Carbon Nanotube Appliques for Fatigue Crack Diagnostics

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structural health monitoring
multi-functional materials
lean enterprise solutions

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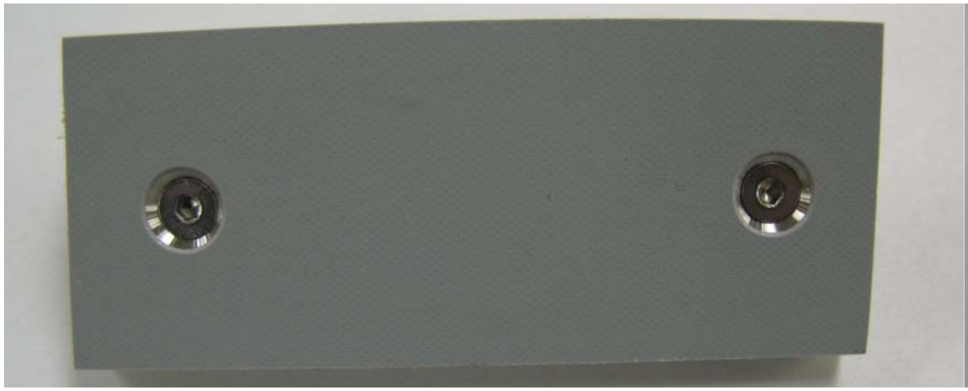
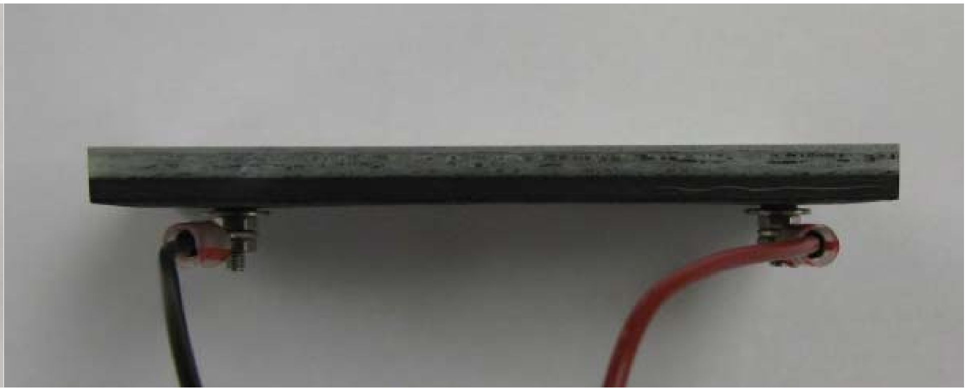
Conformal Multi-functional Assemblies

- Conformal assemblies for composite & metallic host structures
  - ➢ Central carbon nanotube (CNT) layer is core to these properties
  - ➢ Surrounded by electrically insulating layers (film adhesive and/or GFRP)
  - ➢ Selective electrodes integrated to steer current flow
- No impact to physical structure, 100 - 200 μm & 5 - 10 g/m^2
  - ➢ Can be co-cured with composite laminate
  - ➢ Can be installed over composite or metallic skin in secondary process
- Enable multi-functional capabilities: conducting, heating, sensing



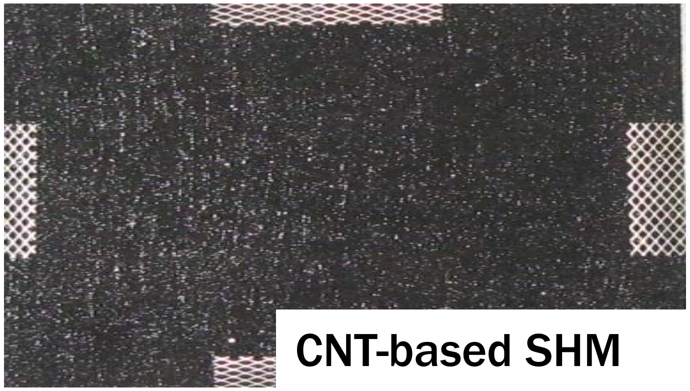


CNT Structural Health Monitoring

- 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 electrodes lighter & more durable than cable
  - ➢ simple to scale over large structure, maintains good local resolution

Traditional SHM



CNT-based SHM

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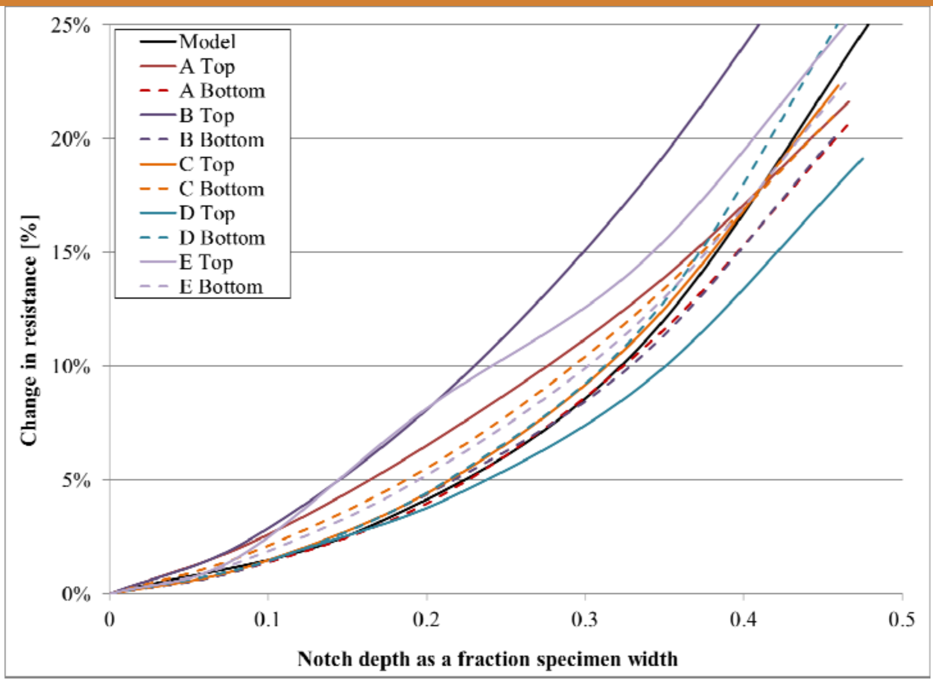
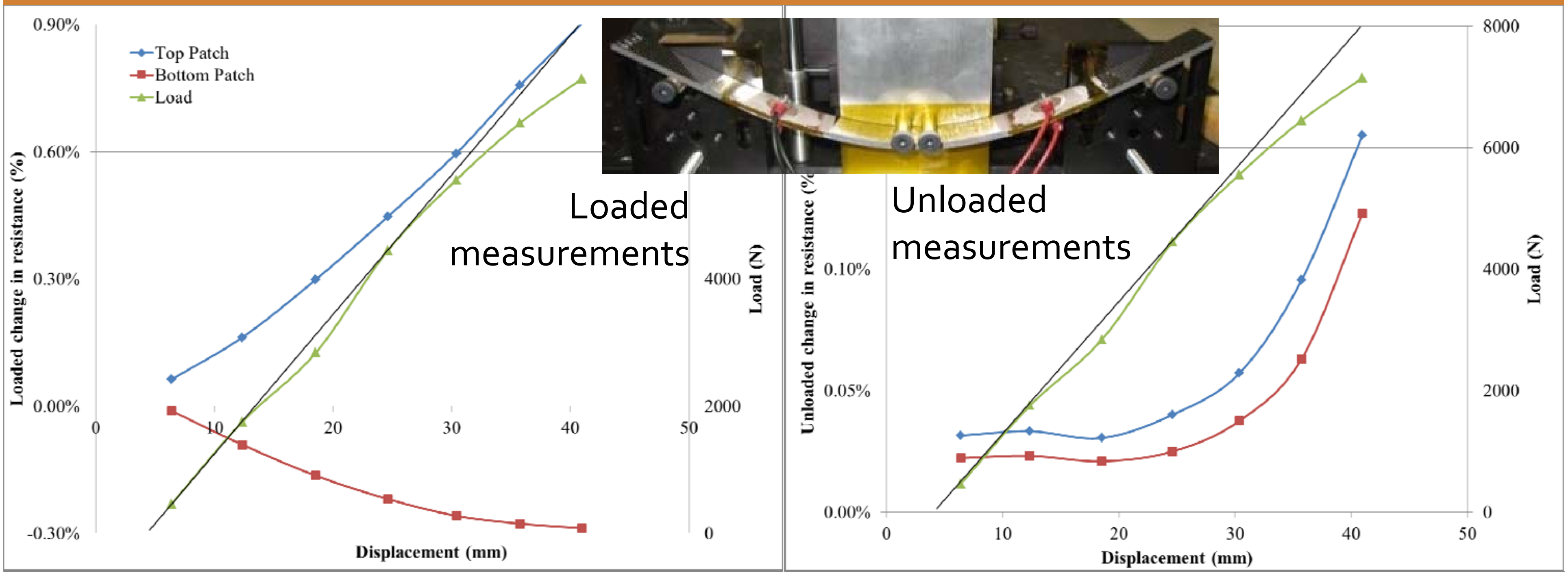
Sparse Electrode Notch-Cutting Tests (N111-067)



- Simple notch-cut experiment presented at prior IWSHM in 2011
  - ➢ 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
- 2D network resistor model in good agreement with data

4-Point Bent Results Under Load (N111-067)

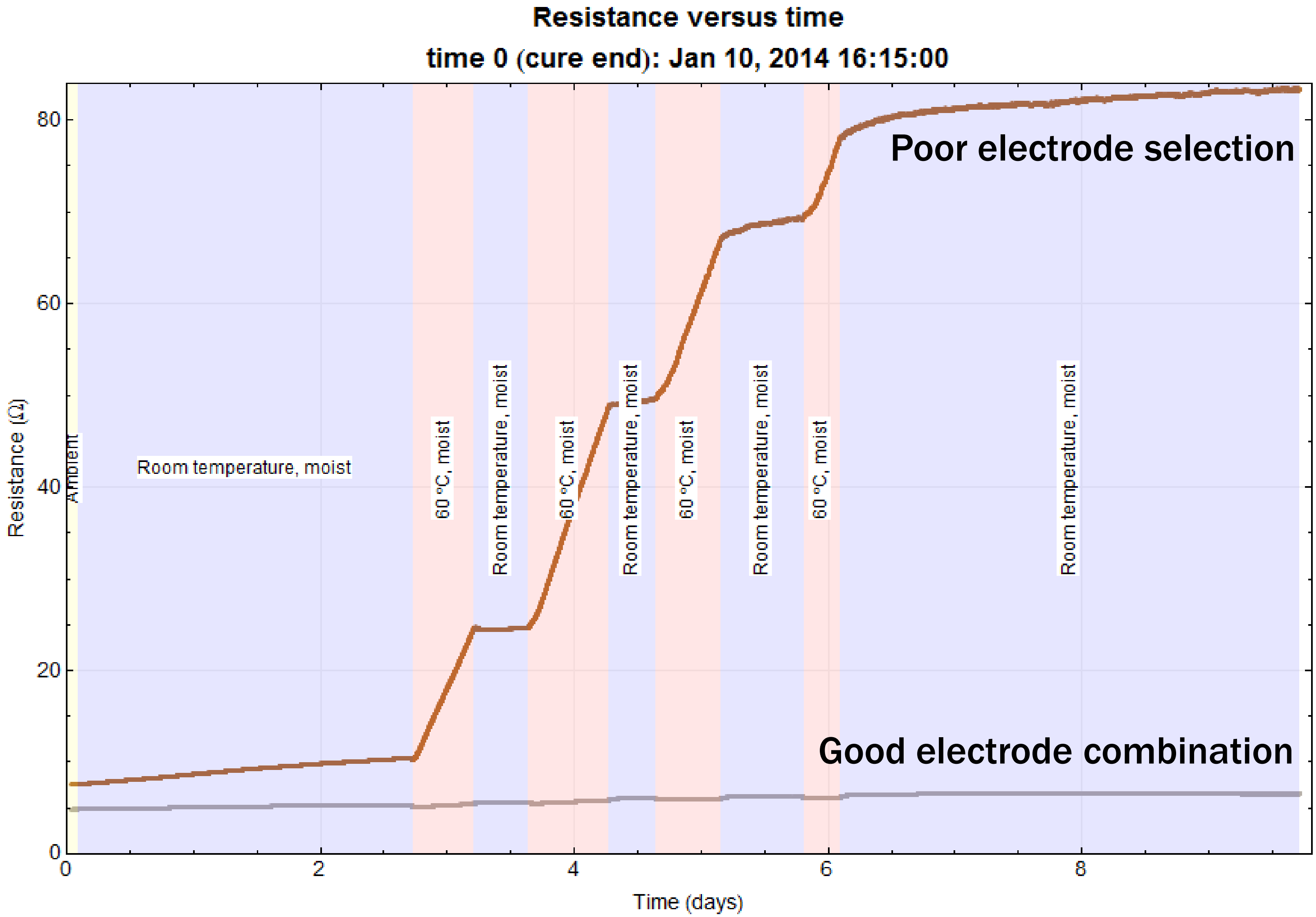


- Simple 4-pt bend experiment also presented at IWSHM 2011
  - ➢ Resistance is proportional to strain for low displacement
  - ➢ tensile-side resistance increases due to CNT network being stretched-out
  - ➢ compressive-side resistance decreases due to CNT being pushed together
- Permanent resistance increase after 25 mm deflection (>400 N)

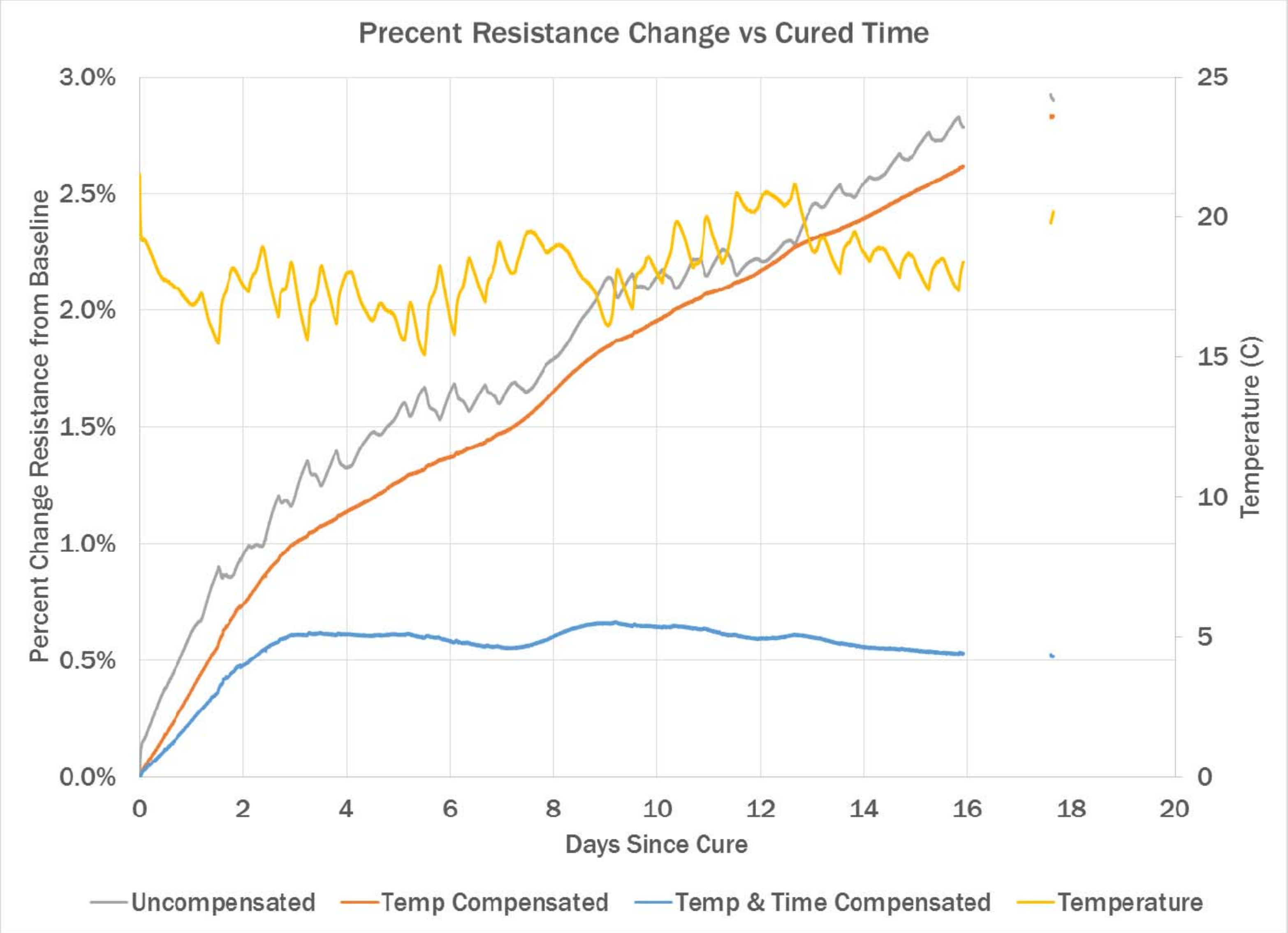
Environmental & Mechanical Studies (N111-067)

- To use CNT as sensors in service, need to evaluate durability
  - Environmental effects
  - Mechanical effects
- Enhanced version of basic 4-point setup from prior tests
  - Rather than static load, used Labview-controlled stepper-motor
  - In-situ monitoring of load, displacement, temp, strain, CNT resistance
  - 1 Hz cycle rate if collecting data, 10 Hz if no data during cycles
- Same setup used for 3 sets of tests, 3 repetitions for each
  - Monitor resistance with various electrode materials & coatings
  - Monitor resistance with various temperature steps
  - Strain (enforced)
  - Fatigue
  - Creep

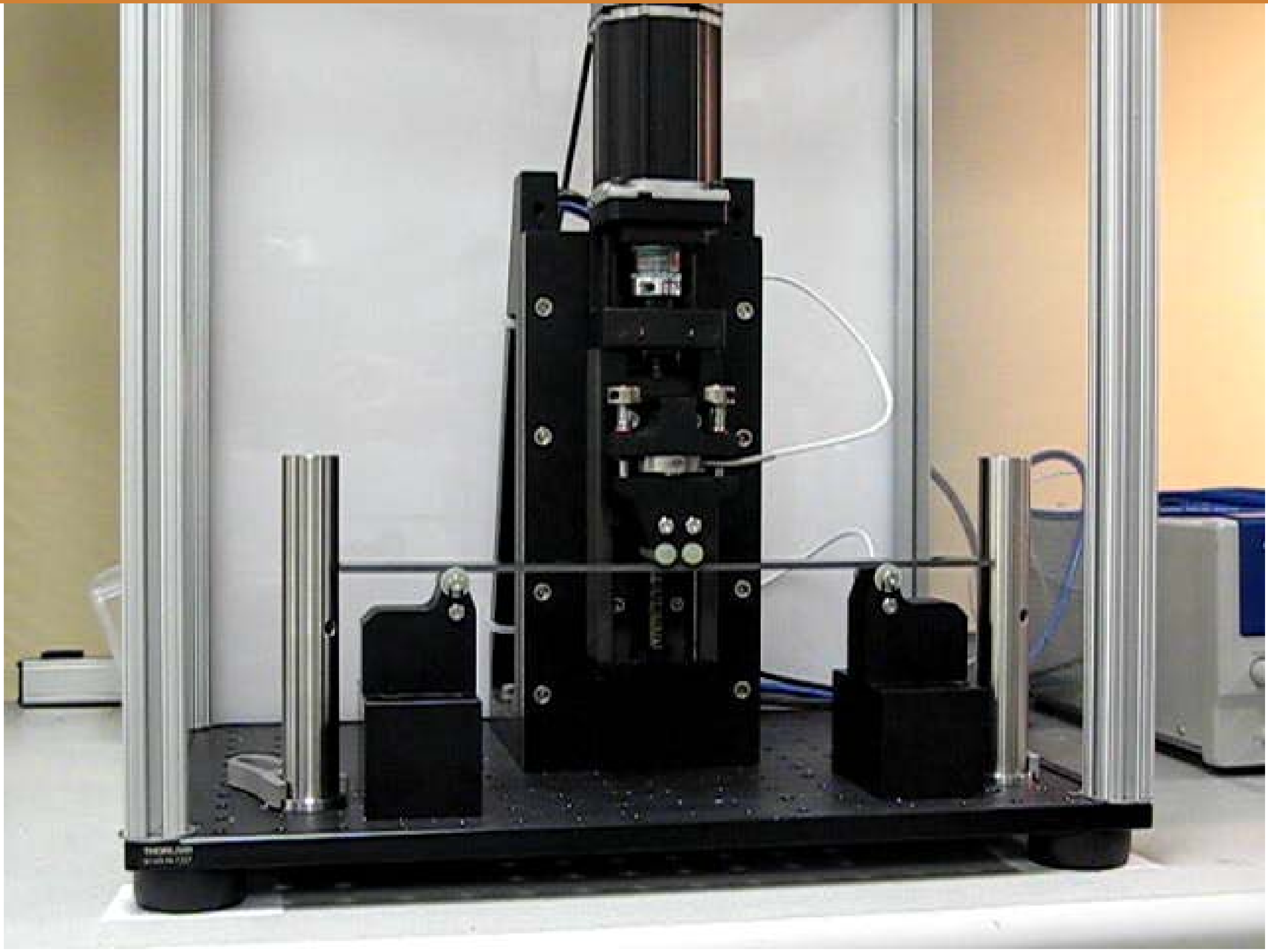
Environmental Testing Results (N111-067)



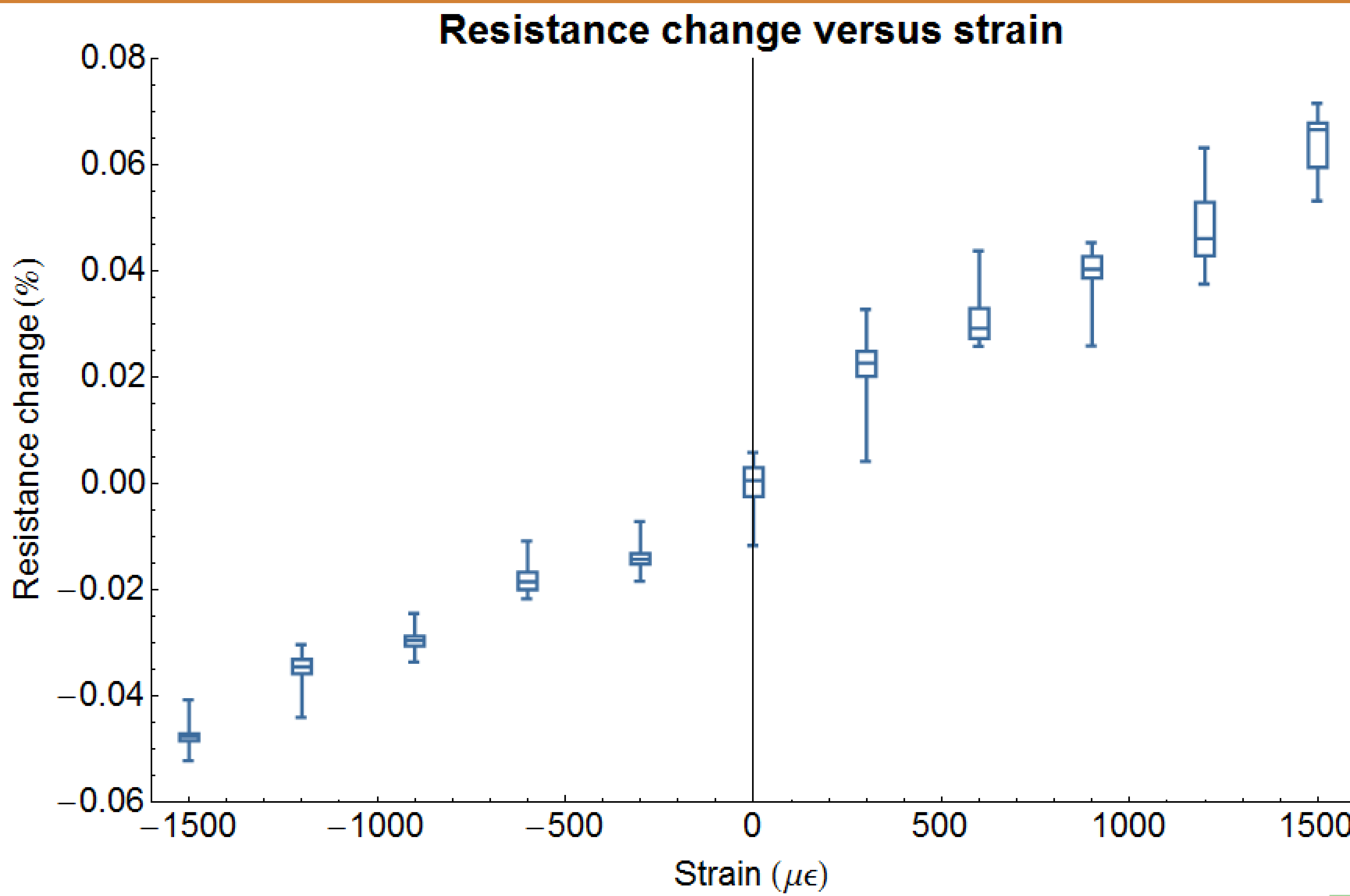
Compensation for α (temp.) & β (hum.) (N111-067)



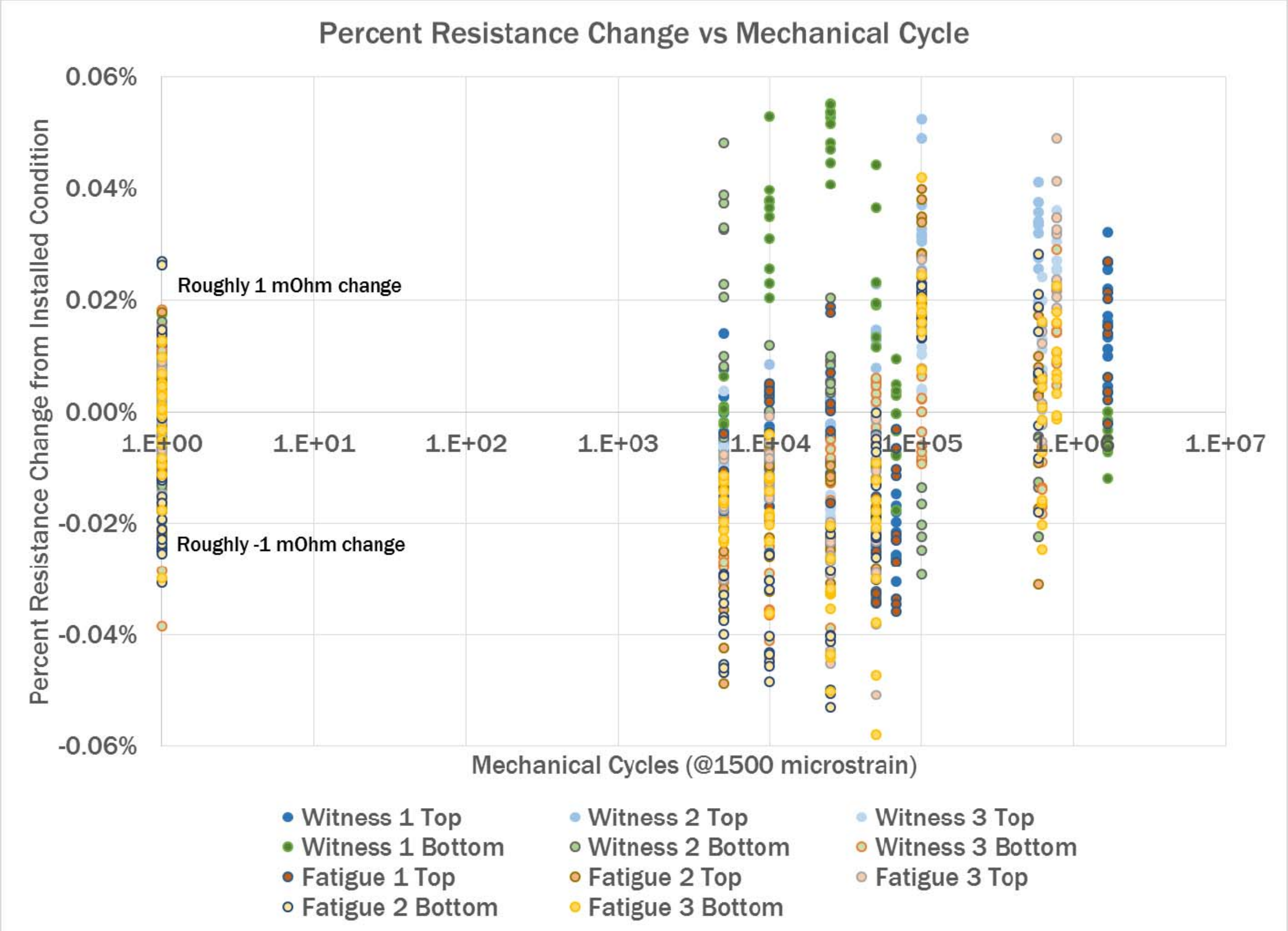
Automated 4-Point Test Bending Rig



Enforced Strain Results (N111-067)



Fatigue Test Results (N111-067)



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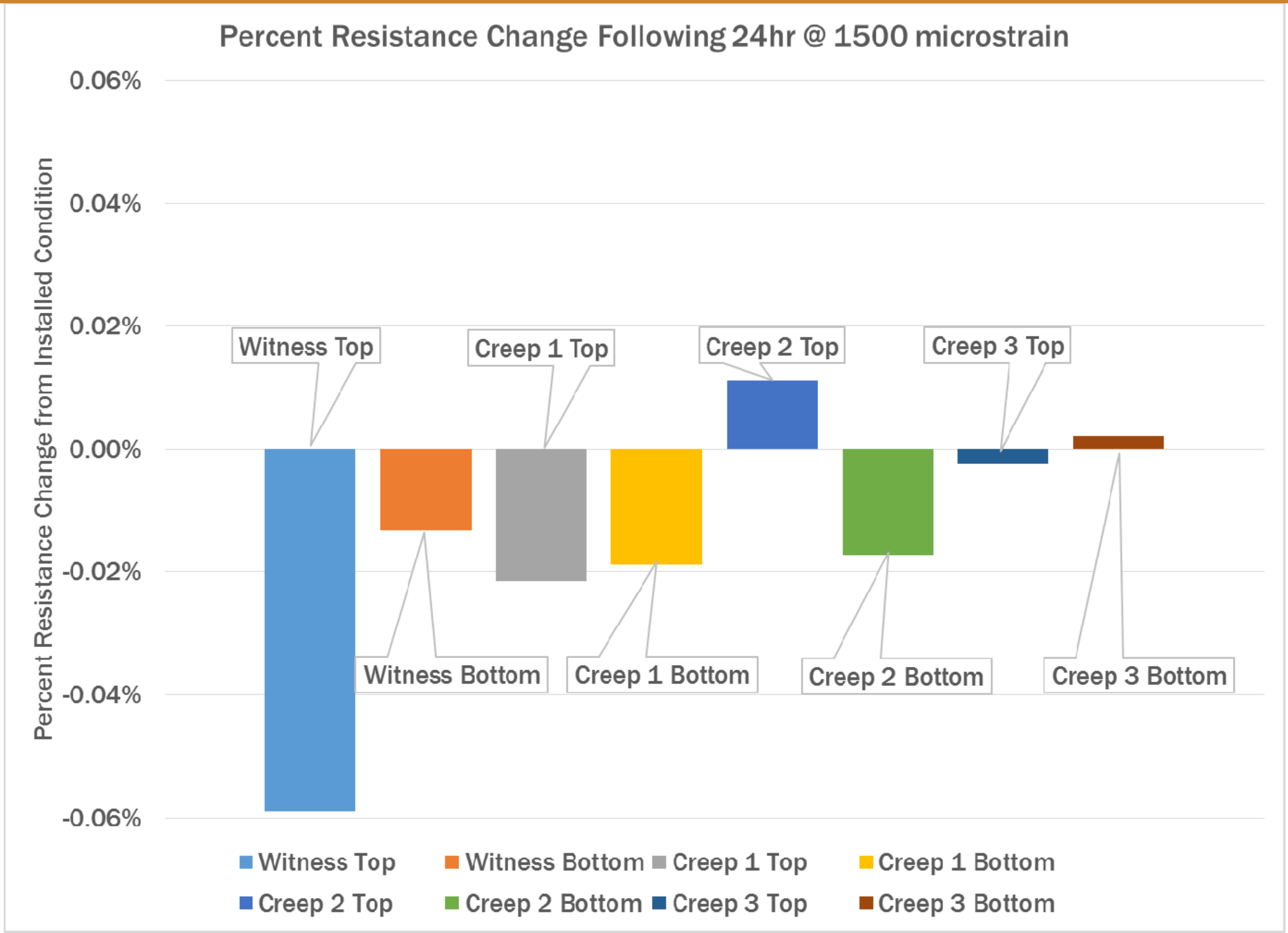
Creep Test Results (N111-067)



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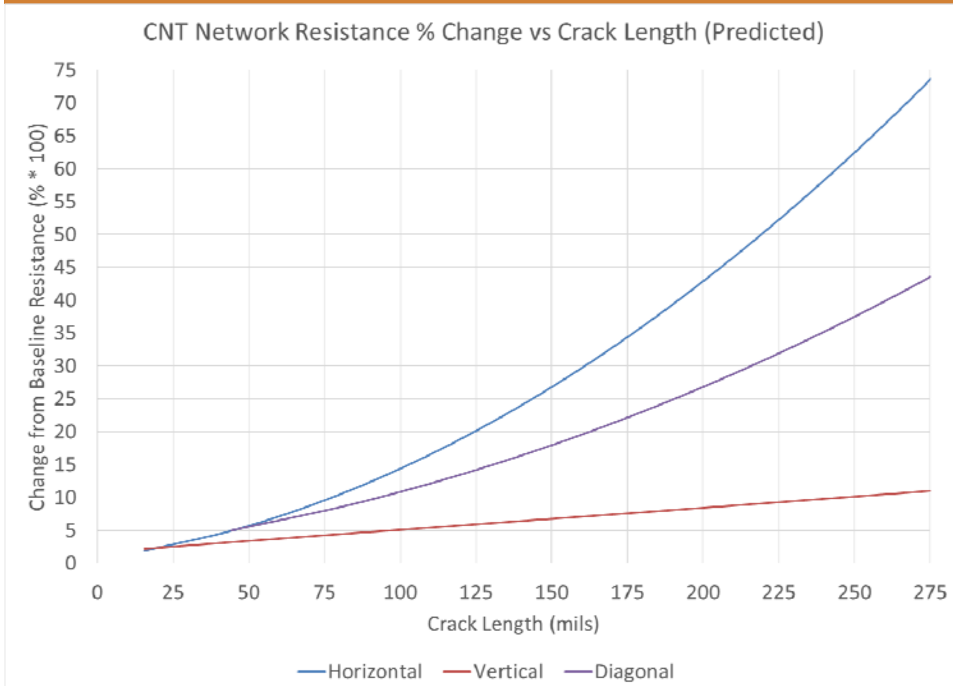
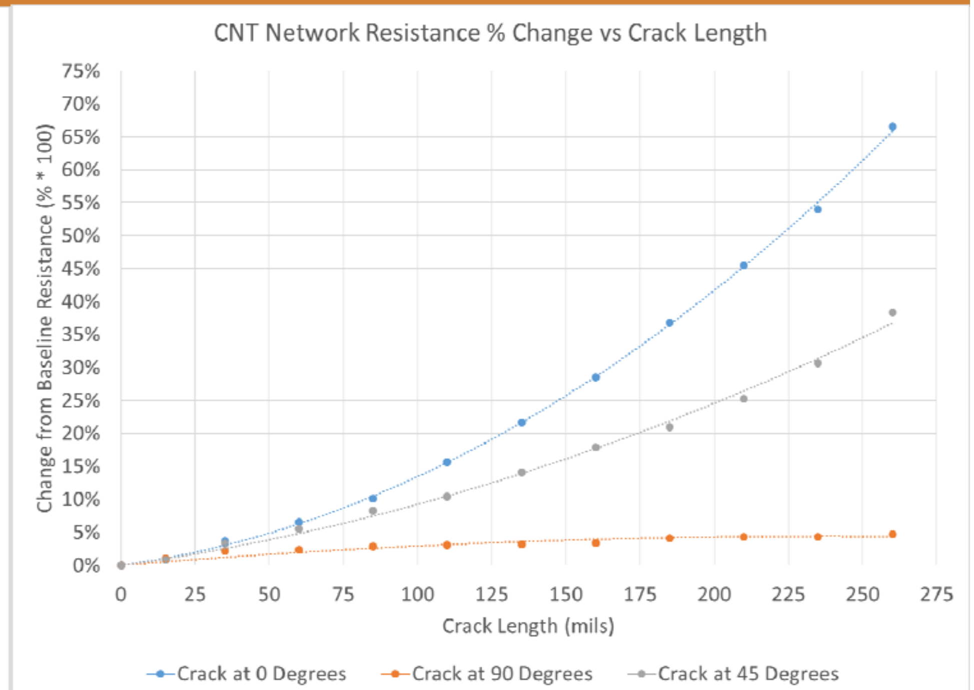
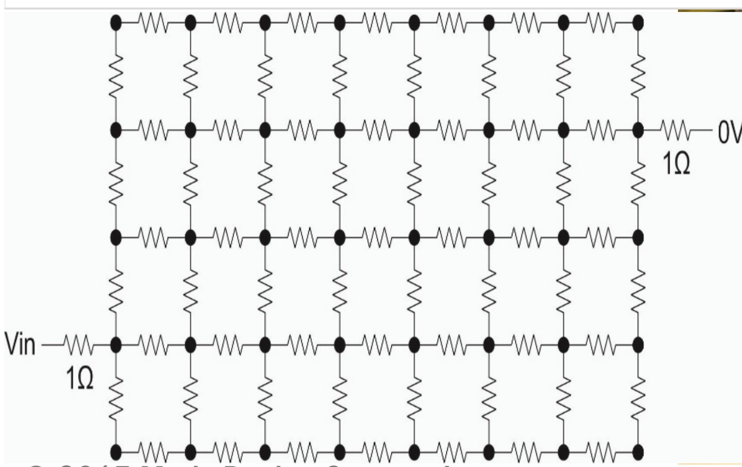
CNT based Continuum Crack Gauge (AF141-065)

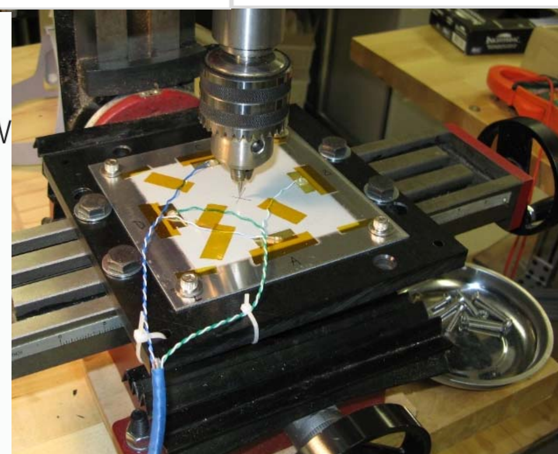
- Targeted detection of flaw growth in known location
  - Addressing fleetwide problems or critical locations
  - Alternative to traditional crack gauge
  - Focus on crack growth in metallic parts for fixed-wing aircraft
- Proposed CNT solution
  - Small (5x5 cm) CNT patch with electrodes around perimeter
  - Ability to detect fatigue crack, estimate length & orientation
  - Non-contact resistance measurements for difficult to access locations
- Phase I Study
  - Funded by AFRL, partnered with LMCO – JSF
  - Calibrated milled-notch results
  - Demonstrated fatigue crack growth monitoring
  - Demonstrated passive wireless data acquisition

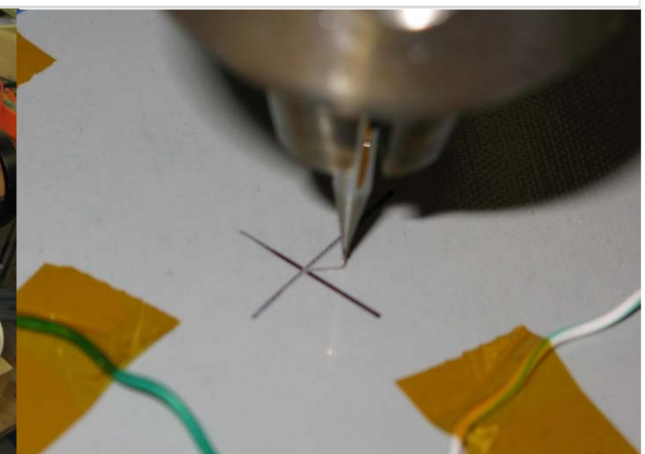
Continuum Crack Gauge Model (AF141-065)



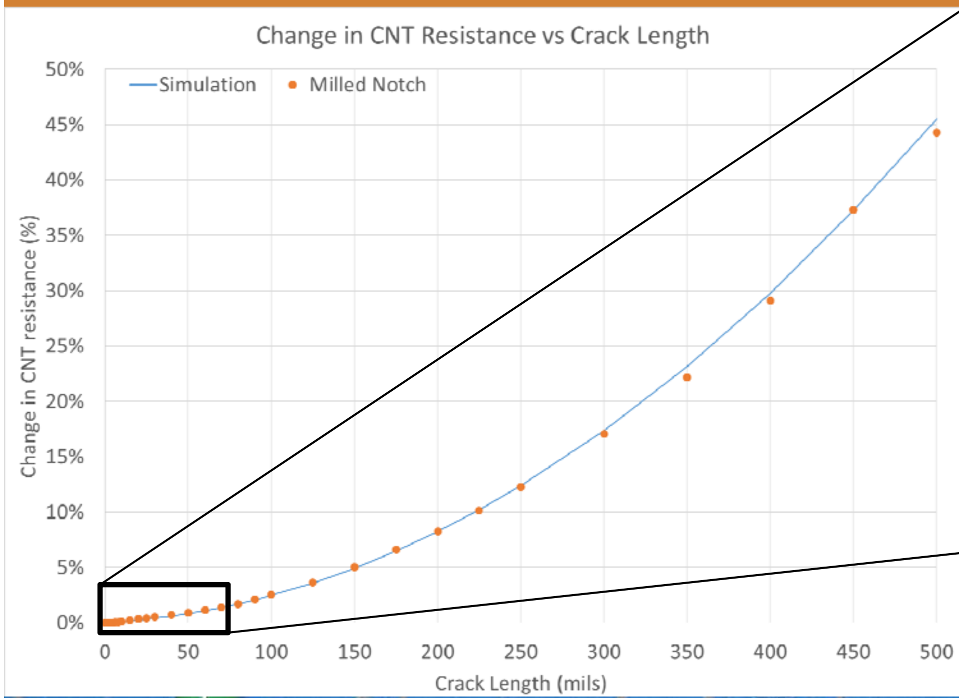


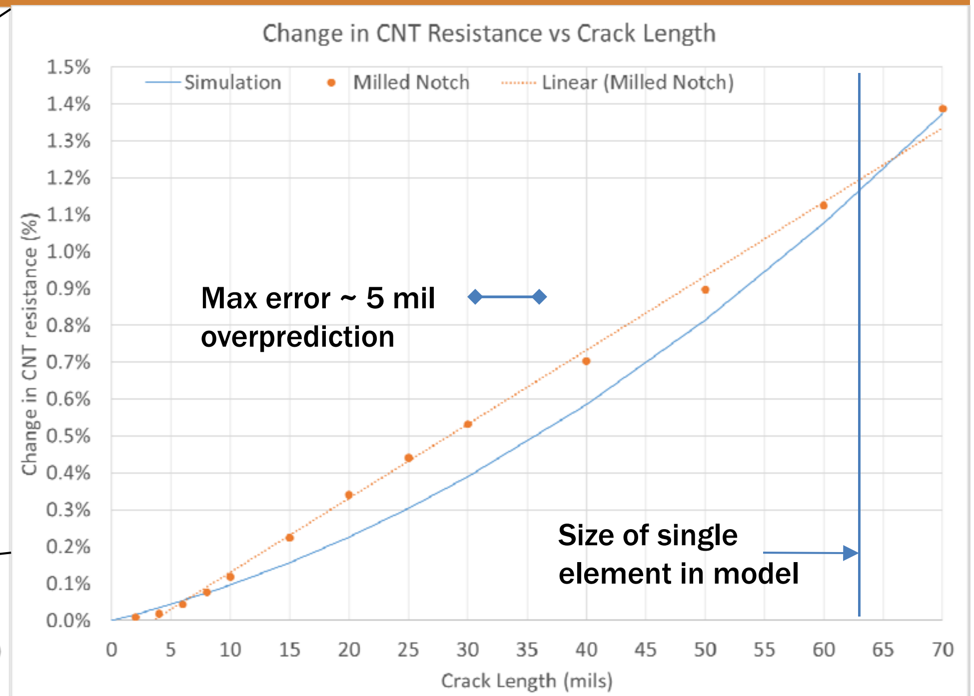


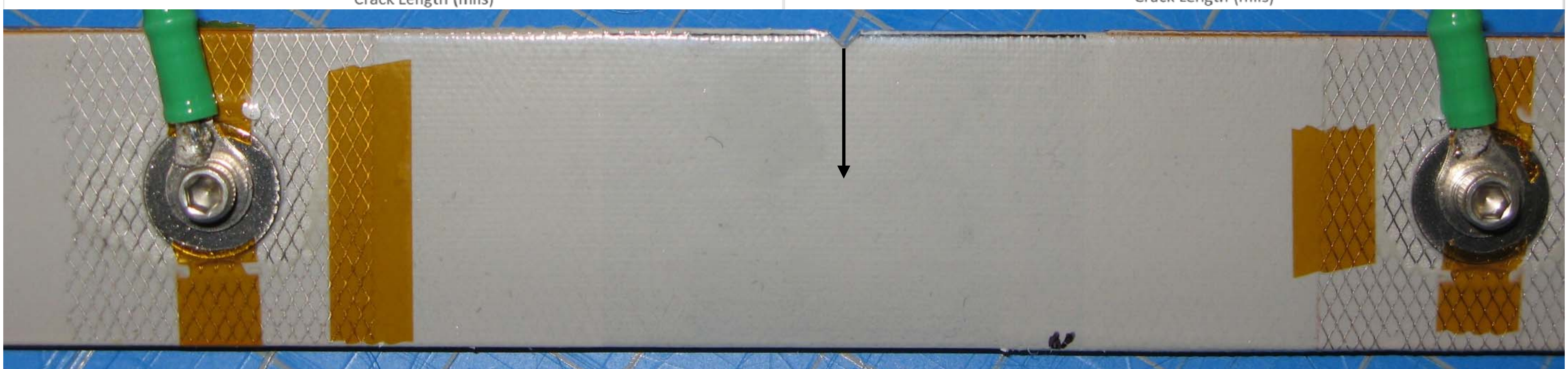




Continuum Crack Gauge Calibration (AF141-065)







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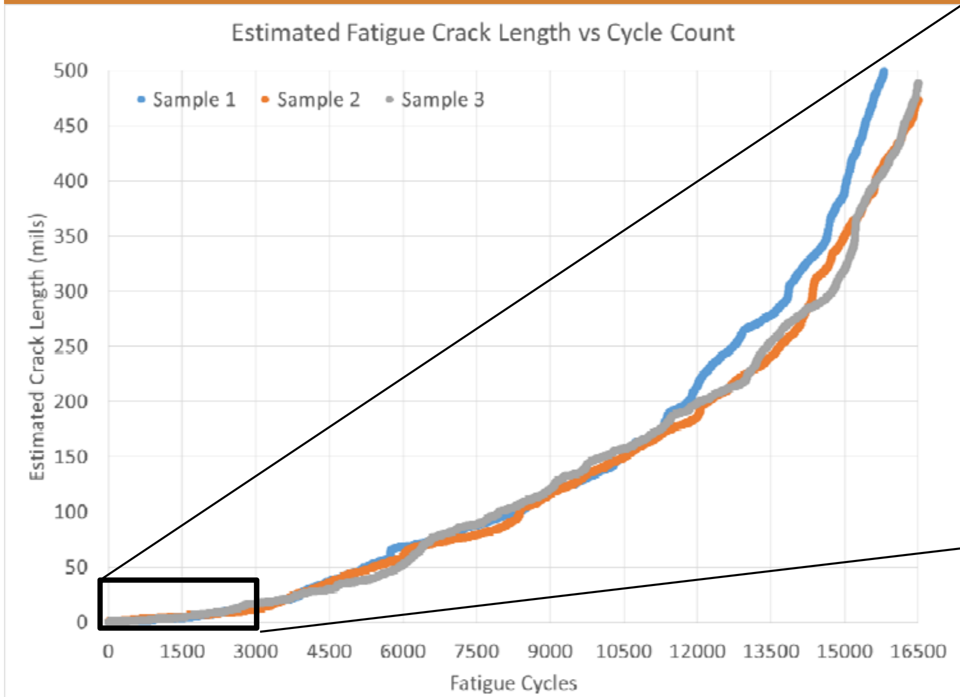
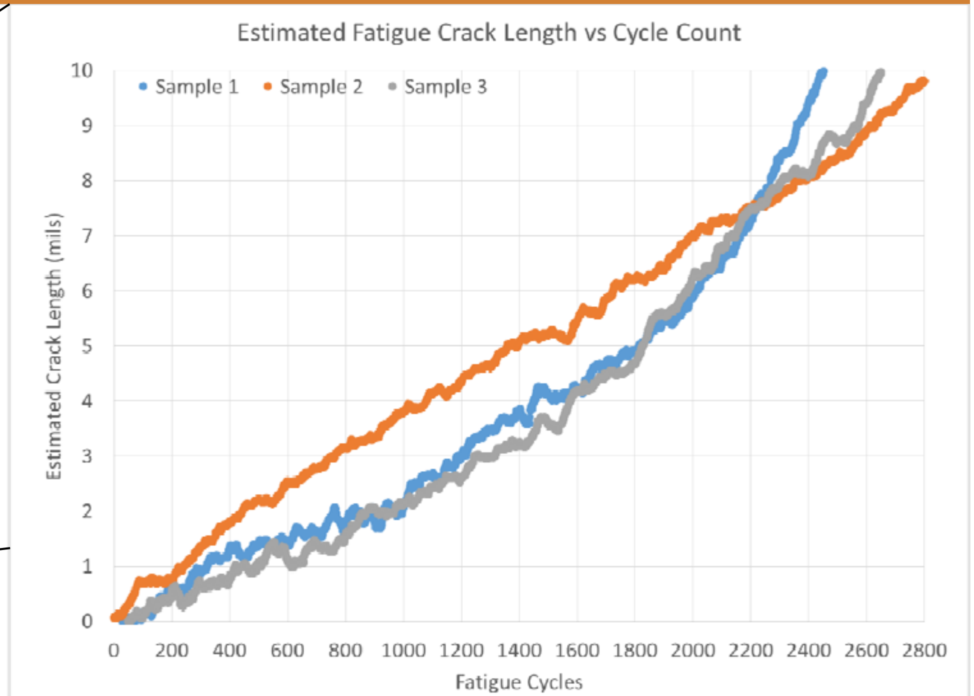
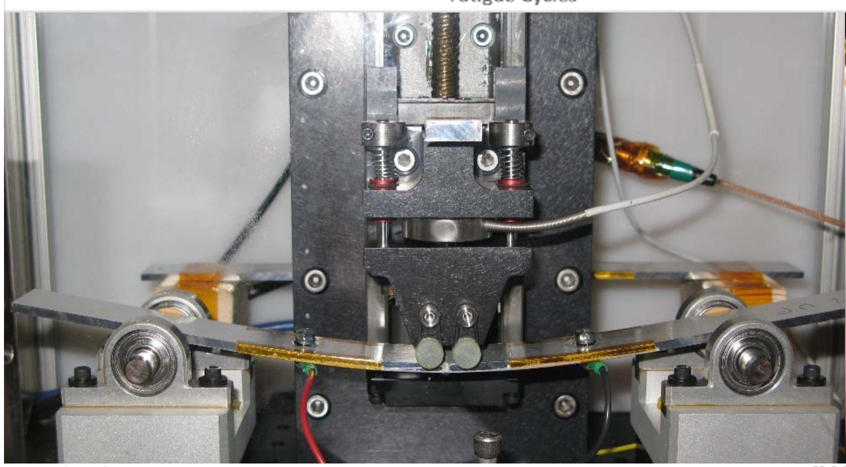
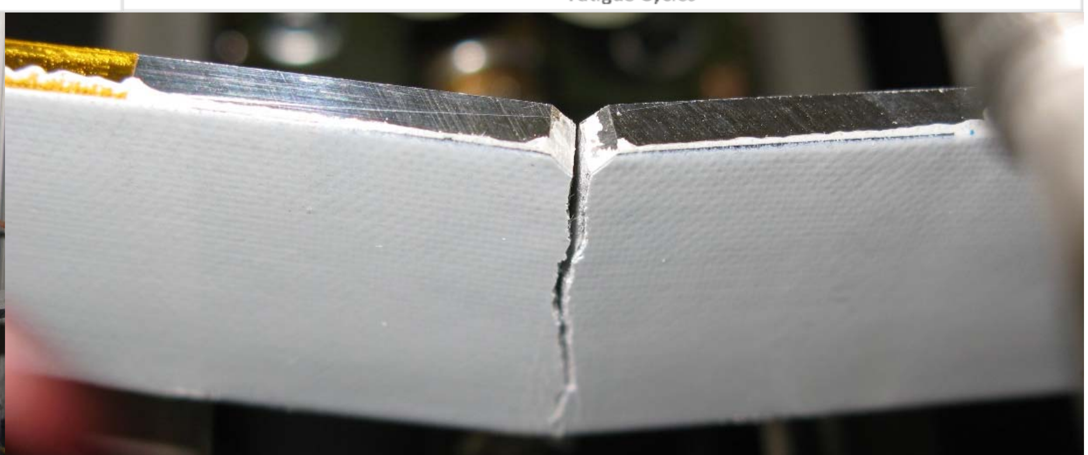
Continuum Crack Gauge Experiment (AF141-065)









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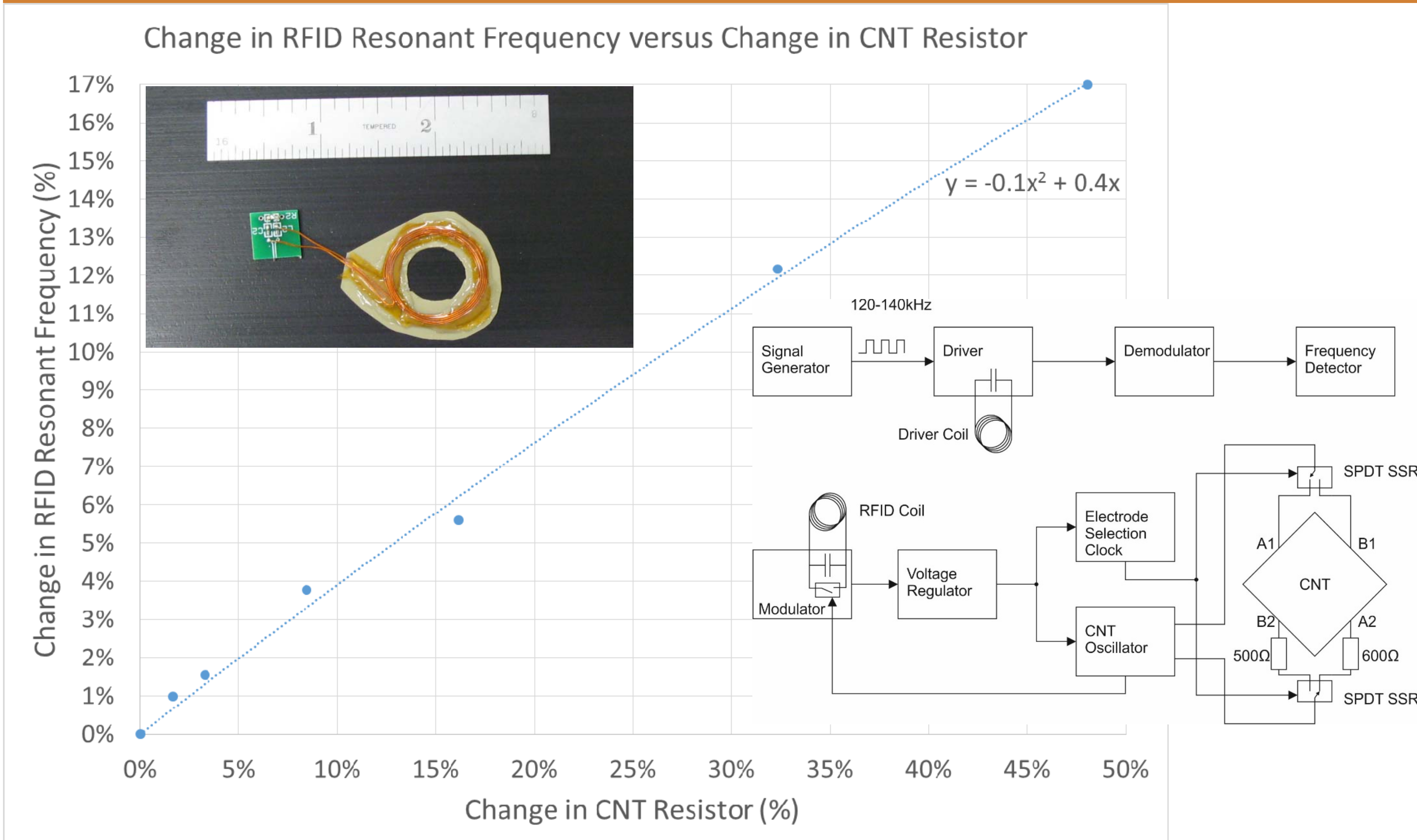
Passive RFID Proof-of-Concept (AF141-065)



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CNT Continuum Crack Gauge Summary

- Use of CNT as sensing method previously explored w/Navy SBIR
  - Showed strong correlation to tensile/compressive strain loads
  - Clear trends observed for impact, notch & overload damage
- Durability of approach was investigated
  - Identified/eliminated sources of drift to improve sensitivity/reliability
  - Quantified/compensated for effects of temperature & moisture absorption
  - Explored repeatability under strain, observed no effects of creep & fatigue
- Demonstrated continuum crack gauge w/AFRL SBIR
  - Simple model in close agreement with experimental results
  - Could calibrate crack length & orientation from orthogonal electrodes
  - Grew real fatigue cracks in 3 specimens, accurate crack length predictions
  - Proof-of concept demo measured resistance change with RFID approach

Future Work (AFRL Phase II SBIR)

- Task 1: Sensor Optimization. materials & fabrication procedure selection. Downselect installation (including self-curing)
- Task 2: RFID Hardware Development. Design, fabricate & test send/receive hardware for collecting data and displaying results
- Task 3: Sensor Calibration & Validation. Conduct several coupon-scale tests to build calibration table for crack size/orientation
- Task 4: Initial Probability of Detection Report. Conduct a first pass PoD assessment for the optimized sensor (MIL-HDBK-1823A)
- Task 5: Durability Assessment. Conduct MIL-STD-810G to determine susceptibility to aircraft environmental conditions
- Task 6: Blind Demonstration. Working with LMCO demonstrate technique blindly on a large F-35 relevant built-up test article

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