Performance Analysis for Carbon Nanotube (CNT) based SHM in Composite Structures

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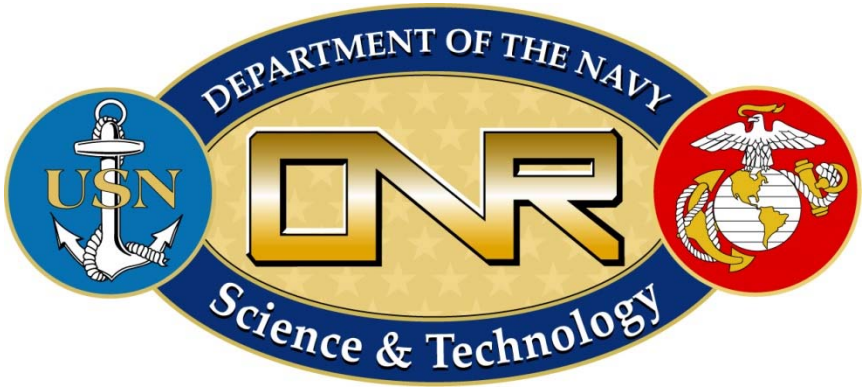

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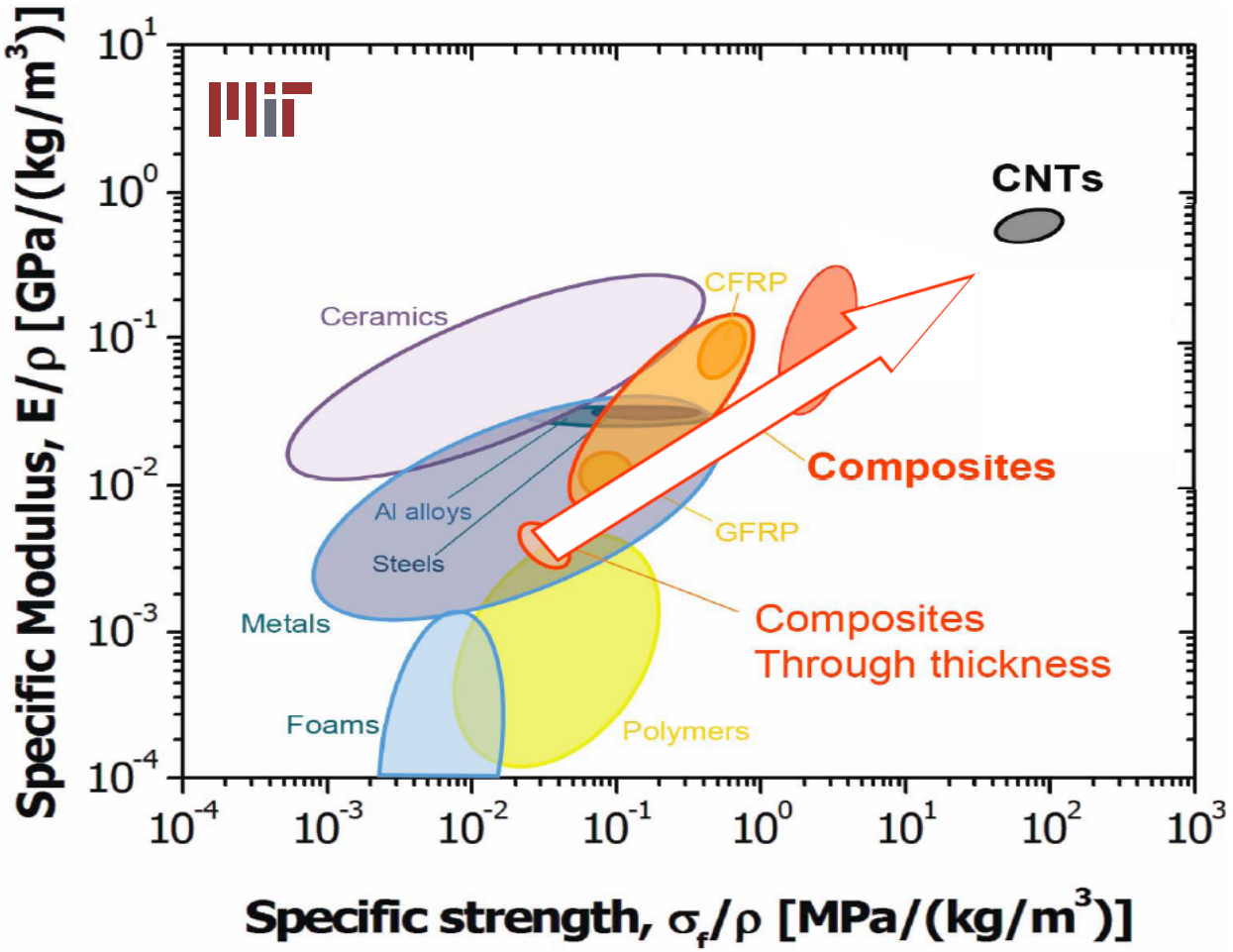
Carbon NanoTubes (CNTs)



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

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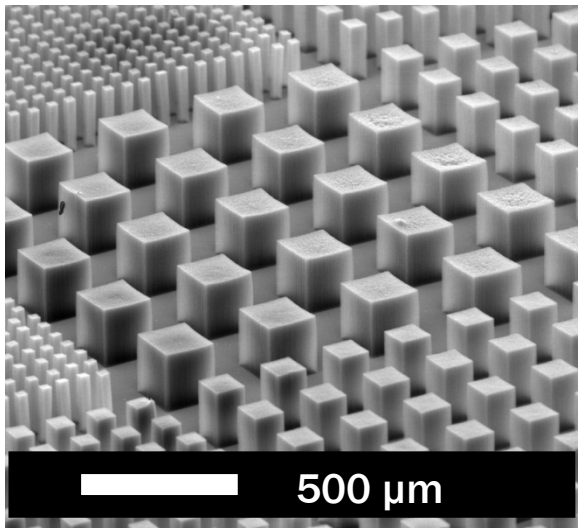
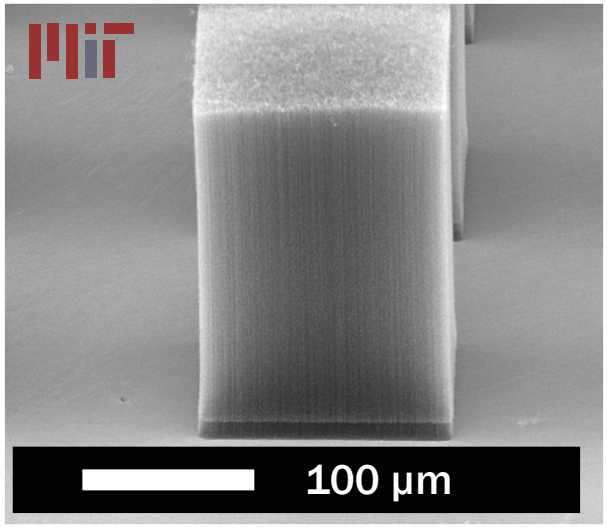
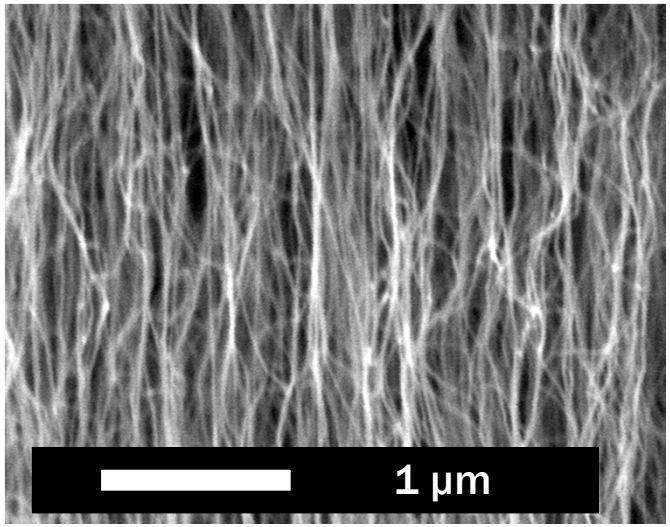
Aligned CNTs @ MIT







- MIT has developed a novel patented CNT fabrication process
  - CNTs grown radially aligned on fibers or on substrate to be transferred
  - good alignment, dispersion, adhesion & yields high CNT volume fraction

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

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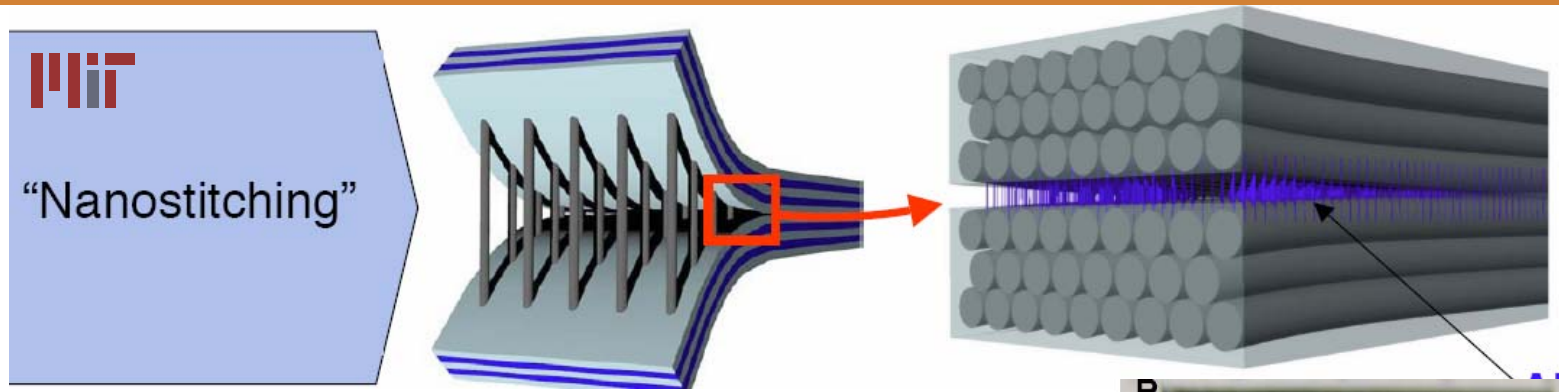
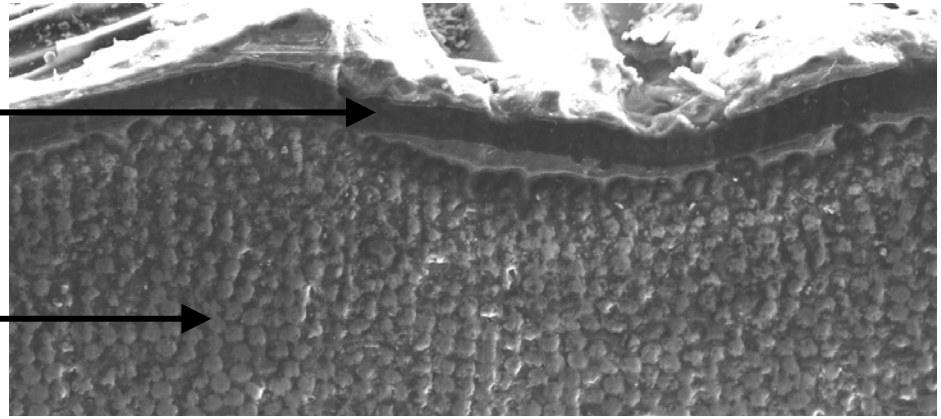
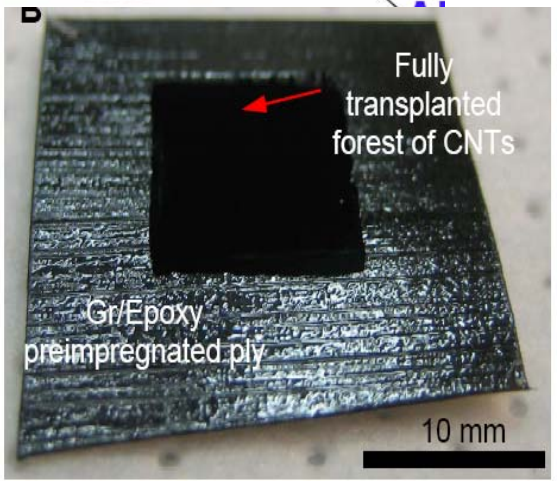
“Nanostitched” Composites







- Grow aligned CNTs on high-temperature substrate
- Transplant CNTs to pre-preg at RT or into composite post-cure
- Adds very little thickness (~30 μm) or mass (~5 g/m^2)

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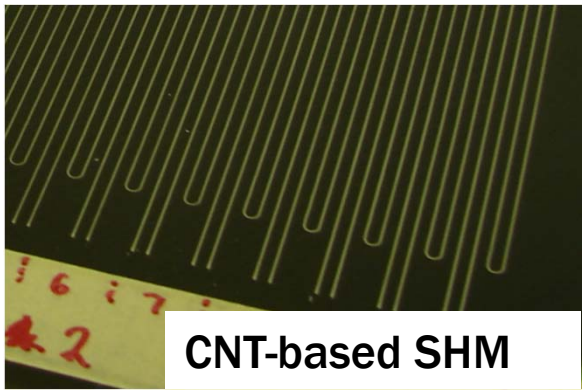
CNT Structural Health Monitoring

- **SHM improves reliability, safety & readiness @ reduced costs**
  - sensors add weight, power consumption & computational bandwidth
  - cables add weight, complexity, as well as durability & EMI concerns
  - scaling SHM for large-area coverage has presented challenges

- **Advantages of proposed CNT-based SHM methodology**
  - sensing elements actually improve specific strength/stiffness of structure
  - conformal direct-write (DW) or copper mesh electrodes lighter
  - simple to scale over large structure, maintains good local resolution

Traditional SHM



CNT-based SHM

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Coupon-Level Testing

- Prior experience with patterned silver traces
  - not all applications require such a fine pattern for localization
  - concerns about practicality and durability for DoD applications

- Series of experiments designed to calibrate effects of damage
  - close attention to design so that focus is on CNT, not electrodes or setup
  - representative types of failure predicted for composite components
  - observe trends in resistance changes with some statistical significance

- 3 types of tests selected
  - impact (falling weight on vertical linear sled)
  - notch (abrasive slitting saw)
  - 4-point bend (measured loaded & unloaded)

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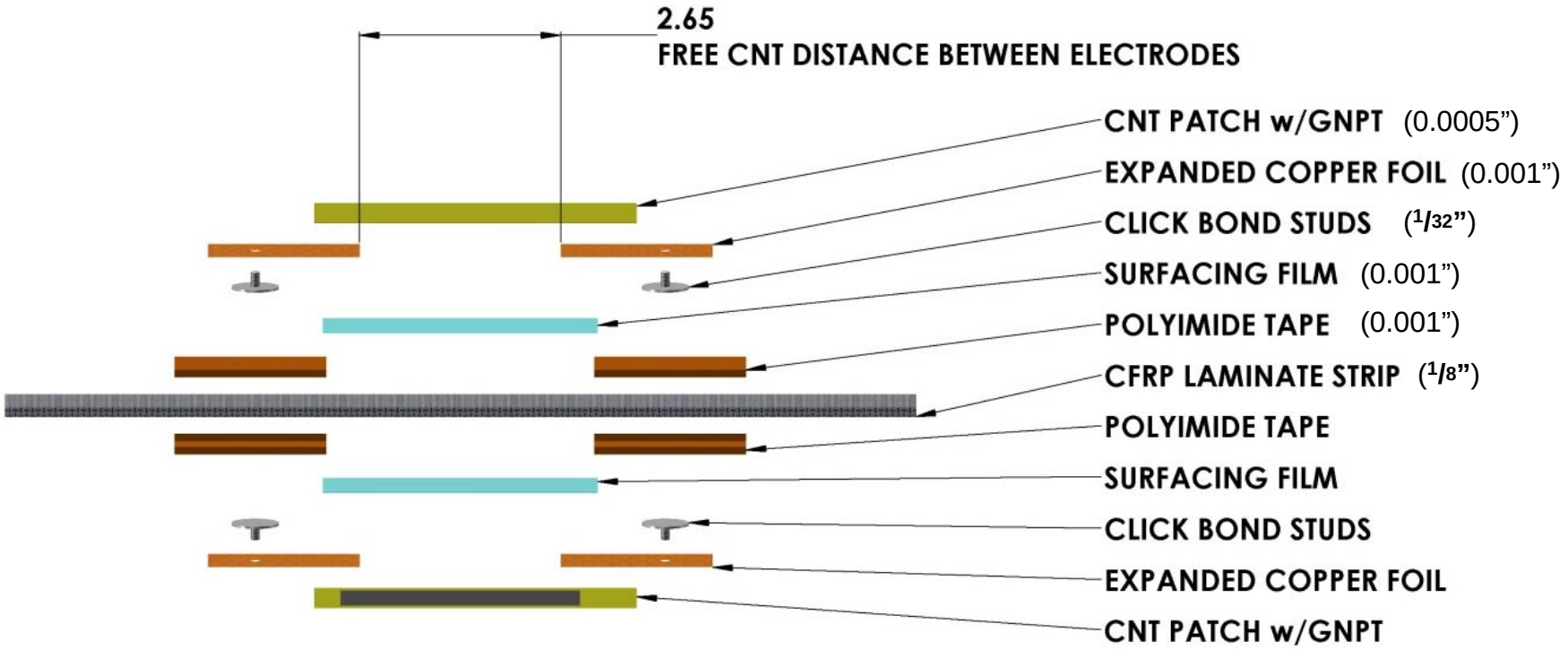
Calibrated Damage Detection Specimens



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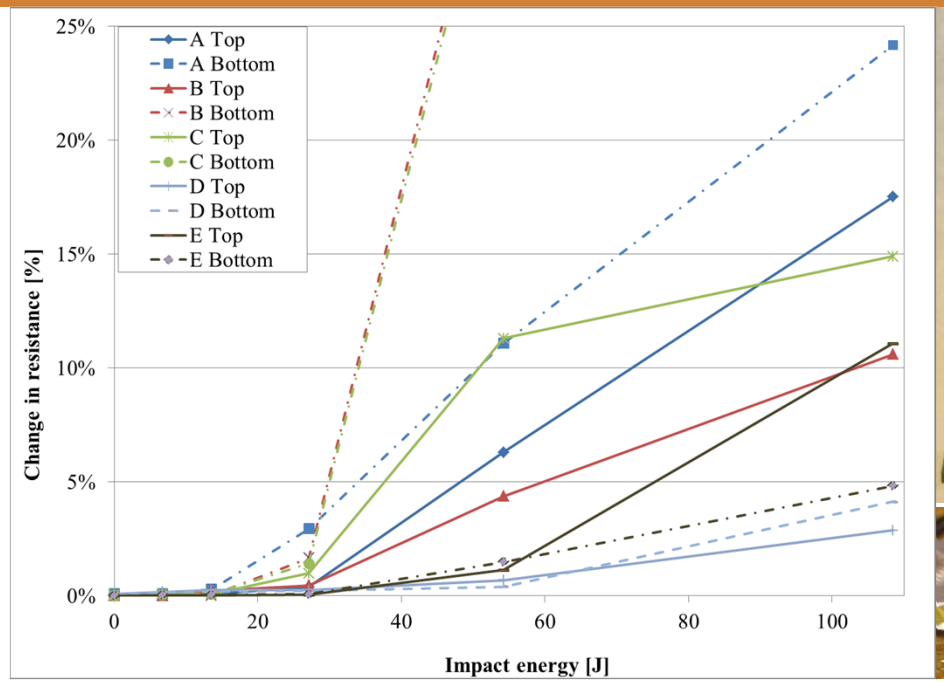
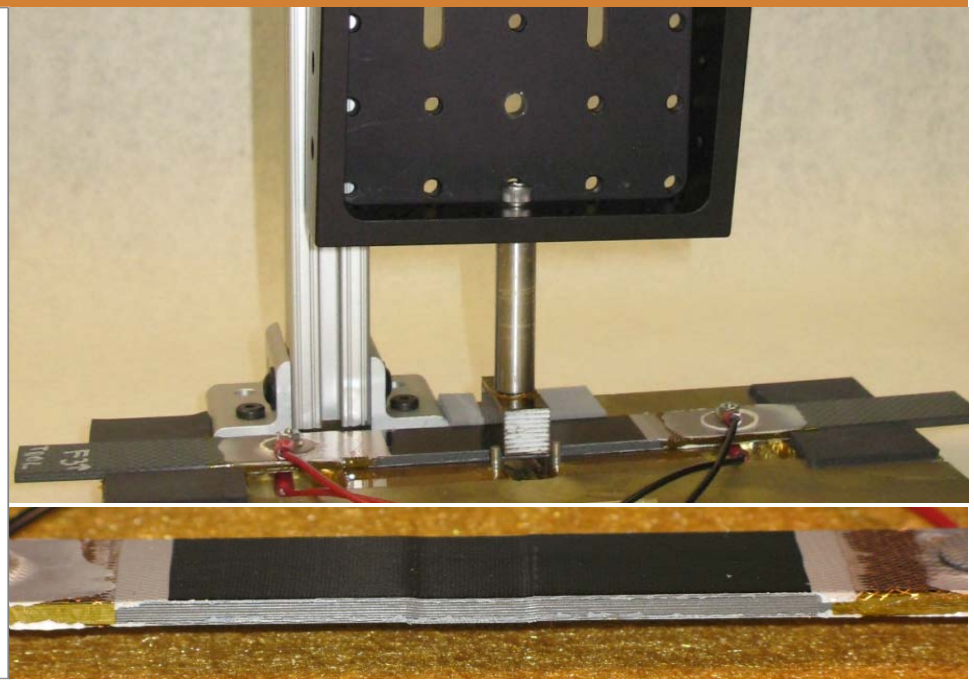
Impact Tests





- Impacts below threshold of 30 J had <0.25% change in resistance
  - impacted surfaces exhibited >1% change in resistance after 30 J impacts
  - majority of specimens showed increase of ~15% after 110 J impacts
  - possible to increase CNT monitoring patch length to 1 m with 0.1% change
- Variability due to impact events, could be observed in “dents” too

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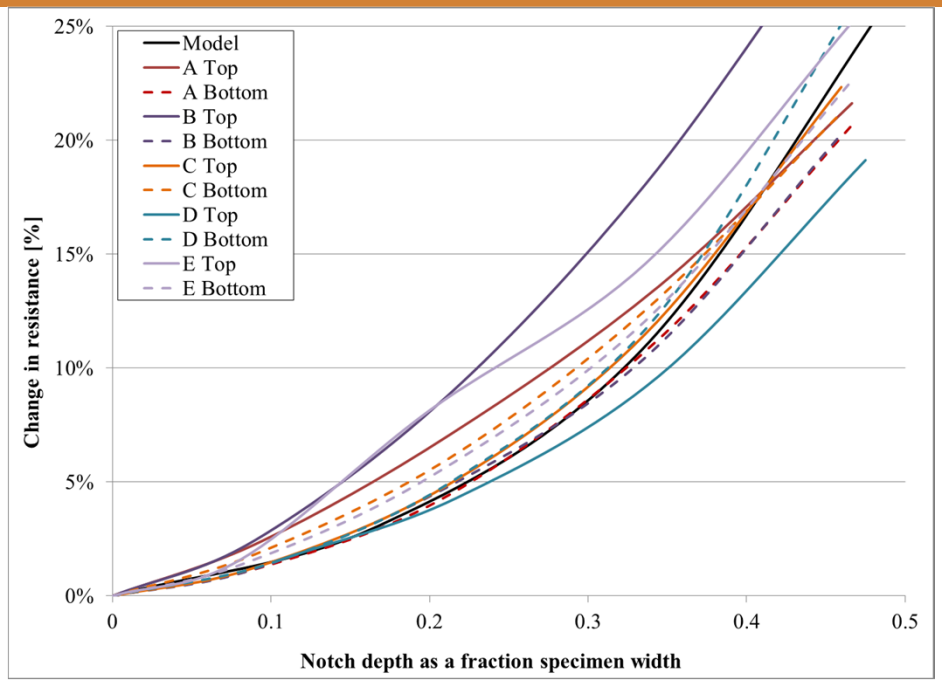
Notch-Cutting Tests



- Detection sensitivity strong function of CNT network aspect ratio
  - 2400 mm² CNT w/160 mm² damage yields ~25% in resistance increase
  - same damage in 1 m long strip of same width would yield ~2% change
  - 10 mm² damage would still be over noise floor
- Simple 2D network resistor model in good agreement with data

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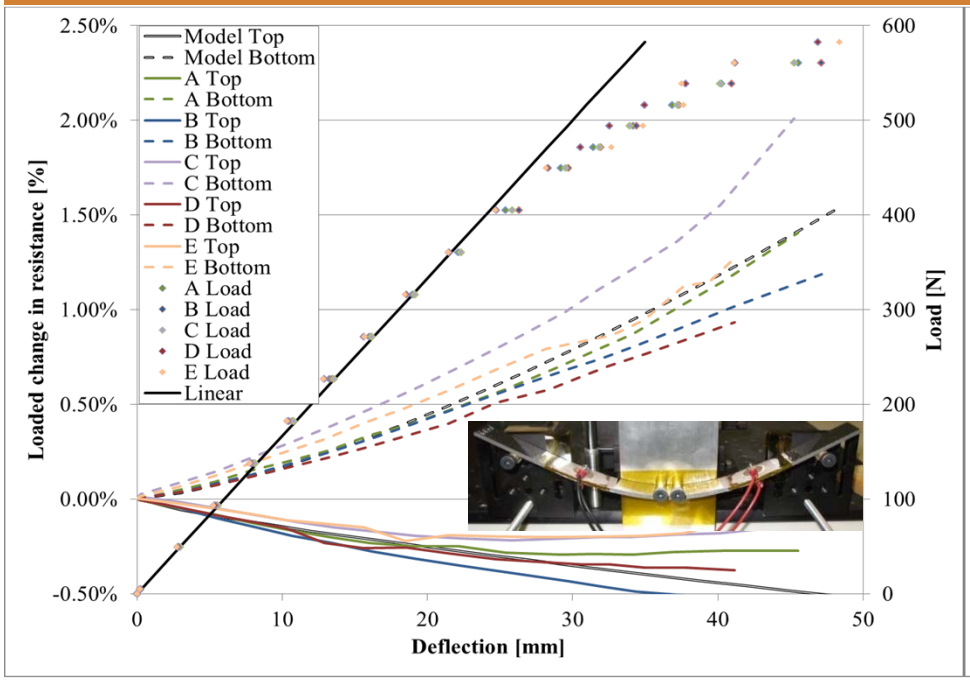
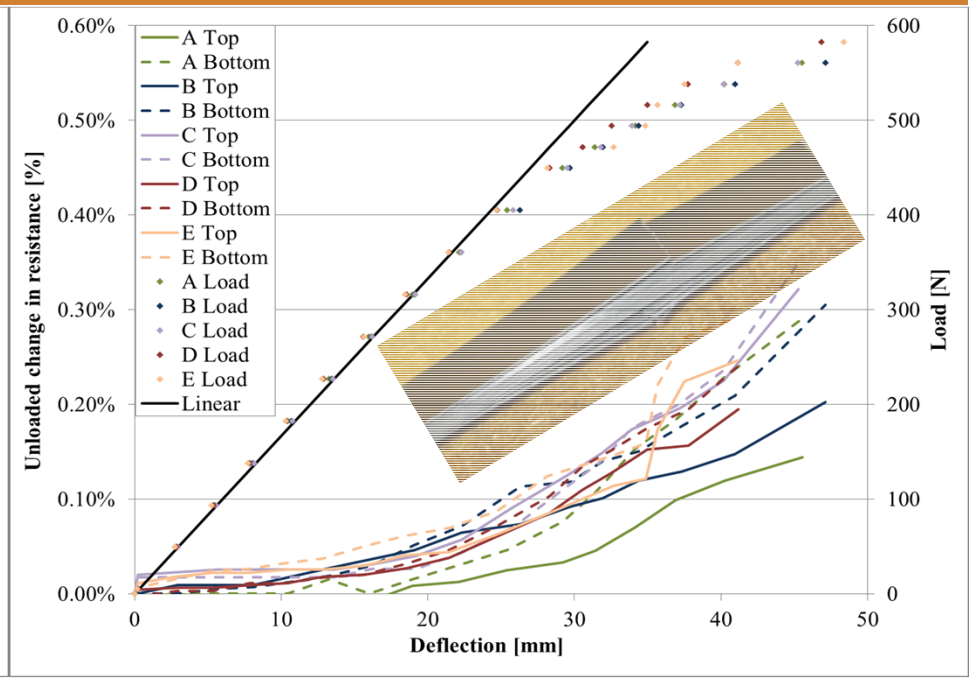
4-Point Best Test





- Resistance is proportional to strain for low displacement
  - load/displacement curves for all specimens are in close agreement
  - tensile-side resistance increases due to CNT network being stretched-out
  - compressive-side resistance decreases due to CNT being pushed together
- Permanent resistance increase after 25mm deflection (>400 N)

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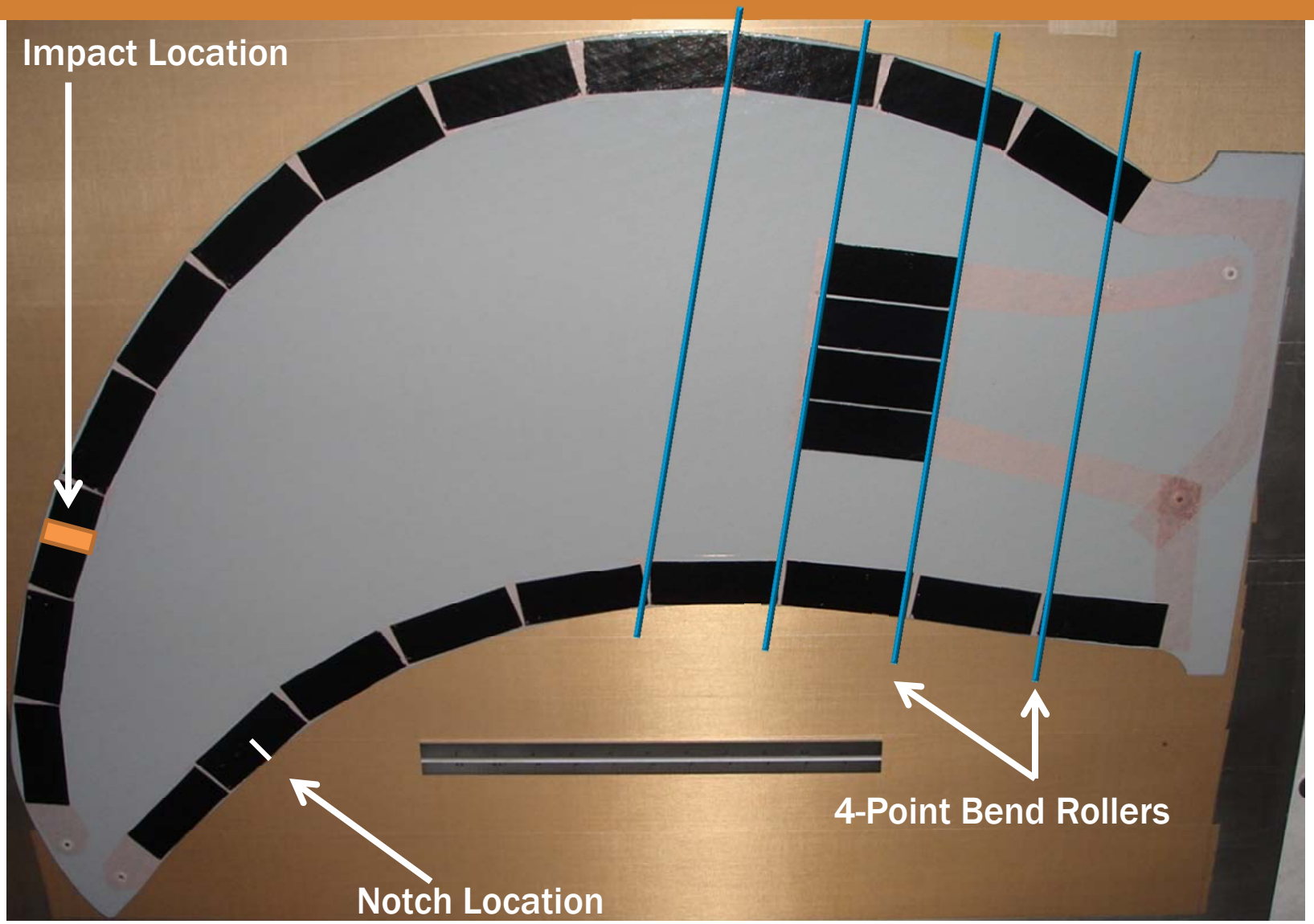
1m Test Specimen



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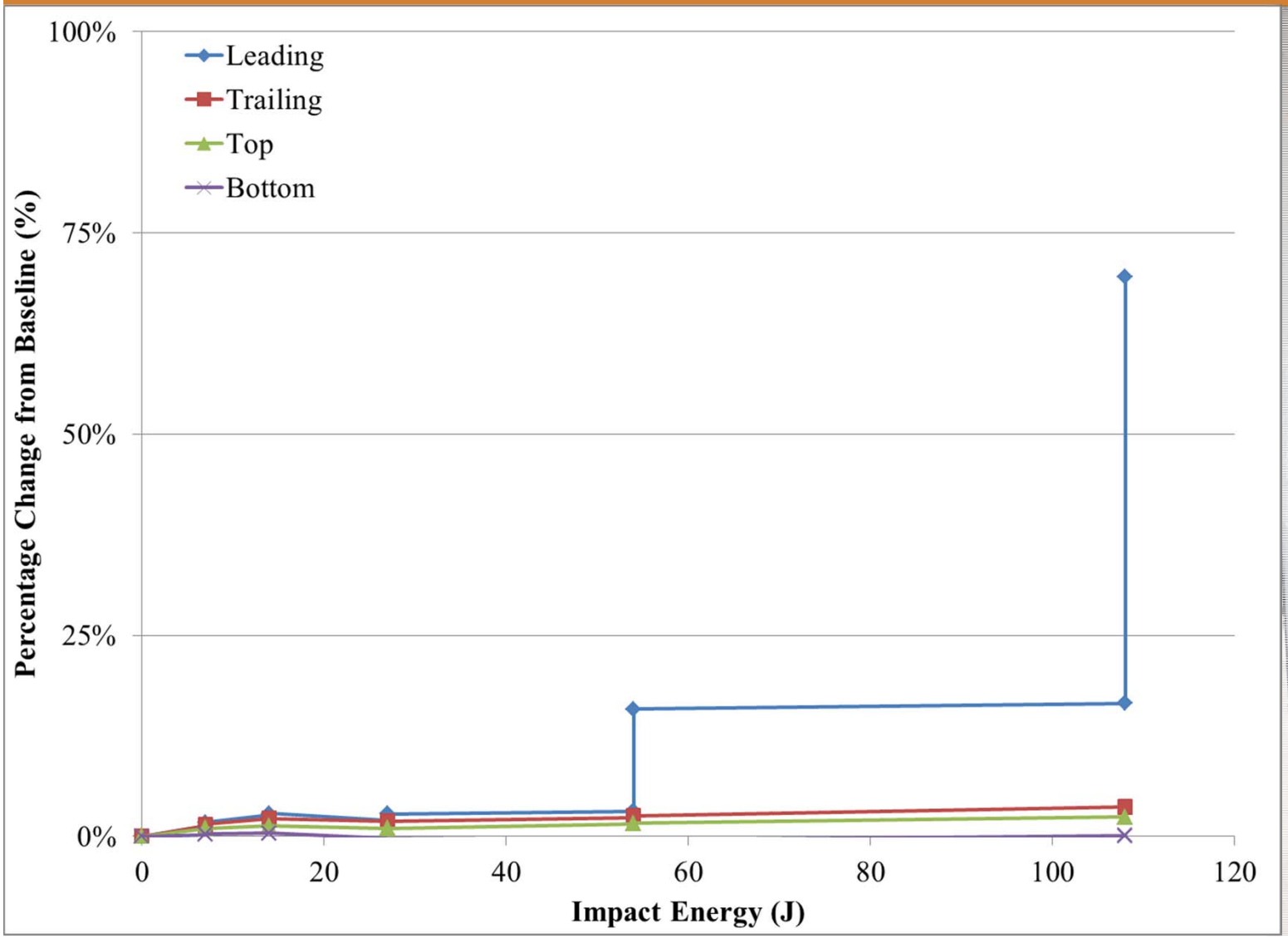
Impact Testing



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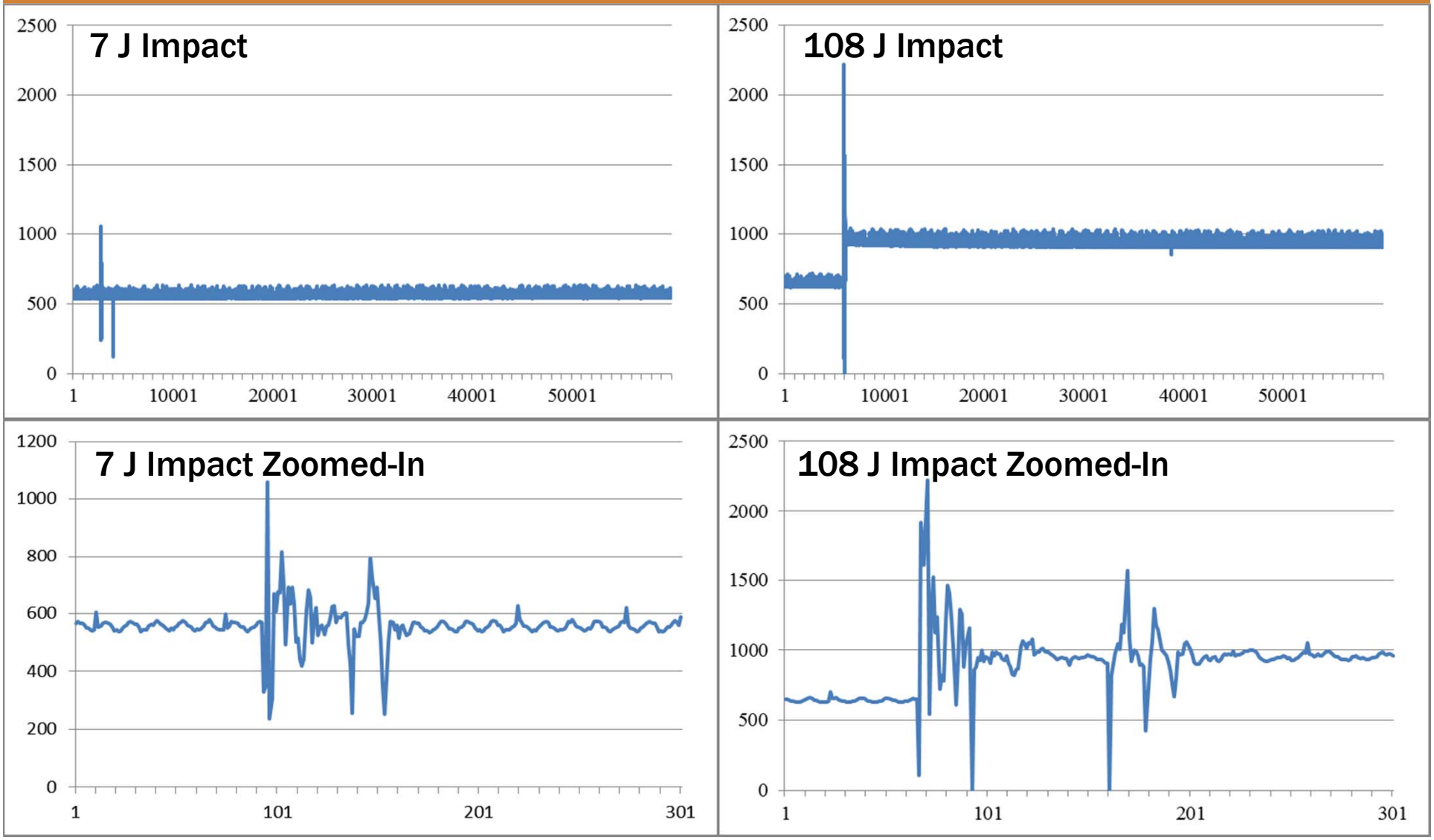
Impact Acoustic Emission



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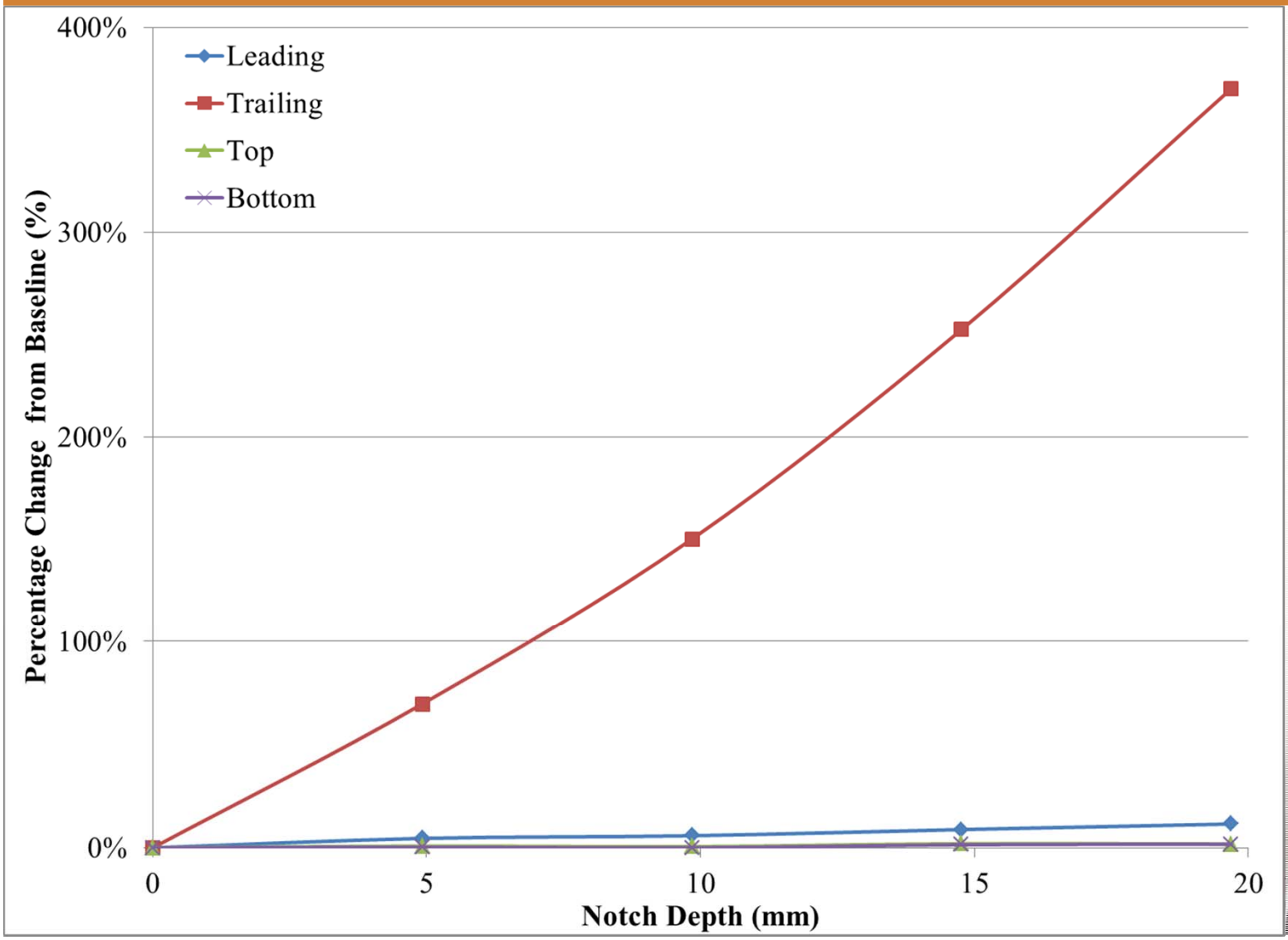
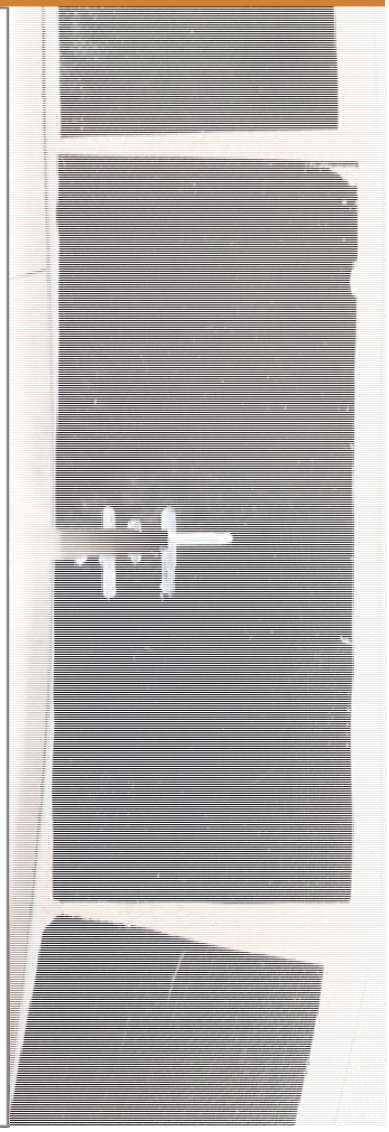
Notch Testing





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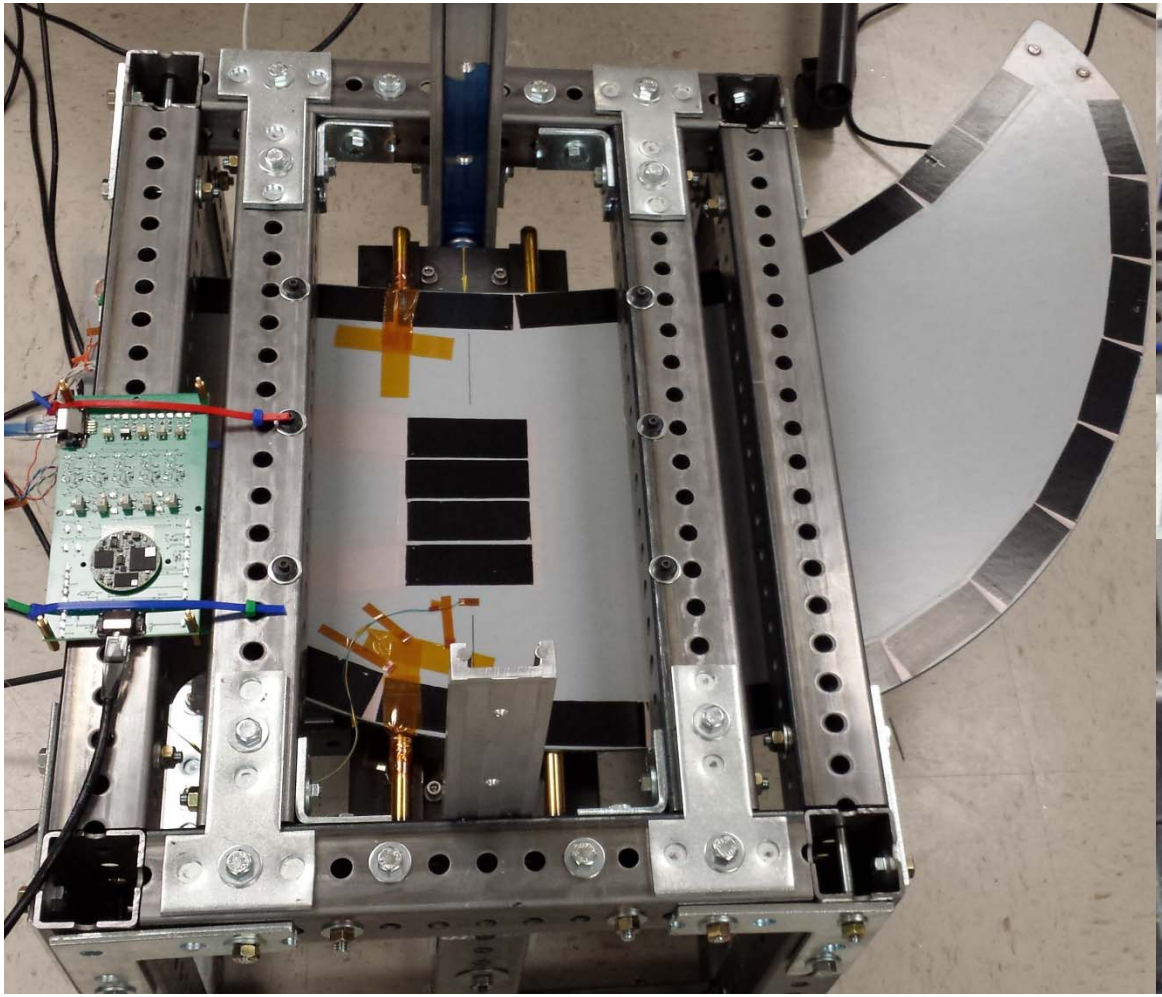
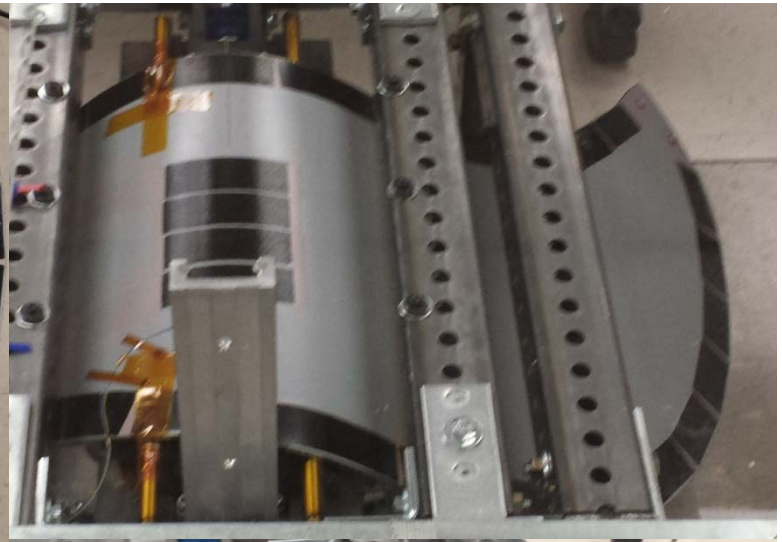
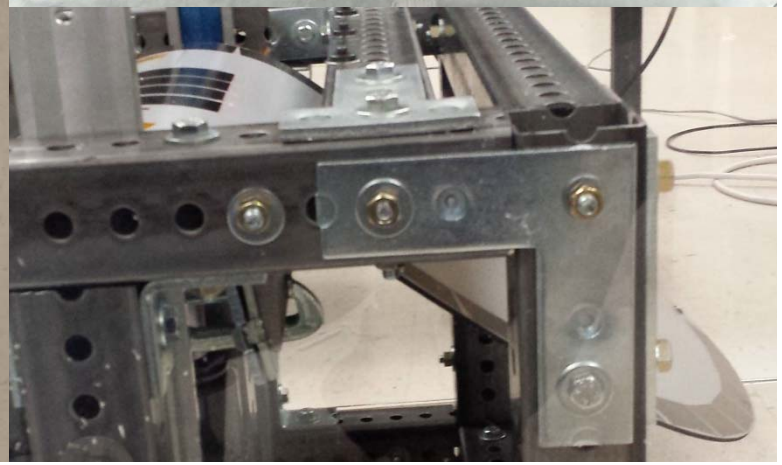
4-Point Bend Test Setup







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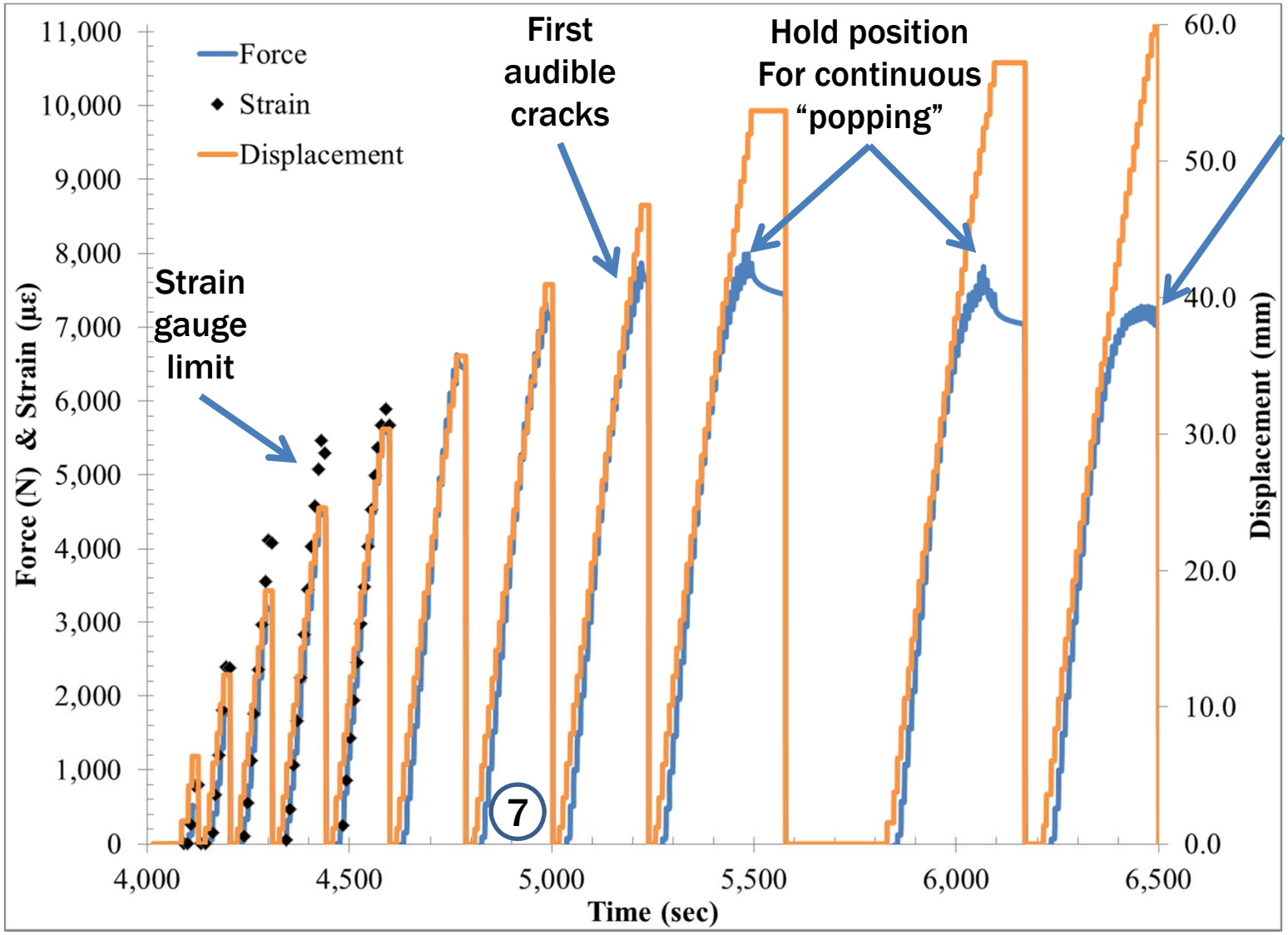
4-Point Bend Results: Load/Displacement/Strain



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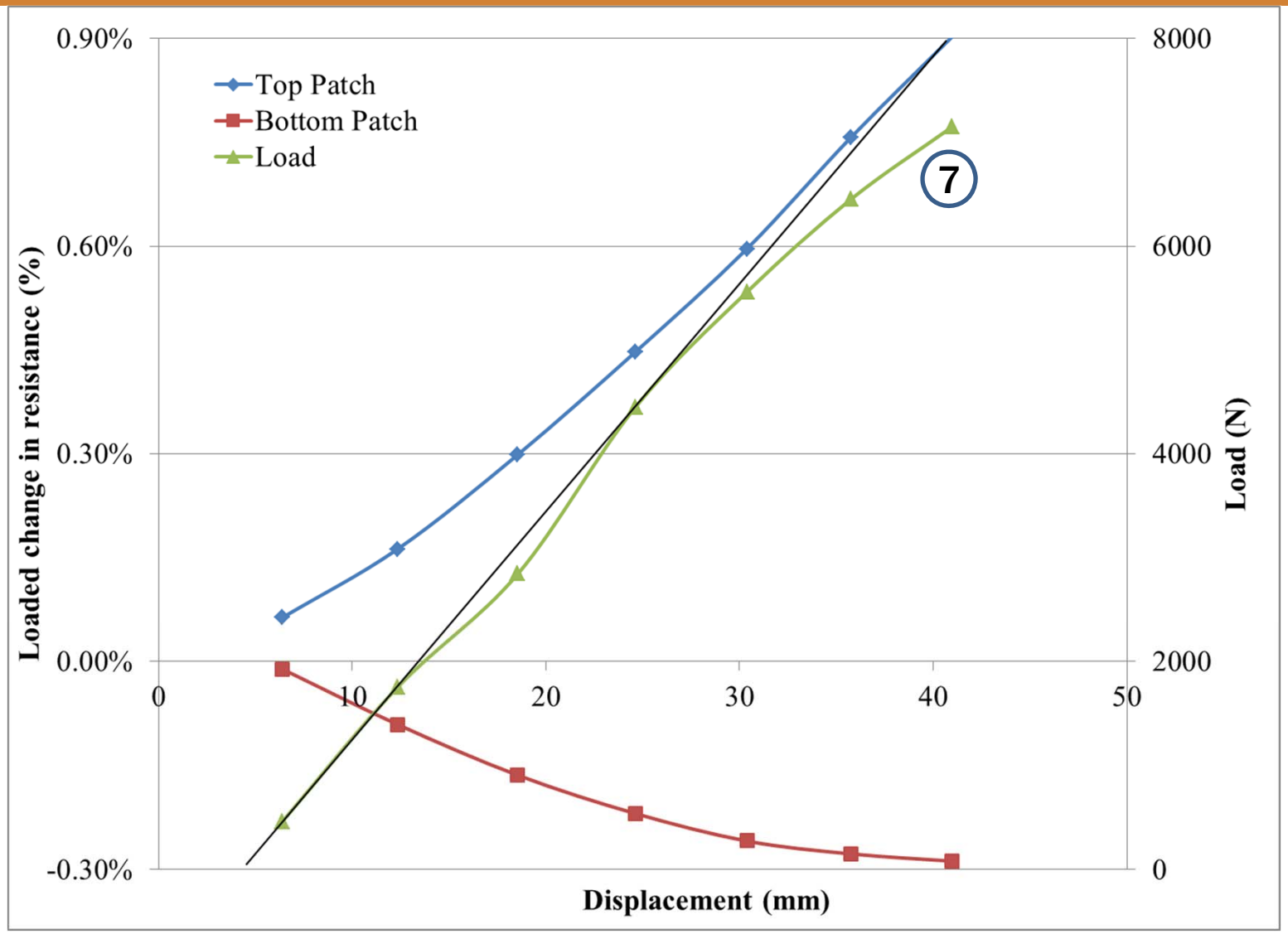
4-Point Bend Results: Max Load Resistances



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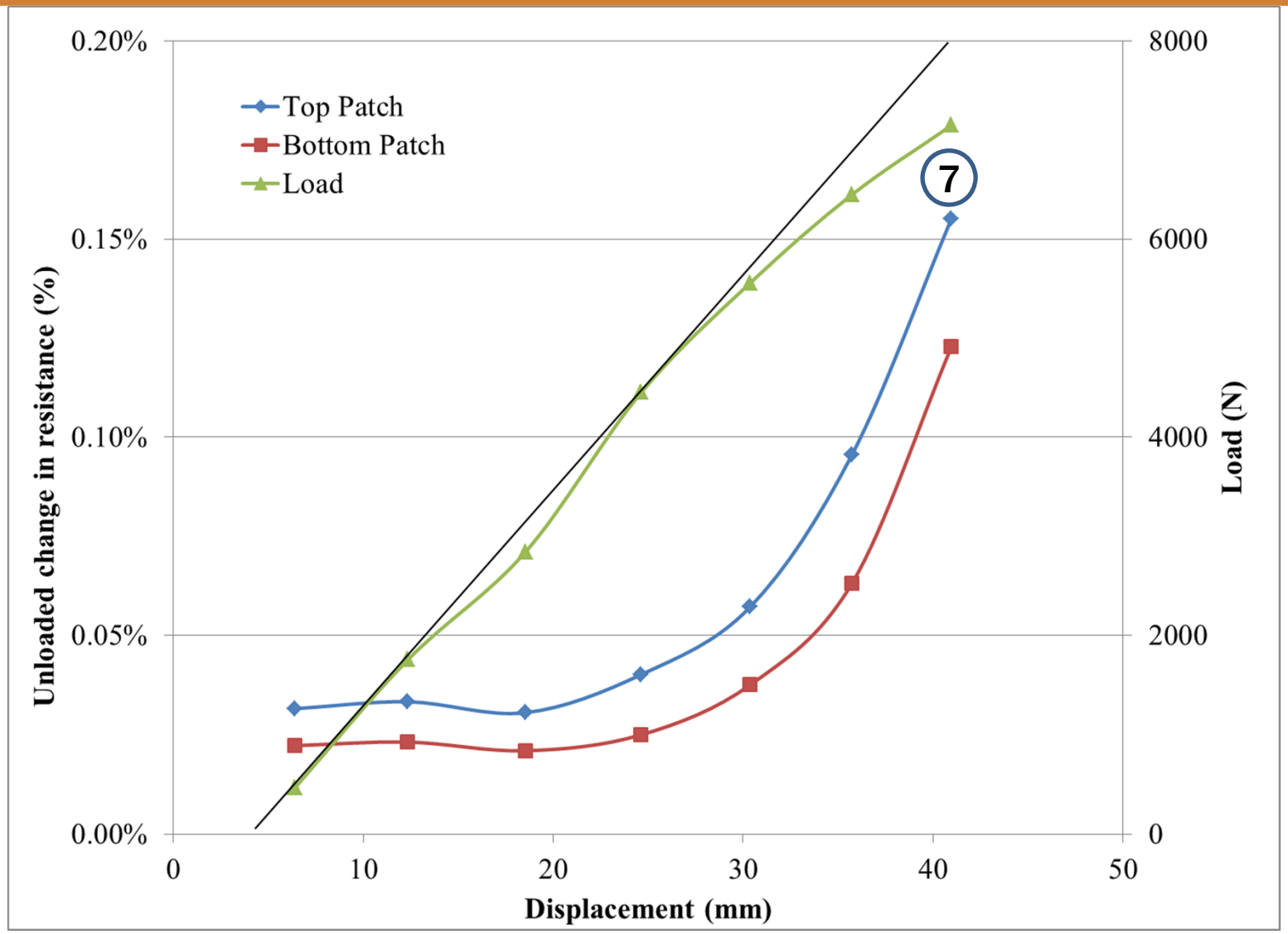
4-Point Bend Results: Unloaded Resistances



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Summary

- Coupon level testing conducted
  - demonstrated sensitivity of system to relevant damage modes
  - calibrated models for expected resistance change due to real damage
  - refined CNT sensor system integration

- Large-scale (1m) testing conducted
  - demonstrated same trends as coupon level at full-scale (failure @~25 mm)
  - validated hardware
  - validated models used for system design
  - able to indicate precursors to audible & visual failure

- CNT-based SHM a practical means for monitoring strain, recording acoustic events and indicating permanent damage in composite, providing large-area coverage with durable, lightweight network

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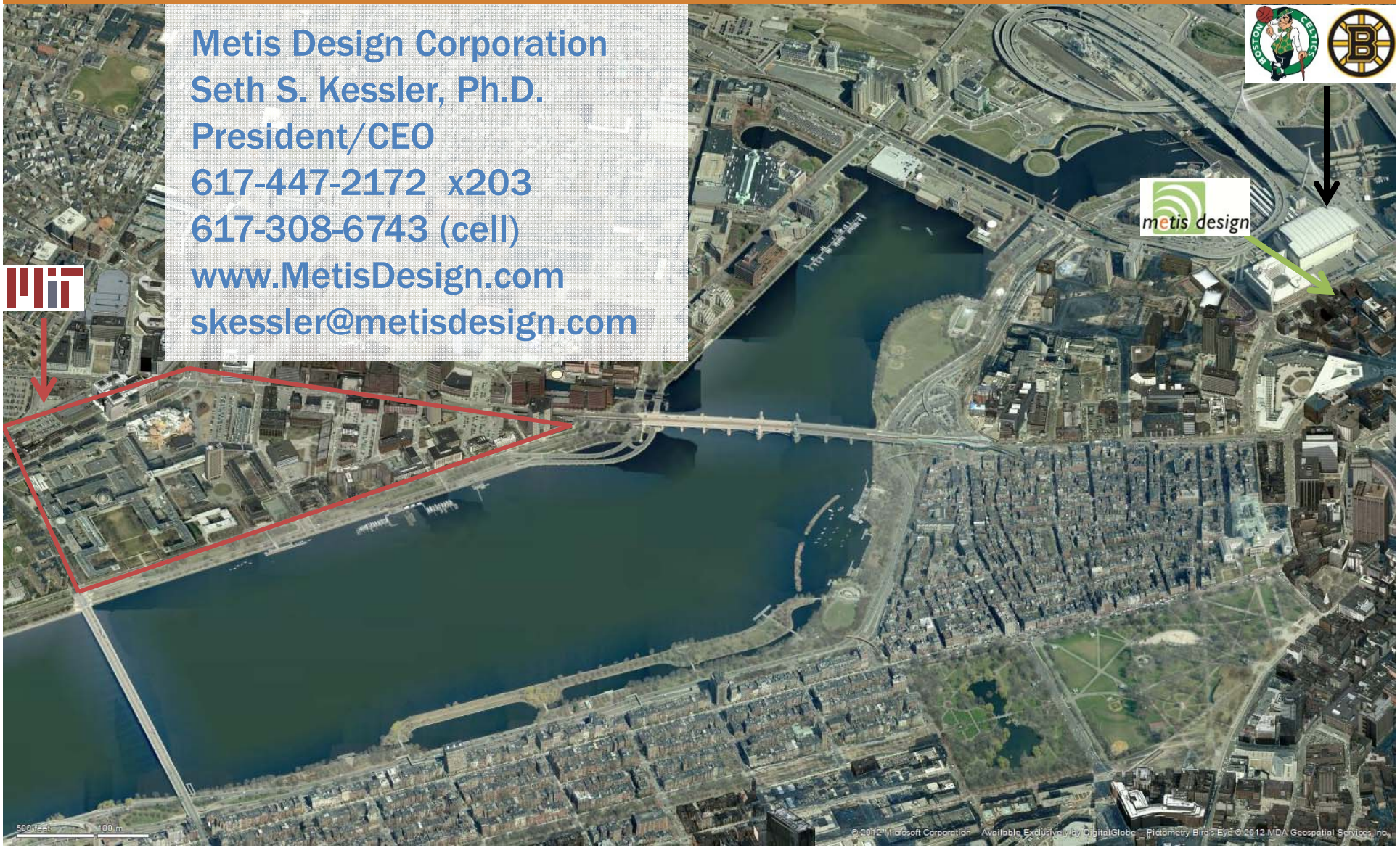
Technical & Business Contact



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