SAND2014-2855P

Exceptional service in the national interest

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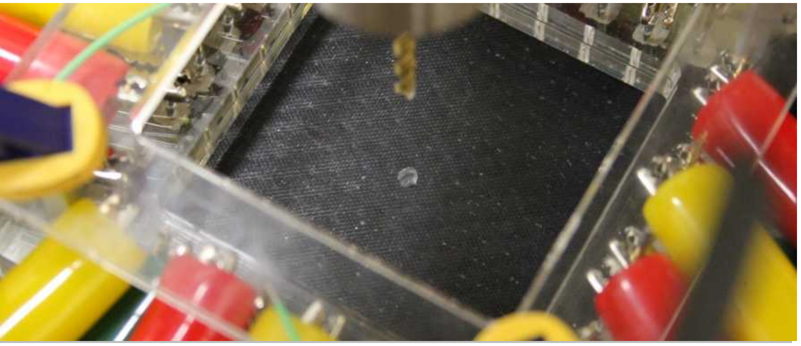

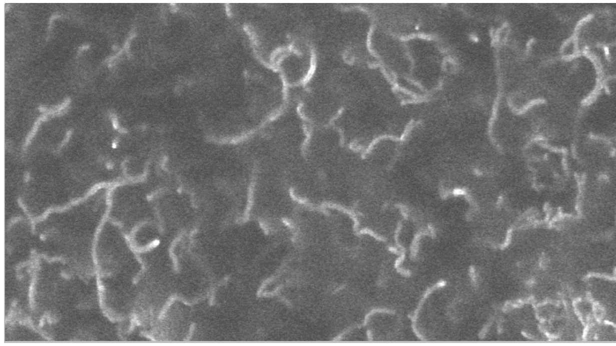

Spatially Distributed Structural Health Monitoring using Electrical Impedance Tomography

Bryan R. Loyola, Steven Paradise, and Christopher Hall

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

U.S. DEPARTMENT OF ENERGY

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NNSA National Nuclear Security Administration

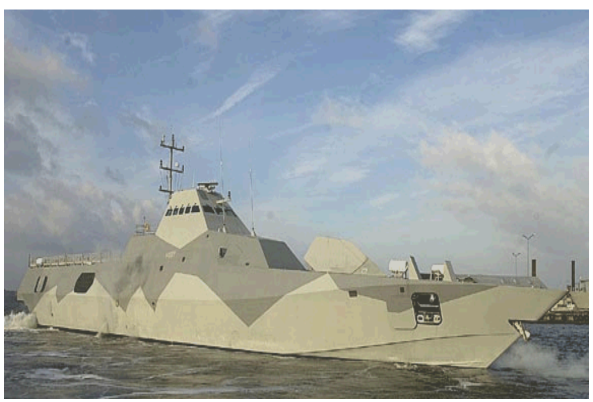
Usage of Fiber-Reinforced Composites

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

Commercial aircraft systems

Future and legacy spacecraft

Military aircraft



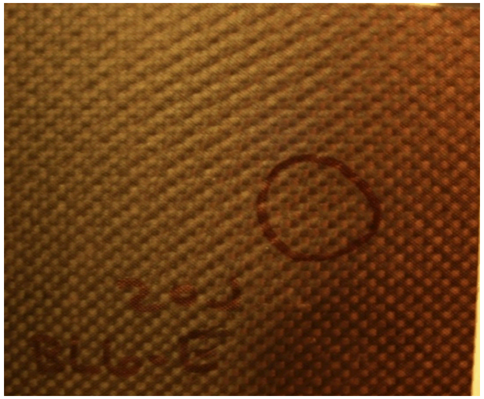
Naval structures

Wind turbine blades

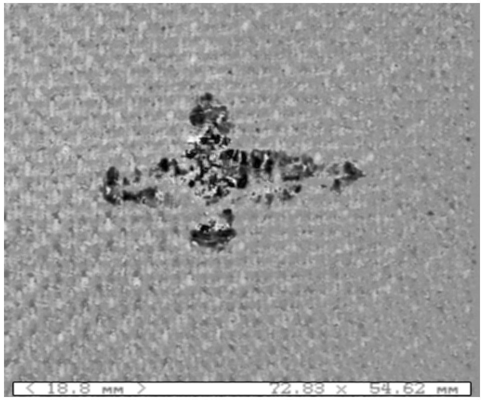
CFRP cable stay bridge

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

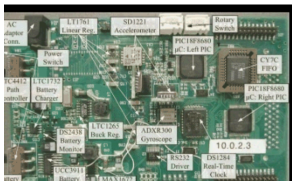
CFRP panel after 20 Joule impact

Aircraft ultrasonic inspection (Composites World)

Emerging Sensing Technologies

Sandia National Laboratories

Wireless Sensors and Sensor Networks

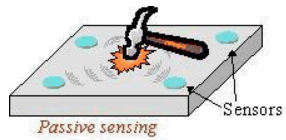


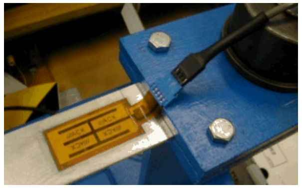
WiMMS
Wang, *et al.* (2008)

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

- **Advantages:**
  - Low Cost
  - Dense instrumentation
  - Reconfigurable
- **Disadvantages**:
  - Point sensors
  - In direct damage detection
  - Physics-based models

Ultrasonics and Guided-Waves

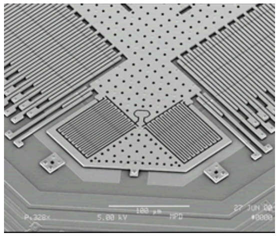


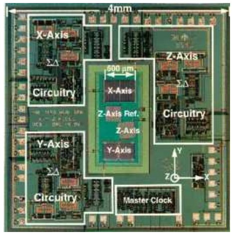


Array of piezoelectric ceramic sensors and actuators

- **Advantages:**
  - Sensors and actuators
  - Spatial damage detection
- **Disadvantages:**
  - Indirect damage detection
  - Wave propagation models or pattern recognition
  - Thin 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

Successful SHM systems:

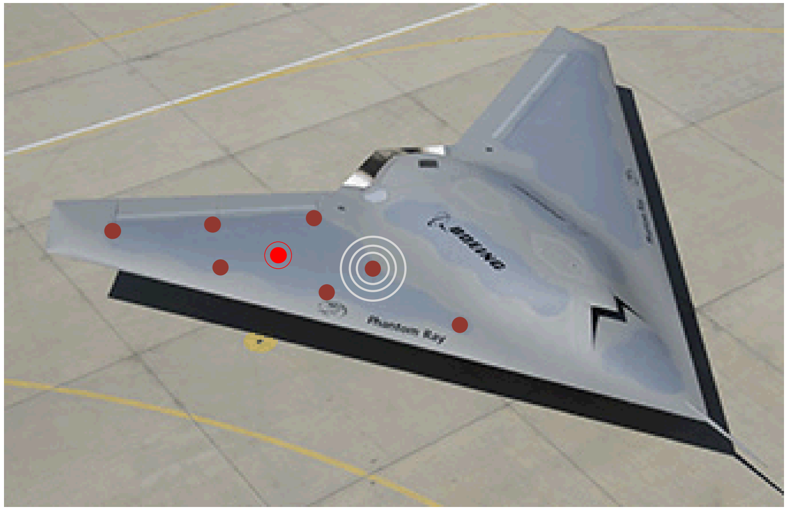
1. Directly detect and measure damage
2. Determine the damage location
3. Ascertain the size of the damage
4. Quantify the severity of the damage
5. Achieve multi-modal sensing capabilities (i.e., delamination, cracking, and chemical penetration)

Boeing 787 (Boeing)

Golden Gate Bridge (Wikipedia)

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

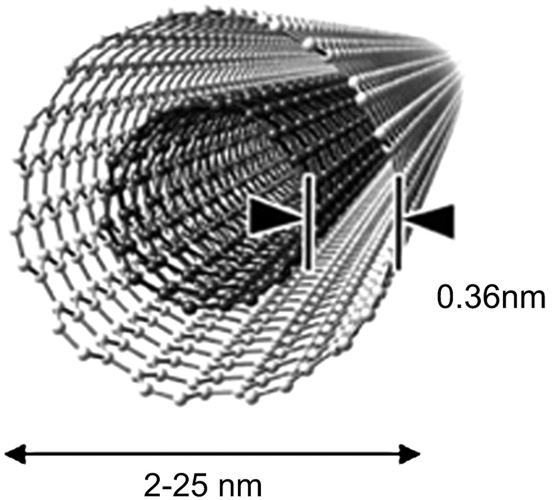


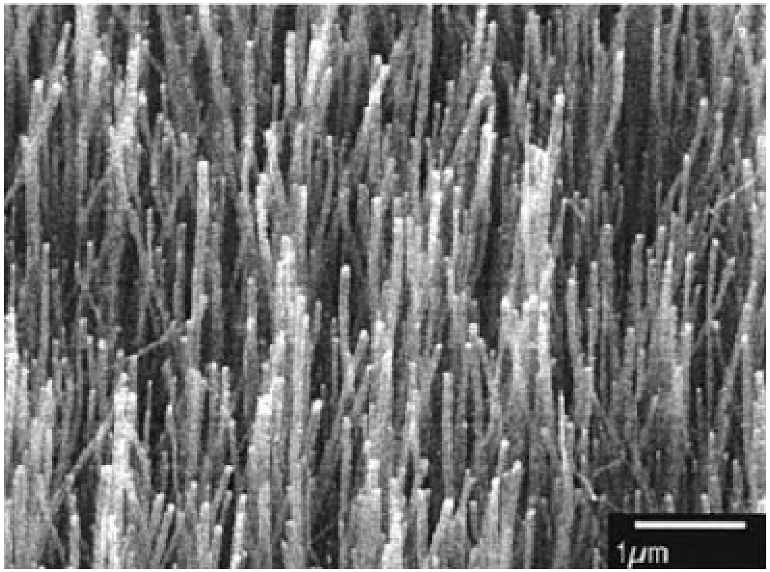
(Boeing)

(Boeing)

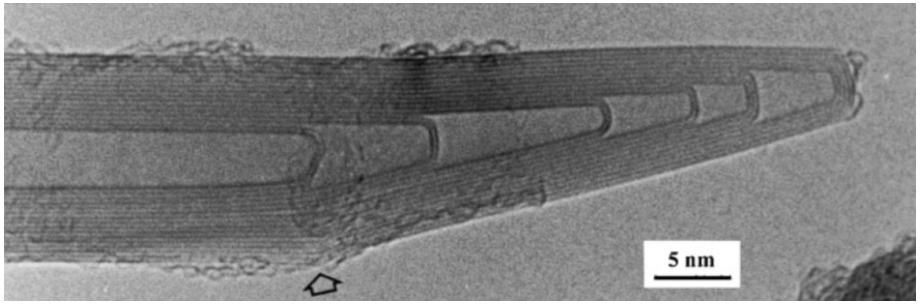
Carbon Nanotubes

- 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





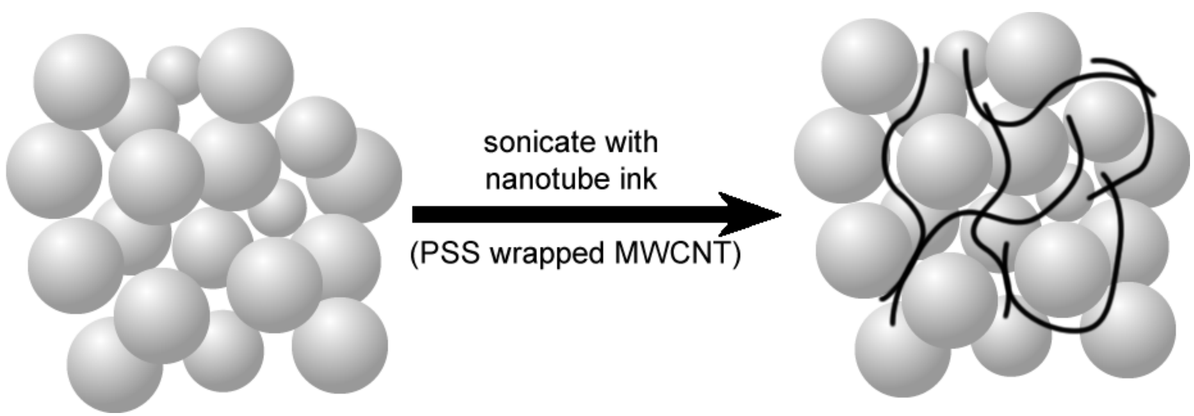
Aligned carbon nanotube forest
Thostenson, et al. (2001)



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

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



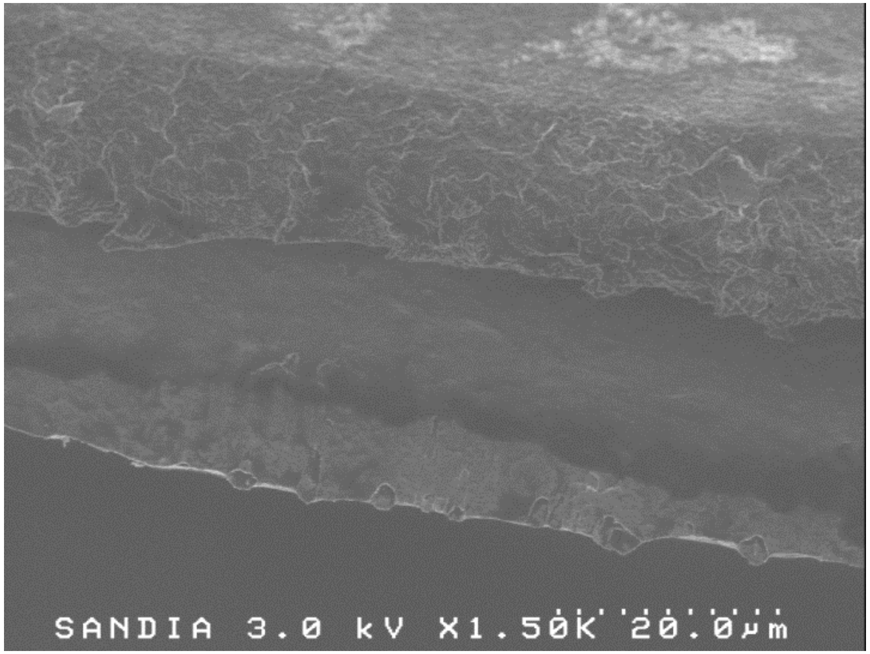
Kynar Aquatec™ latex solution (avg. particle size 150nm)

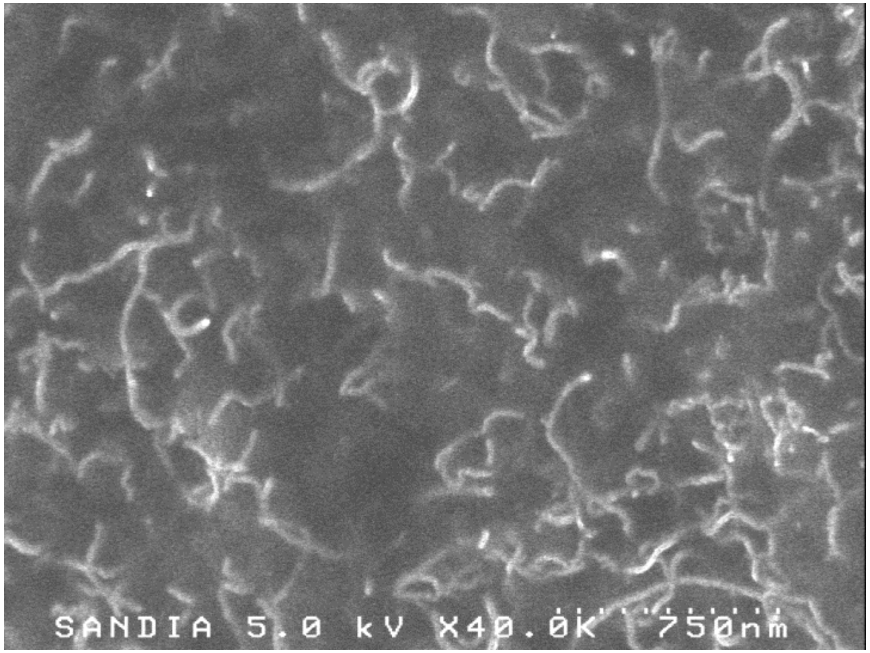
Forms segregated MWCNT network

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

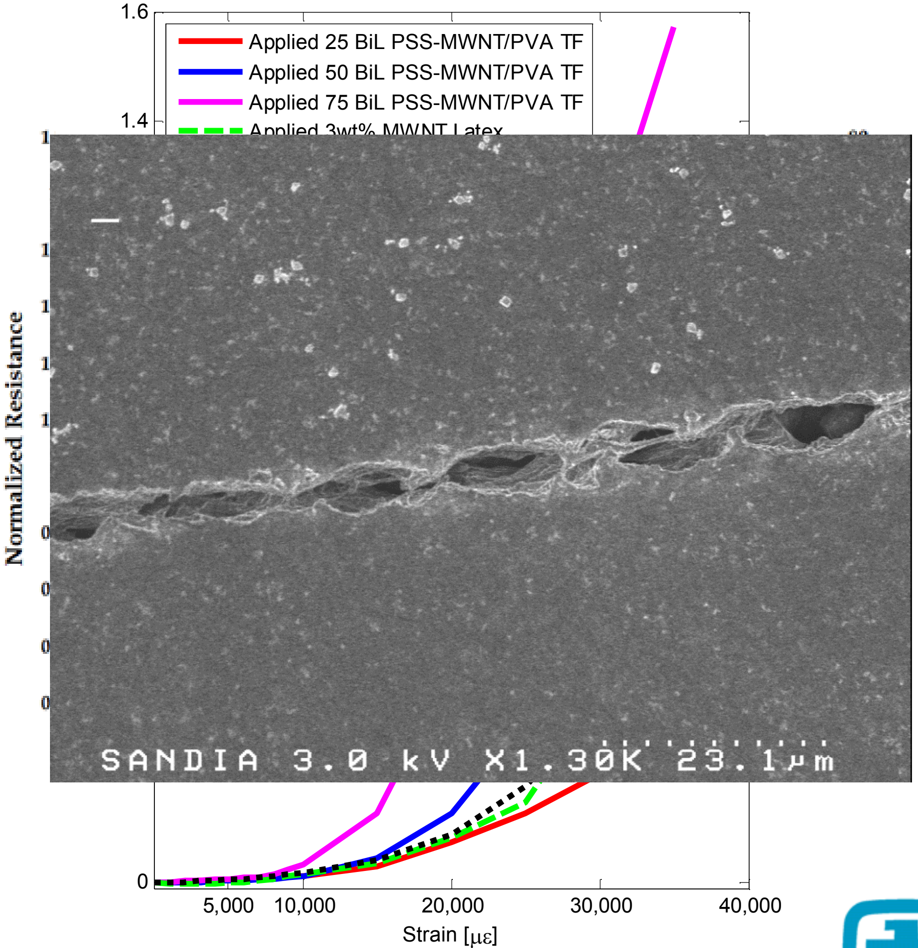




Cross-section and MWNT network SEM images of 3wt% MWNT-Latex film

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



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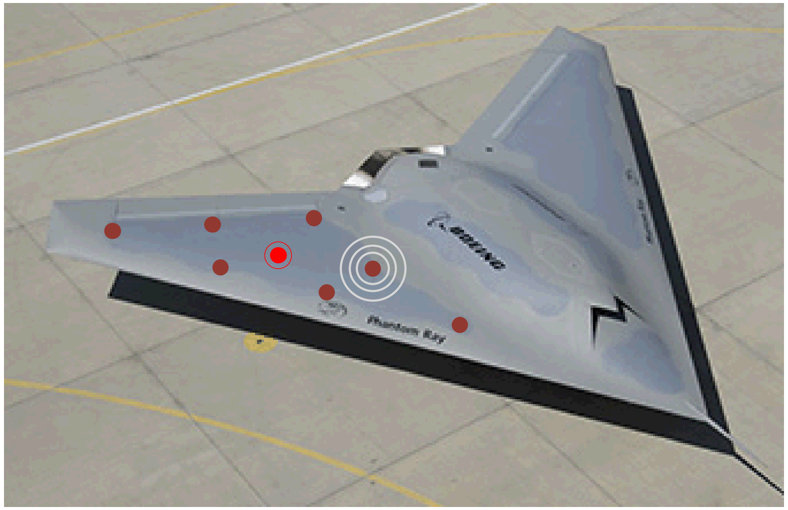
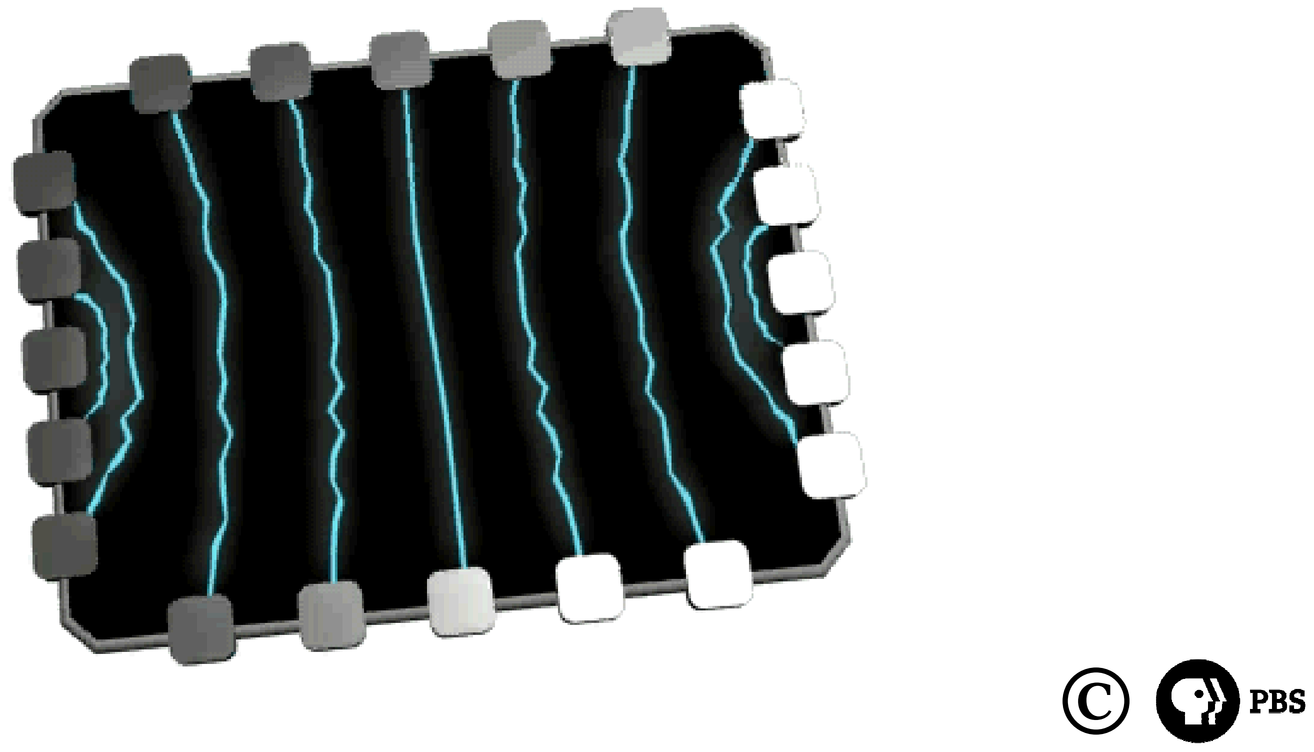


(Boeing)

(Boeing)

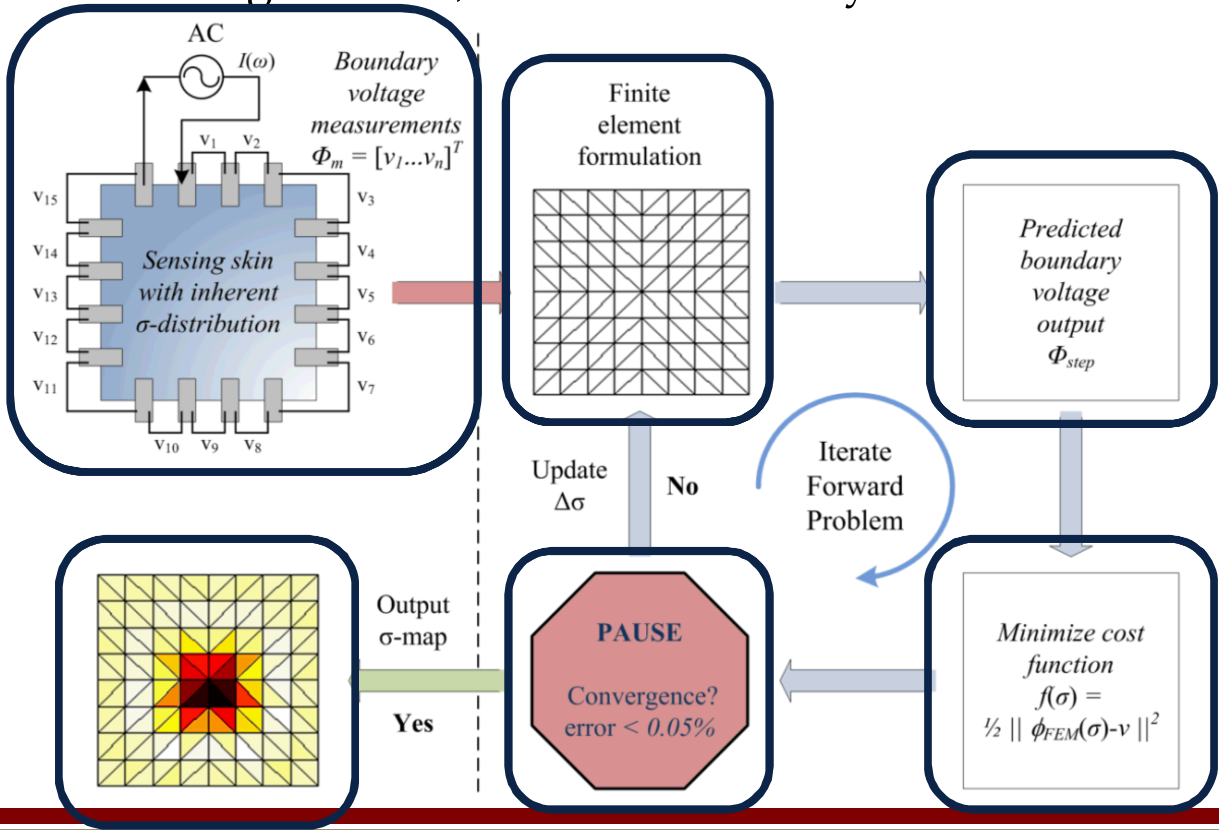
Electrical Impedance Tomography

- 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

Sandia National Laboratories

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

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

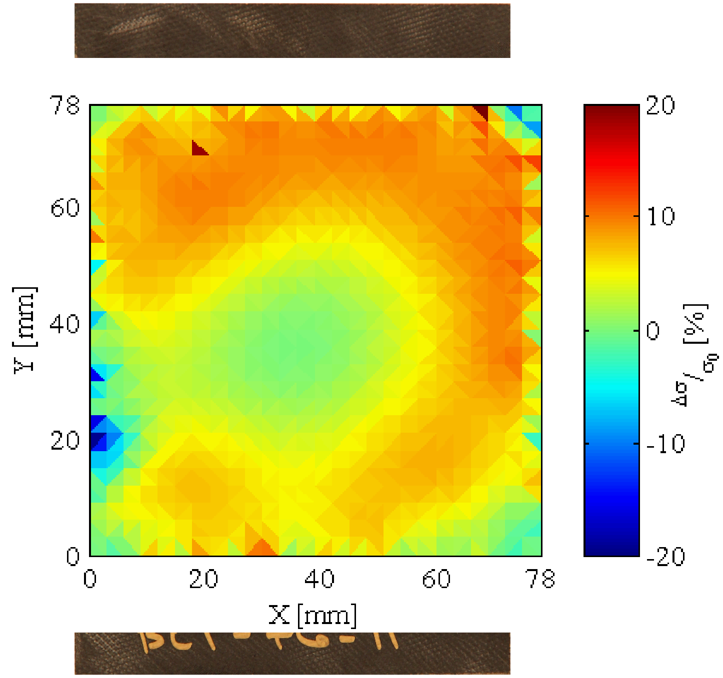
  - Regularization hyperparameter: λ
    - Noise figure

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

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

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

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



Applied Spatial Sensing

Spatially Distributed Sensitivity

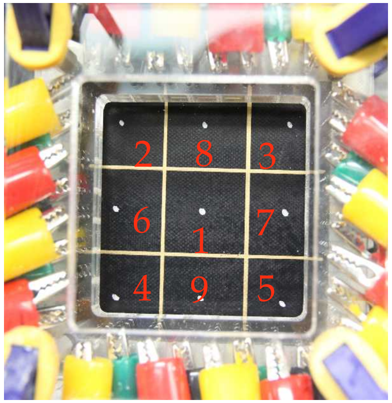
- Understand sensitivity to prescribed damage w.r.t. spatial position in sensing area
- 9 holes distributed across specimen
- 6.35 mm diameter

Spatially Distributed Strain Sensitivity

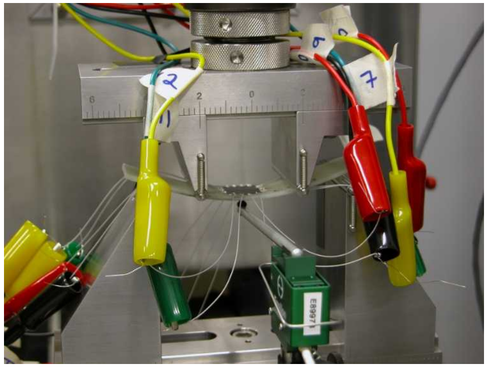
- 4-pt bending specimens
  - Homogeneous strain between inner supports
- Tensile and compressive strain values
- Small changes in conductivity

Damage Size Sensitivity

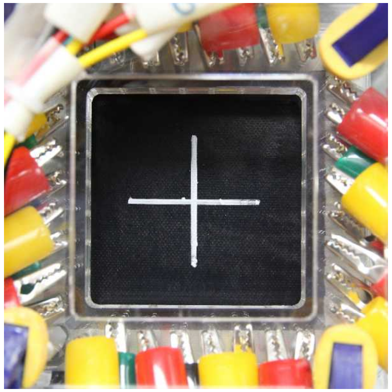
- Understand sensitivity to increasing damage at center of specimen
- Least sensitivity point in sensing region
- 6 progressively larger holes
  - $^1/_{16}$″, $^1/_8$″, $^3/_{16}$″, $^1/_4$″, $^5/_{16}$″, $^3/_8$″



Spatially Distributed Sensitivity Specimen



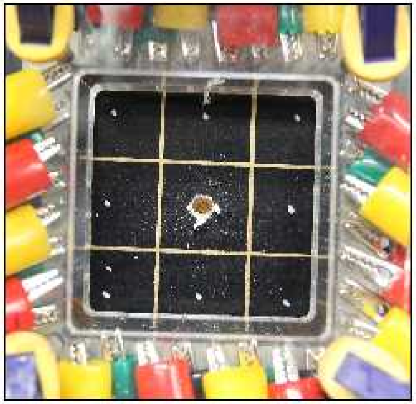
Spatially Distributed Strain Sensitivity Specimen



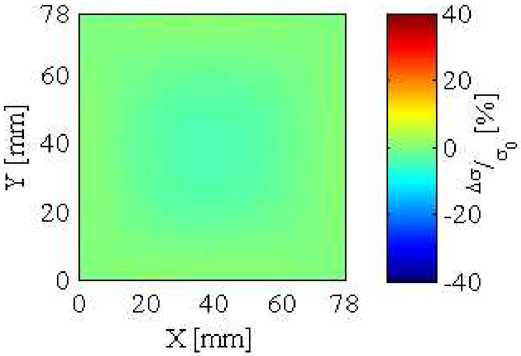
Damage Size Sensitivity Specimen

Spatially Distributed Sensitivity

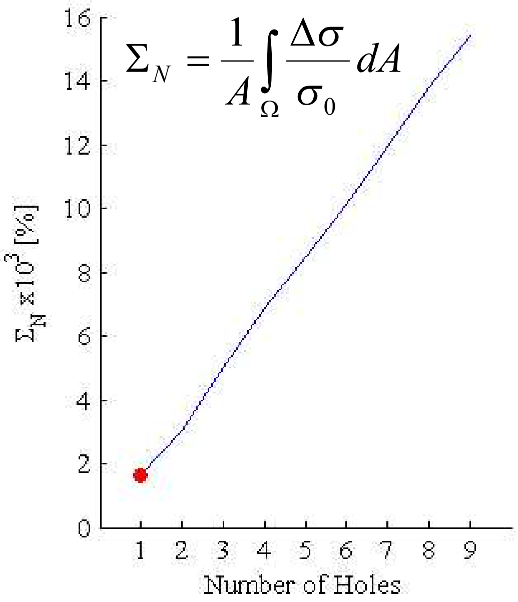
- EIT Response
  - Consistent cumulative amplitude response
    - Linear response to increasing sustained damage
  - Further from center, response more disperse
    - Mean response at correct damage location



Specimen



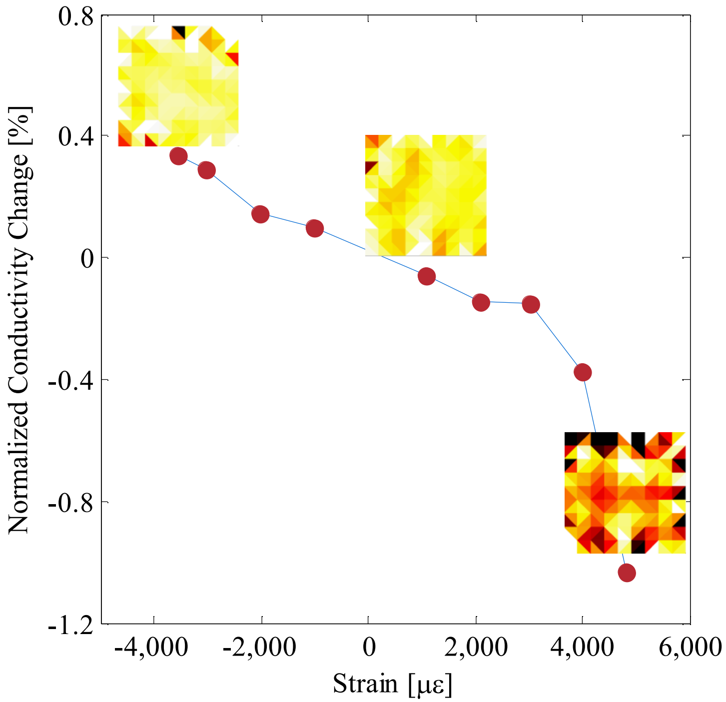
EIT Response

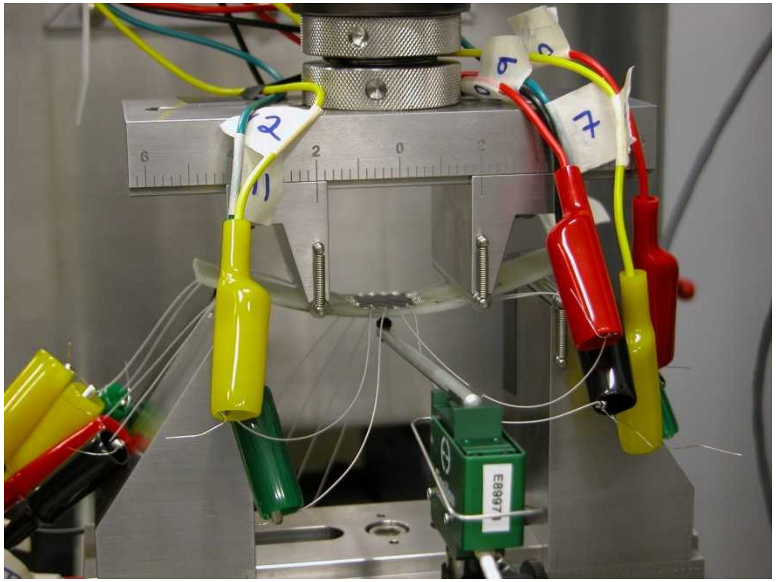


Damage Metric

Spatial Strain Sensing

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

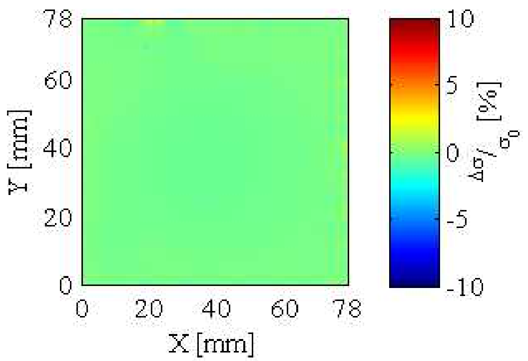




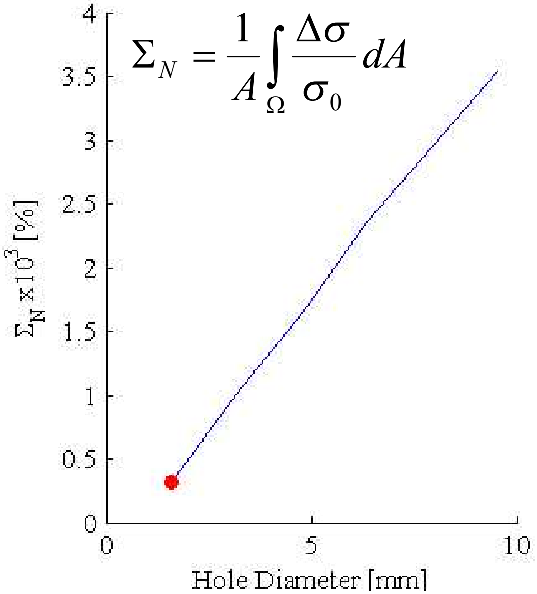
Damage Size Sensitivity

- EIT Response
  - Increasing EIT response to increasing damage size
    - Nearly linear response to size
  - EIT response at corresponding location to damage but response size is exaggerated

Specimen



EIT Response

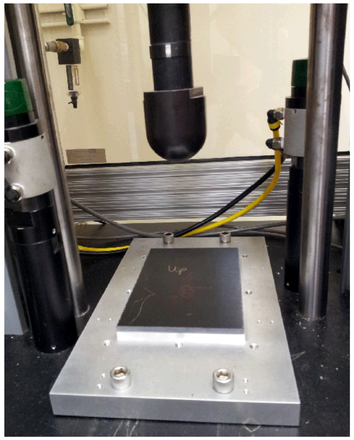


Damage Metric

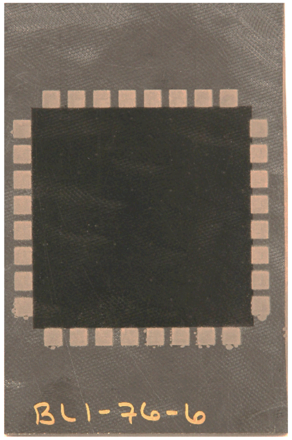
Impact Damage Detection

- 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:
  - Photographic Imaging
    - Surface damage

Drop-weight impact tester



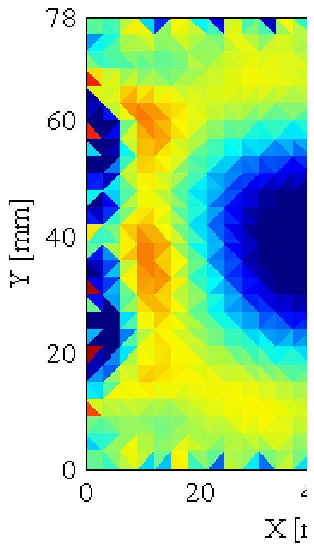
Impact setup



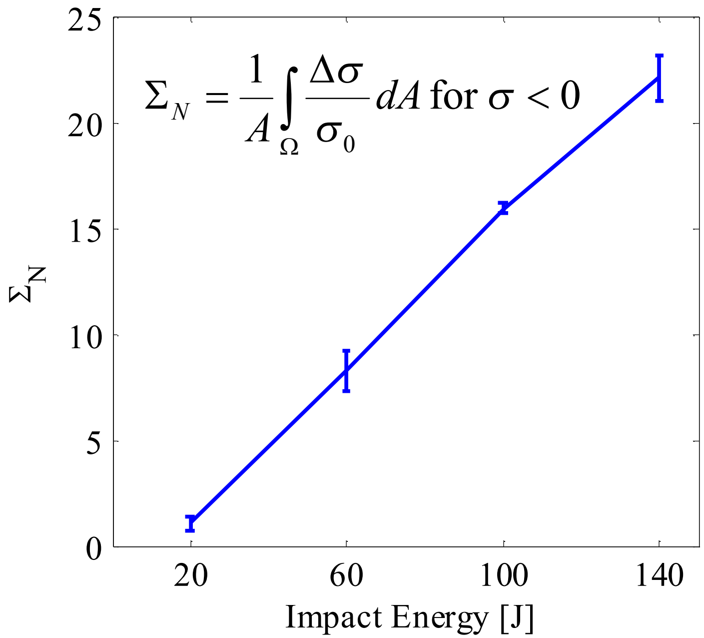
Impact specimen

Impact Damage Detection

- EIT reconstruction captures conductivity decrease in damaged region
  - Decreasing amplitude and increasing response region with increase in impact energy
- Linear response w.r.t. damage metric with good repeatability



EIT Response

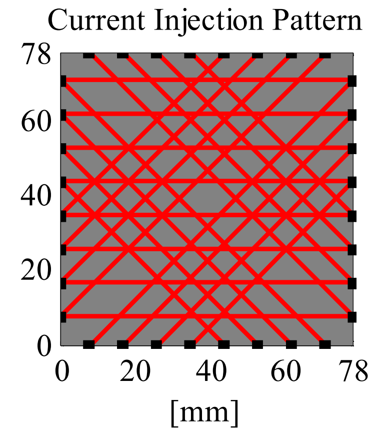


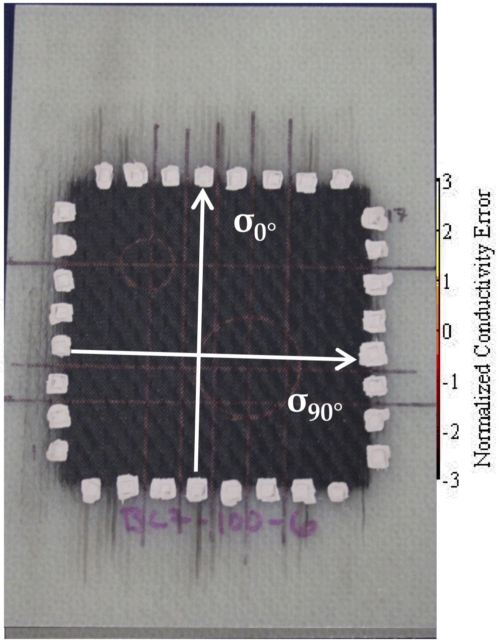
Plot of the damage metric versus impact energy

Opposite face of impacted specimen

Embedded Spatial Sensing

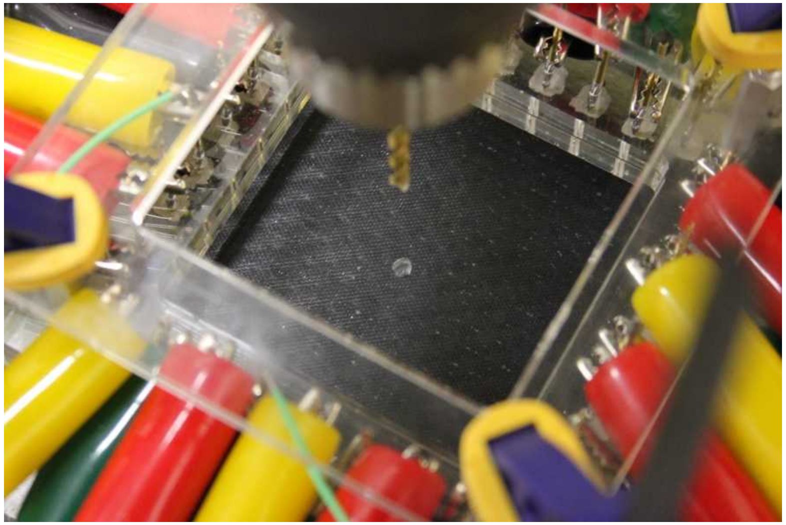
- Embedded sensing architecture
  - MWNT-Latex on GF fiber weave
  - Embedded within epoxy matrix
- Specimens
  - $[0^o/+45^o/90^o/-45^o]_{2s}$
  - Unidirectional GF
  - 150 mm x 100 mm
    - ASTM D7146 Standard
- Anisotropic EIT
  - Isotropic ► Anisotropic
  - Scalar ► Matrix: σ
  - $\sigma_{0°} > \sigma_{90°}$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

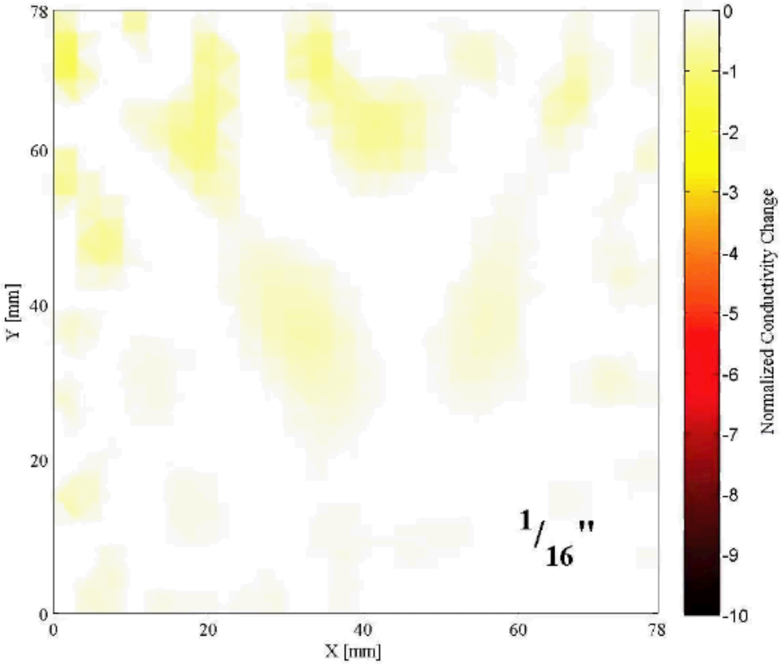




Embedded Spatial Sensitivity

- 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





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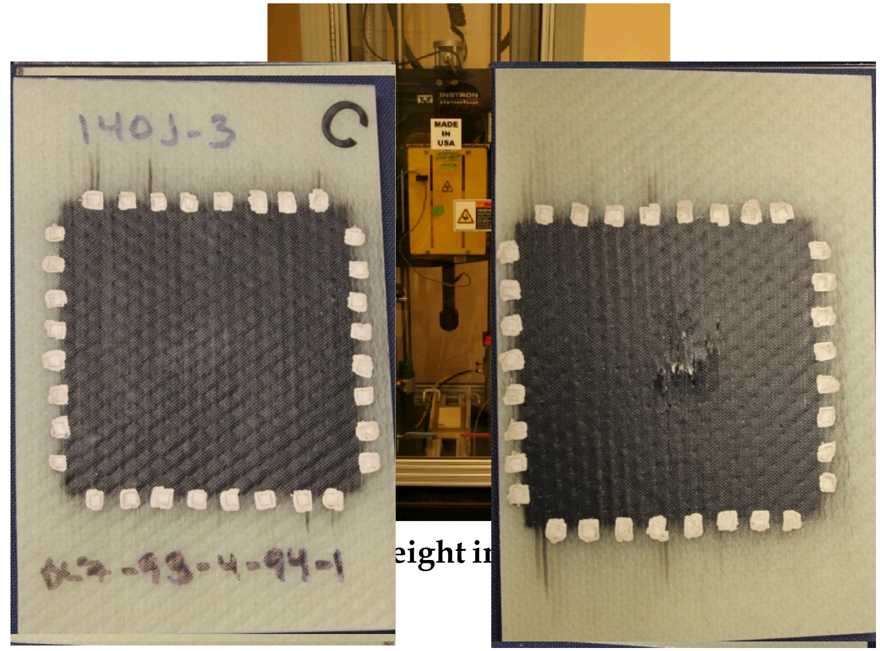
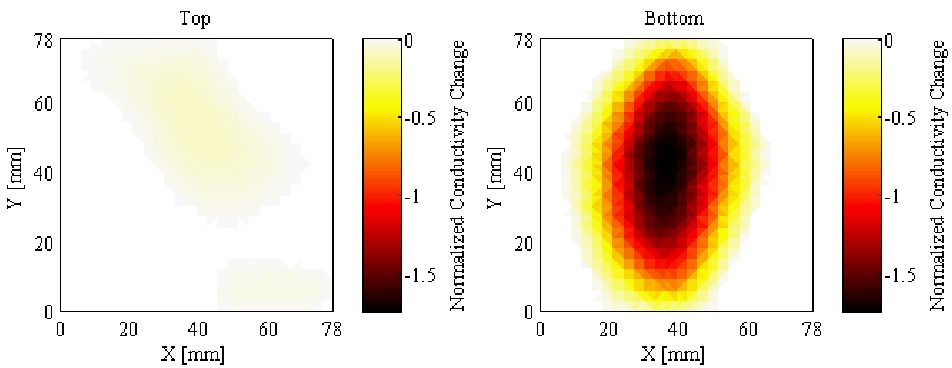
  - **ASTM D7146**
  - 78 mm by 78 mm sensing region
  - MWNT-latex on glass fiber weave
  - Impact energy: 20, 60, 100, 140 J
  - Before/after EIT measurements

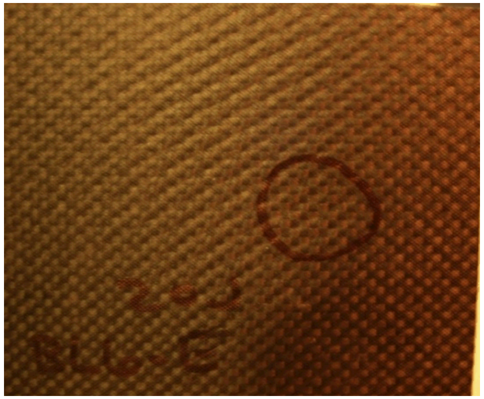
- Verification:
  - Thermography
    - Matrix Cracking
    - Delamination
  - Photographic Imaging
    - Surface damage



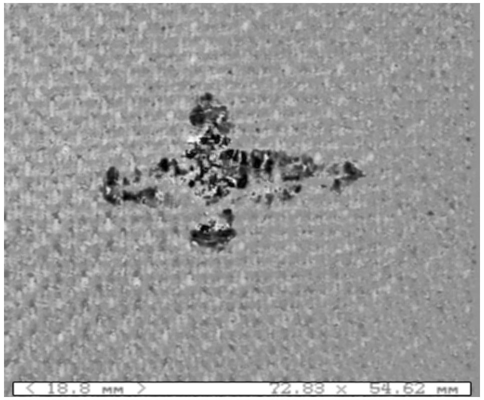


CFRP Damage Detection

- Carbon Fiber-Reinforced Polymers
  - High-strength-to-weight ratio applications
  - ~50% weight of Boeing 787
  - Primary structural material in SpaceShipTwo

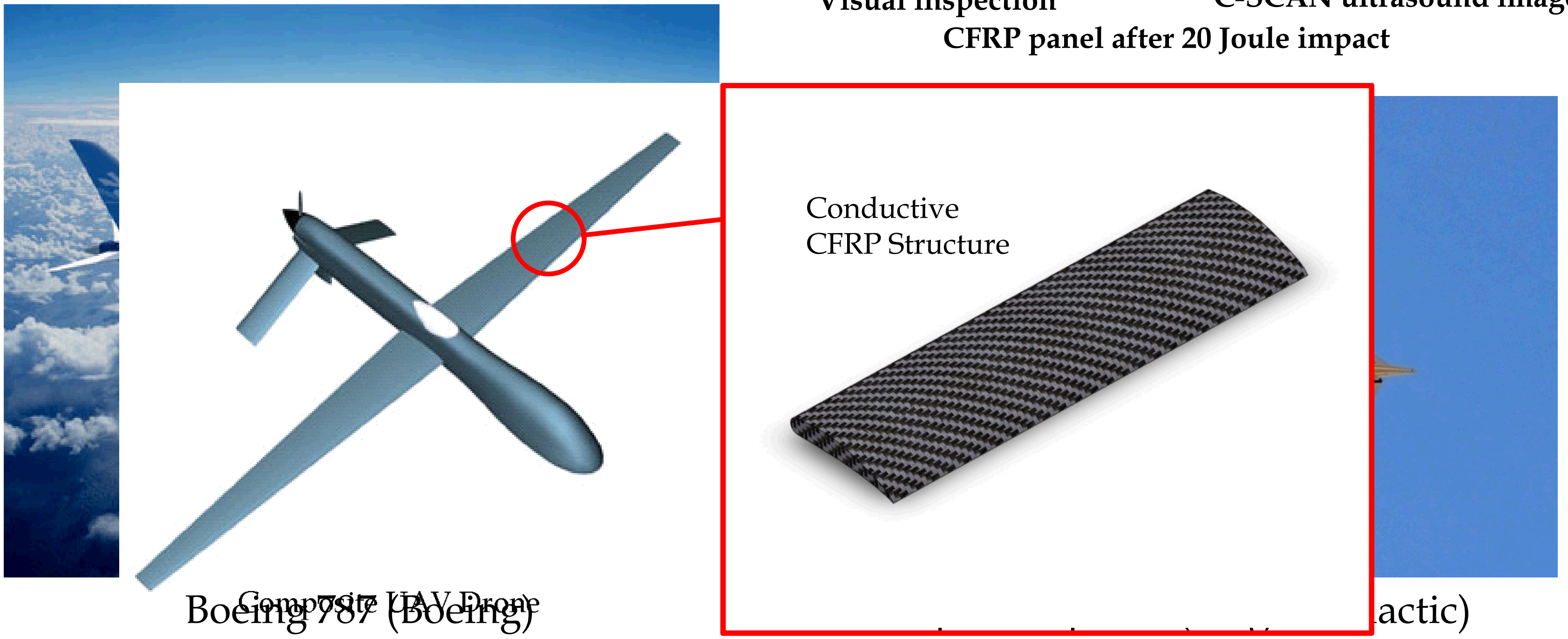


Visual inspection



C-SCAN ultrasound image

CFRP panel after 20 Joule impact



Composite UAV Drone

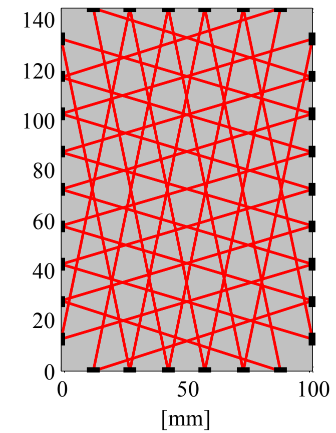
Boeing 787 (Boeing)

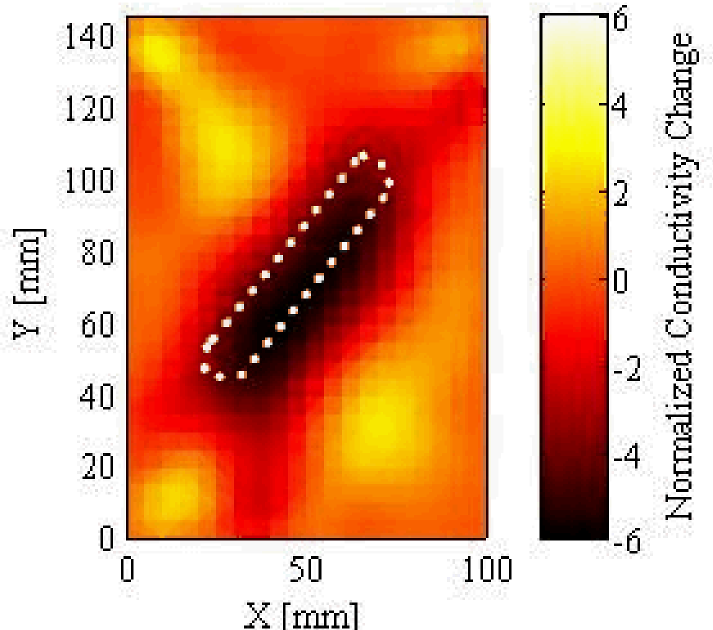
actic)

CFRP EIT Validation

- Applied sensing measurements
  - $[\pm 45, 0/90]_{8s}$ CFRP composite
  - 100 mm x 145 mm sensing region
  - 6 × 9 electrodes scheme = 30 electrodes
    - 5 mm electrodes
    - 10 mm spacing
  - Anisotropic material injection scheme
- Investigate stability and efficiency:
  - Computational demand
    - ~ 1 s reconstruction time
- Accuracy characterization:
  - Conductivity:
    - Known removal of material
  - Spatial feature ID sensing resolution
    - 6.3 mm diagonal line

Current Injection Pattern

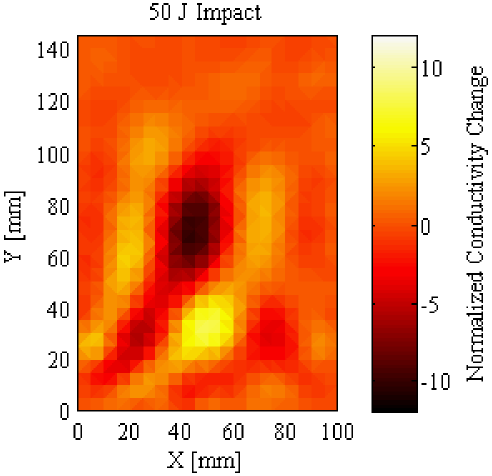




CFRP Impact Damage Detection

- Drop-weight impact tests
  - ASTM D7146
  - $[\pm 45, 0/90]_{8s}$ CFRP composite
  - 100 mm × 145 mm specimens
  - Impact energy: 20, 35, 50 J
  - Before/after EIT measurements

EIT Response



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
  - Response to temperature swings
- Outline validation of EIT for damage detection
  - Applied GFRP, embedded GFRP, and CFRP specimens
  - Strain sensitivity
  - Damage sensitivity
  - Impact damage

Thank You!

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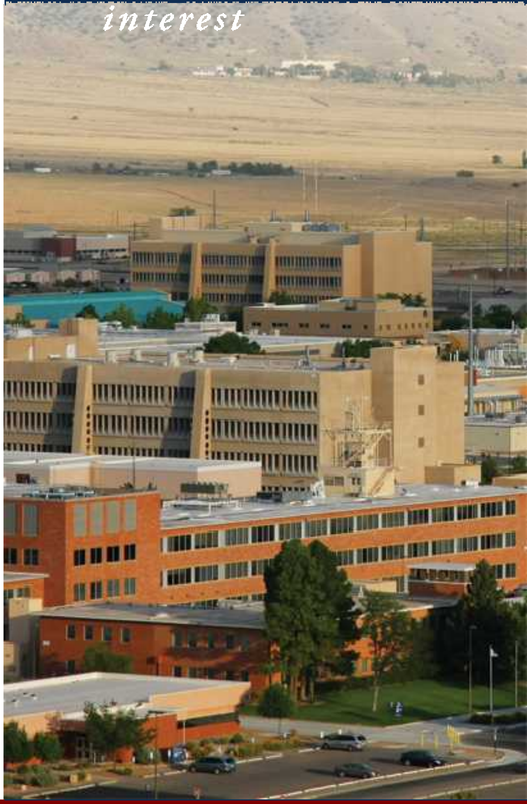

Questions?

Acknowledgements:

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