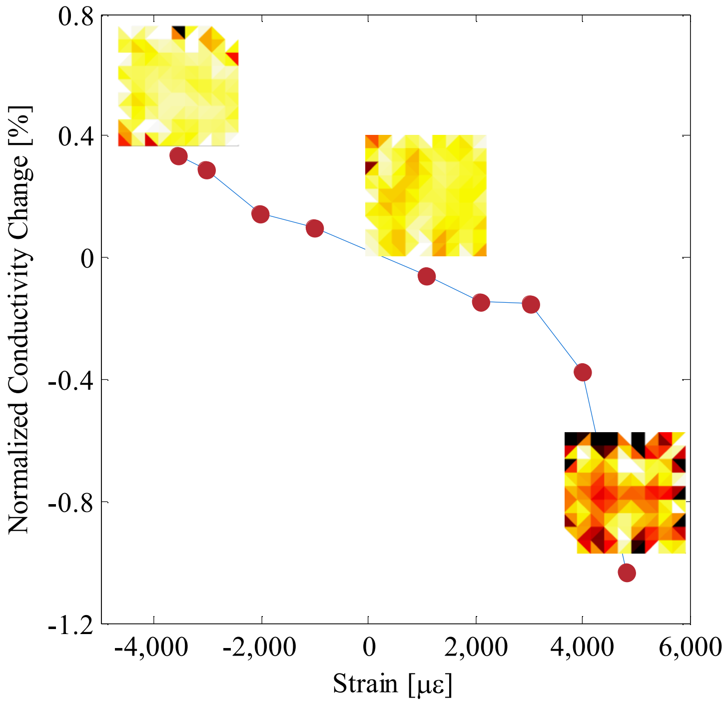
- Applied sensing measurements
  - MWNT-Latex deposited upon cured GFRP composites
  - 78 mm x 78 mm sensing region
  - 8x8 electrodes scheme = 32 electrodes
    - 3 mm electrodes
    - 6 mm spacing
- Investigate stability and efficiency:
  - Computational demand
    - ~ 1 s reconstruction time
- Accuracy characterization:
  - Conductivity:
    - Point-to-point resistance map via 4-pt probe
  - Spatial feature ID sensing resolution
    - ~ 6 mm cross at center with -50% Δσ

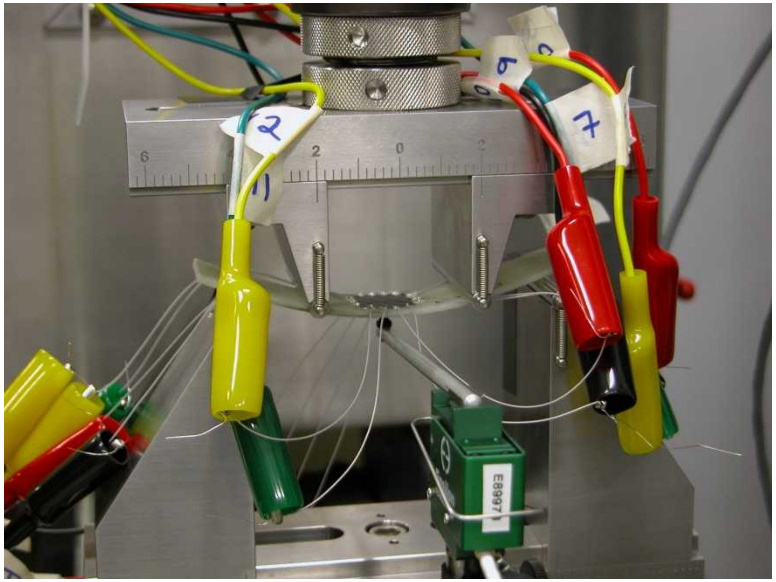




Spatial Strain Sensing

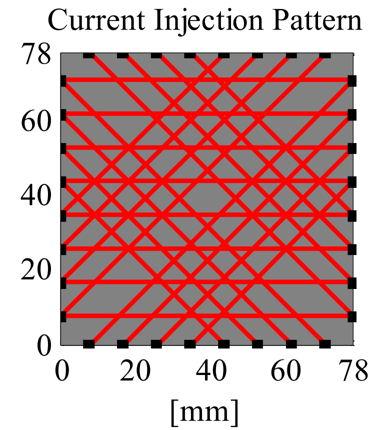
- 4-pt bending
  - **ASTM D7264**
  - MWNT-Latex on GFRP
  - Stepped displacement profile
  - Tensile/compressive strain
- Strain sensitivity
  - Nearly linear

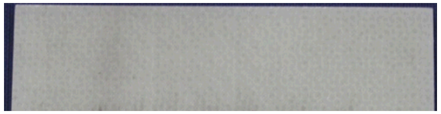


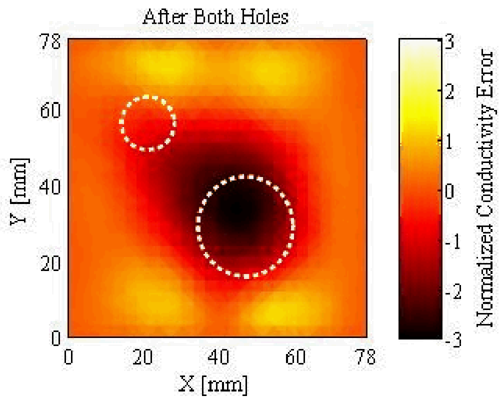


Embedded Spatial Sensing

- 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
  - $\nabla \cdot (\sigma \nabla \phi) = 0$

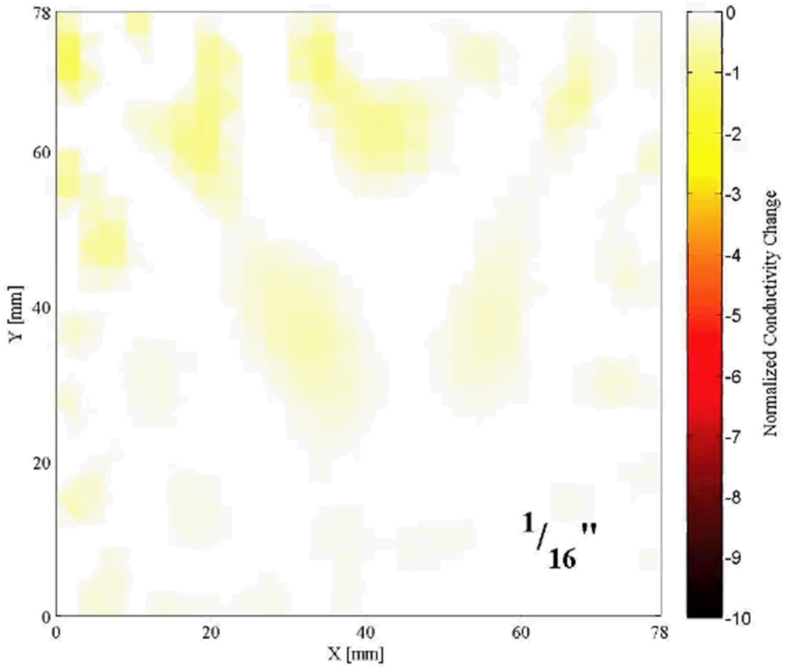


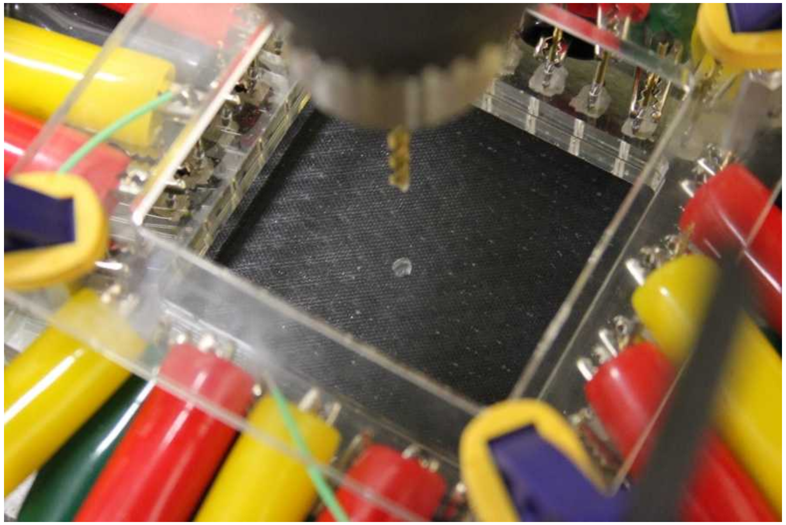




Embedded Spatial Sensitivity

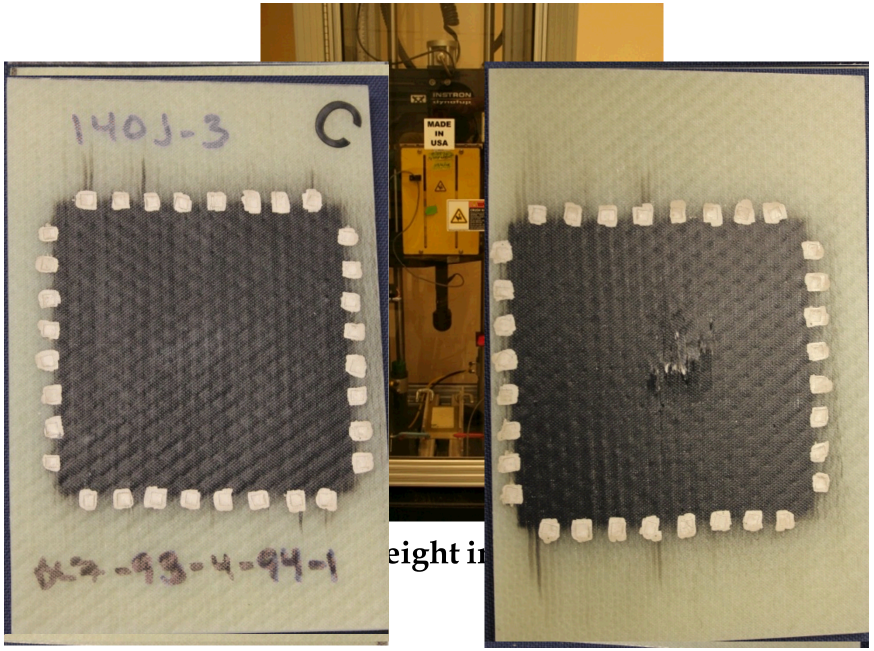
- Embedded sensing validation:
  - Determine conductivity change sensitivity
  - Process:
    - Progressively larger drilled holes:
    - $^1/_{16}$", $^1/_8$", $^3/_{16}$", $^1/_4$", $^5/_{16}$", $^3/_8$", $^1/_2$"
  - Anisotropic EIT performed
    - Conductivity change from pristine sample

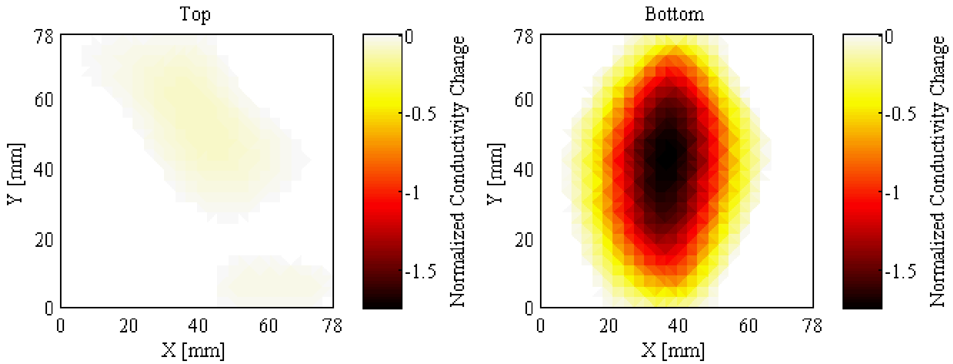




Impact Damage Detection

- 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!

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Questions?

Acknowledgements:

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NATIONAL INSTITUTE FOR NANO ENGINEERING (NINE)

CITRIS Center for Information Technology Research in the Interest of Society

NSF National Science Foundation WHERE DISCOVERIES BEGIN