Assessing Detection Sensitivity for Potential Drop (PD) & Guided Wave (GW) Structural Health Monitoring (SHM) Techniques

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structural health monitoring
multi-functional materials
lean enterprise solutions

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Introduction

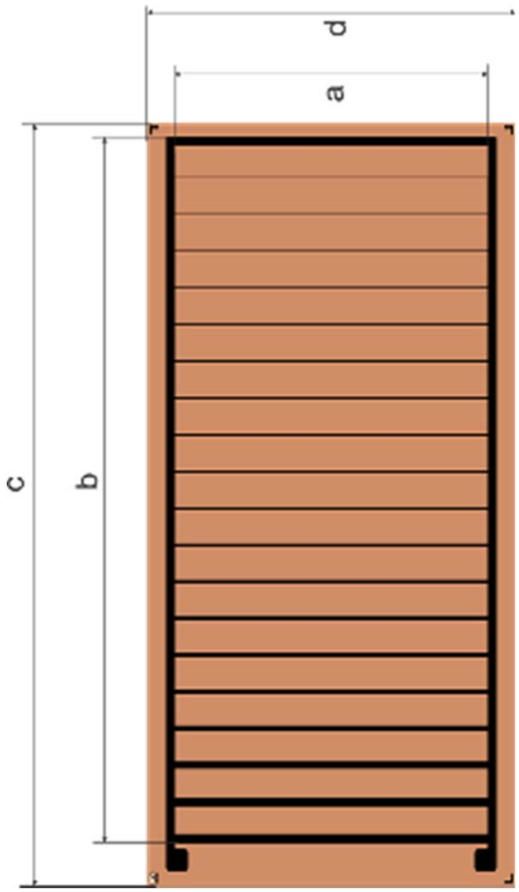
- Structural Health Monitoring (SHM) uses permanently integrated non-destructive sensors
  - Many viable strategies for measuring various types of local or global damage
  - Potential Drop (PD) methods use change in network resistance to indicate a growing flaw
  - Guided Wave (GW) methods use piezoelectric actuators/sensors to detect changes in wave propagation

- MIL-HDBK-1823A typically used to assess sensor detection capabilities
  - Key statistical metric is $a_{90/95}$ - 90% probability of detection (PoD) with 95% confidence
  - Also important to keep a very low false-positive rate (i.e. minimize incorrect indications)

- Challenging to assess detection sensitivity for SHM using traditional approaches
  - Very expensive due to the permanent nature of sensor installations & requirement for many specimens
  - Length at Detection (LaD) approach developed by Sandia Labs as an alternative approach
  - REpeated Measures Random Effects Model (REM^2) developed by Prof. Meeker at Iowa State Univ.

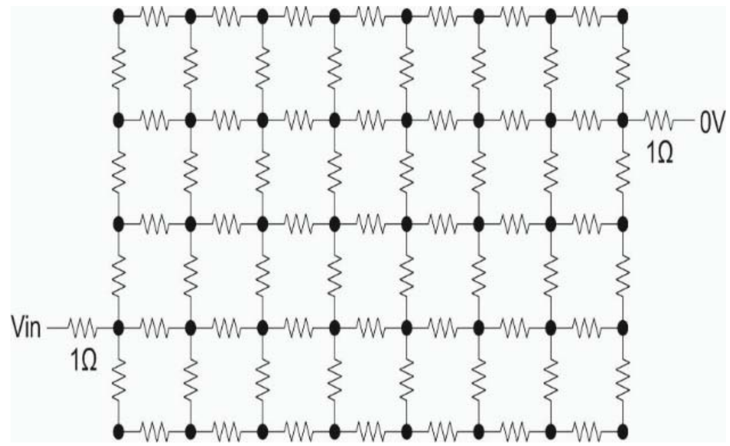
PD Approach: Carbon Nanotube Continuum Crack Gauge

- Crack gauges track flaw growth in known location
  - ➢ Addressing fleetwide fatigue problems or failure critical locations
  - ➢ Focusing on crack growth in metallic components
  - ➢ Can work in other materials, also other damage modes
- Commercial gauges are copper-foil resistive “ladders”
  - ➢ Some have implemented simple single “break-trace” versions
- Benefits over conventional metallic foil crack gauges
  - ➢ Not susceptible to corrosion
  - ➢ More mechanically durable under static & fatigue loads
  - ➢ No single point failures (such as a crack growing into a trace)
  - ➢ Continuous response (as opposed to fixed gated response)
  - ➢ Easy to fabricate in custom sizes and shapes, including cutouts
  - ➢ Capable of indicating crack orientation & length (w/2 electrode pairs)



CNT Crack Gauge Characteristics

- Physical characteristics
  - Thickness ~ 100 micron
  - Mass ~10 mg/cm²
  - Bend-radius ~ 5 mm
  - Footprint ~2x2 cm demonstrated
    - Ideally length of sensor >2x desired crack measurement
    - Ideally width between electrodes >1x length of sensor



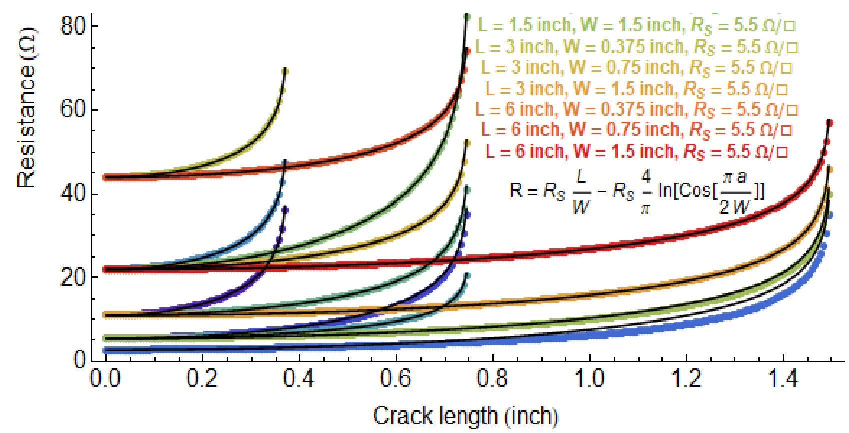
- Crack detection mechanism
  - Laminated CNT assembly bonds conformally to structure like strain gauge
  - CNT network electrical resistance changes proportional to crack length
  - Completely passive sensor, crack “recorded” even when no power applied
  - Temperature range tested -30 to 150° C
  - Strain range tested -4000 to 4000 $\mu\varepsilon$

CNT Network Resistance Modeling

- **ANSYS 18.1 finite element model of the CNT sensor with a crack**
  - ➢ Adjust electrode spacing & width, sheet resistance and crack length
  - ➢ Elements w/voltage degrees of freedom

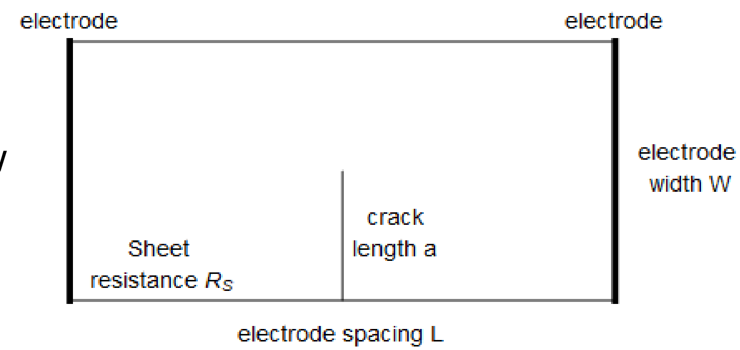
- **R fitted to:** $R = R_0 - R_S \frac{4}{\pi} \ln\left(\cos\left(\frac{\pi\, a}{2\, W}\right)\right)$

- **R_0 is resistance without crack:** $R_0 = R_S \frac{L}{W}$

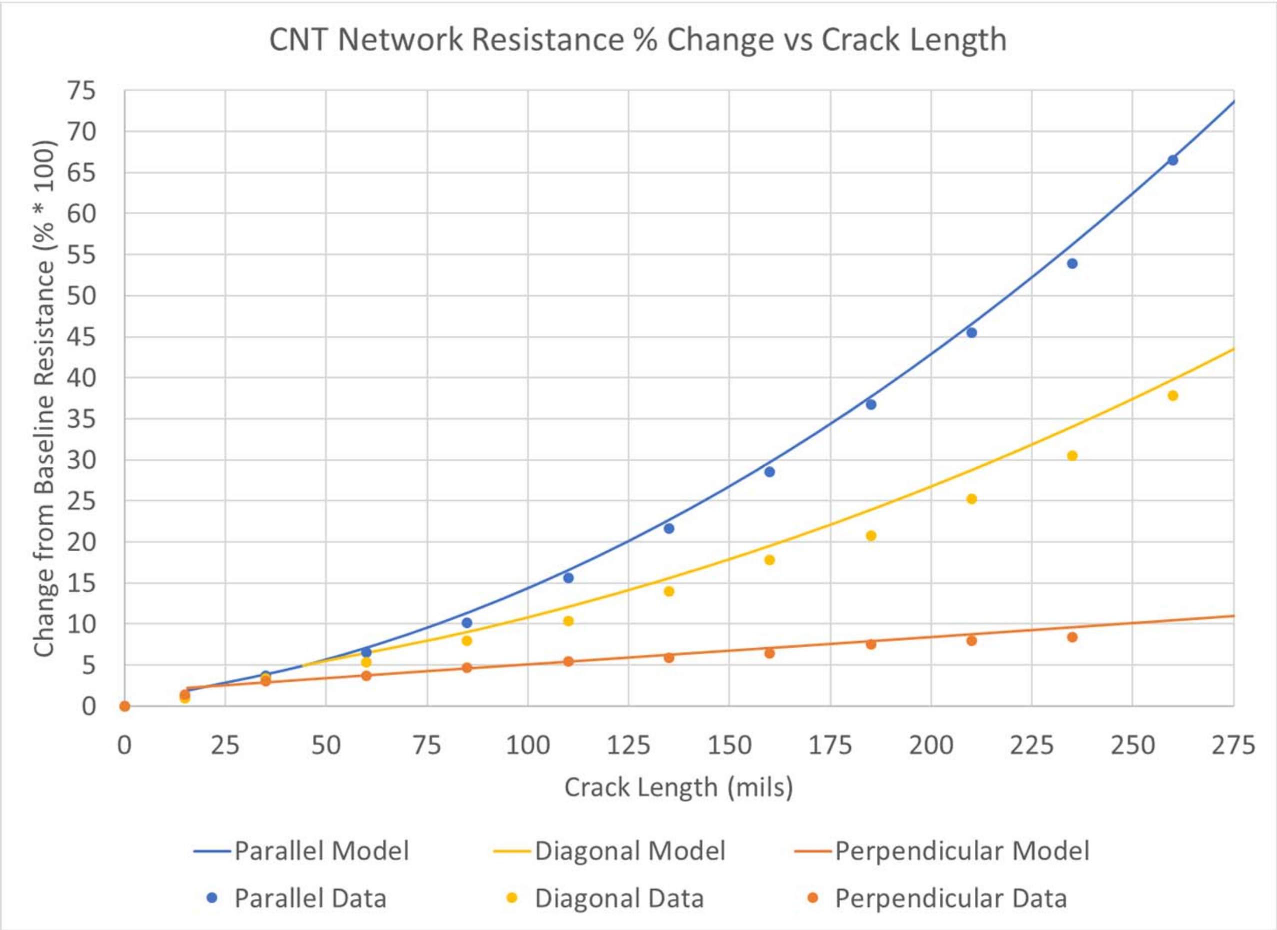


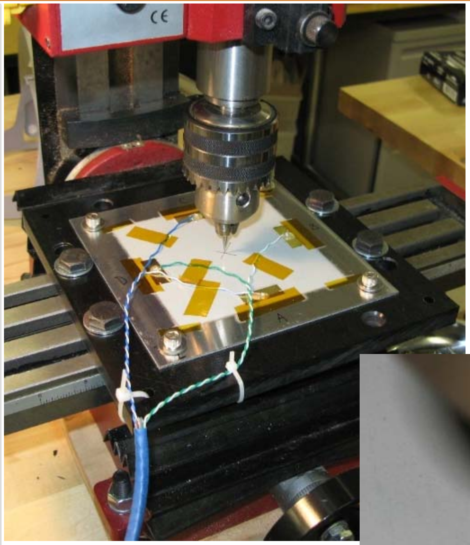
- **Equations fits well to results**
  - ➢ Except for W / L ≥ 2
  - ➢ Equation is approximately given by: $R = R_0 + R_S \frac{\pi\, a^2}{2\, w^2}$ *for small* a/w

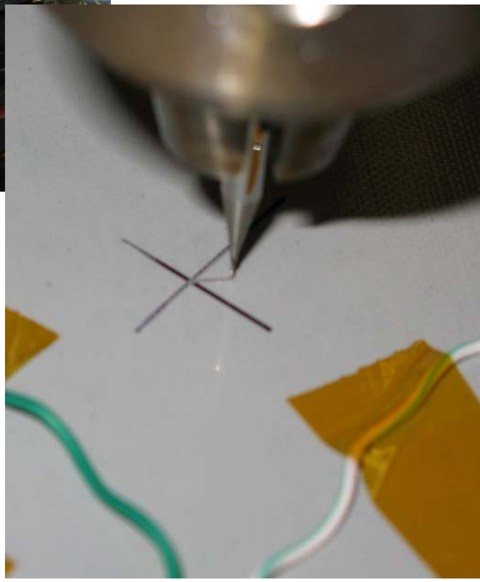
$a = G_f \sqrt{R}$ *for cracks that are less than half the gauge width*



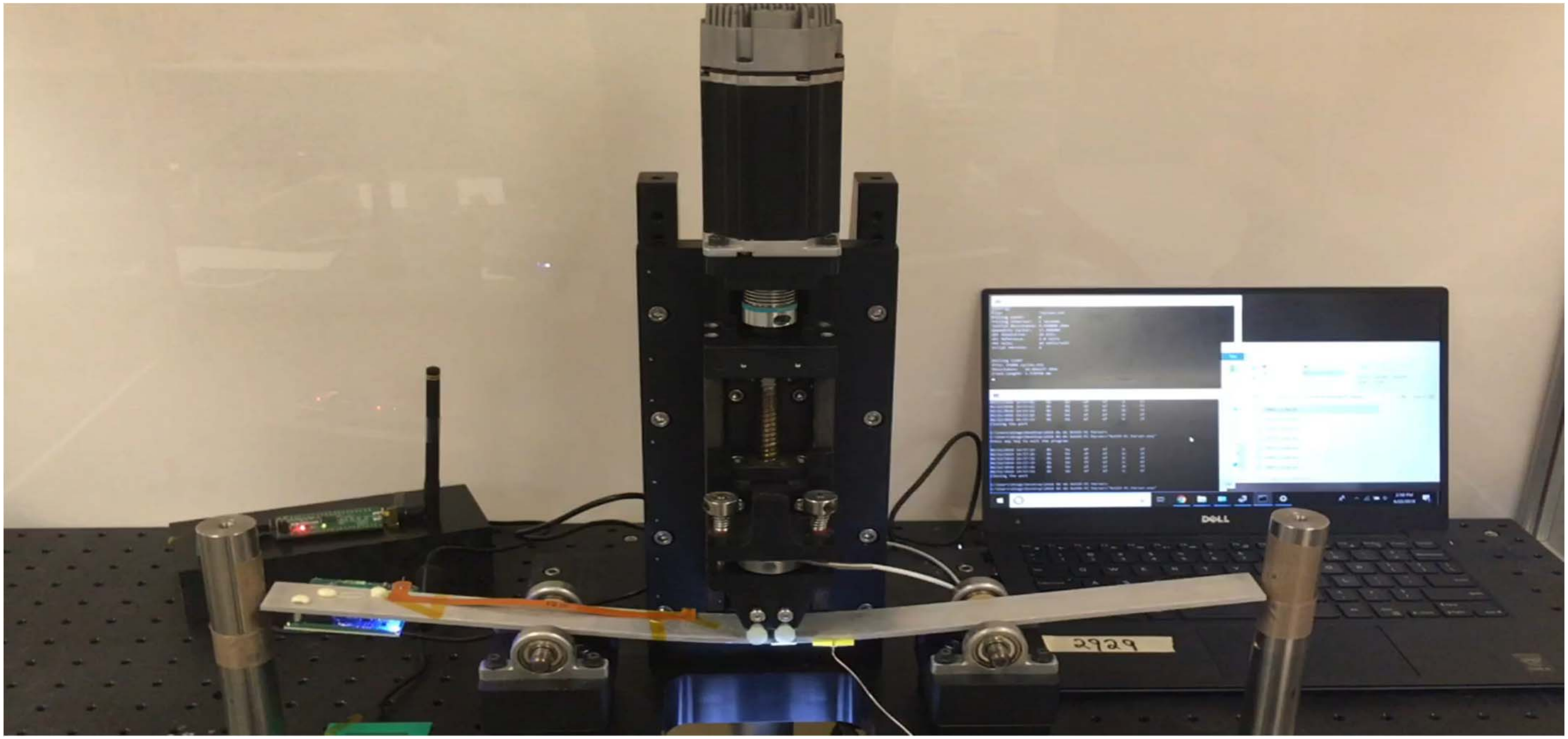
CNT Crack Gauge Model 2D Validation







Hyperlapse Video of 4-Point Bending Fatigue in Action @ 3300 $\mu\varepsilon$



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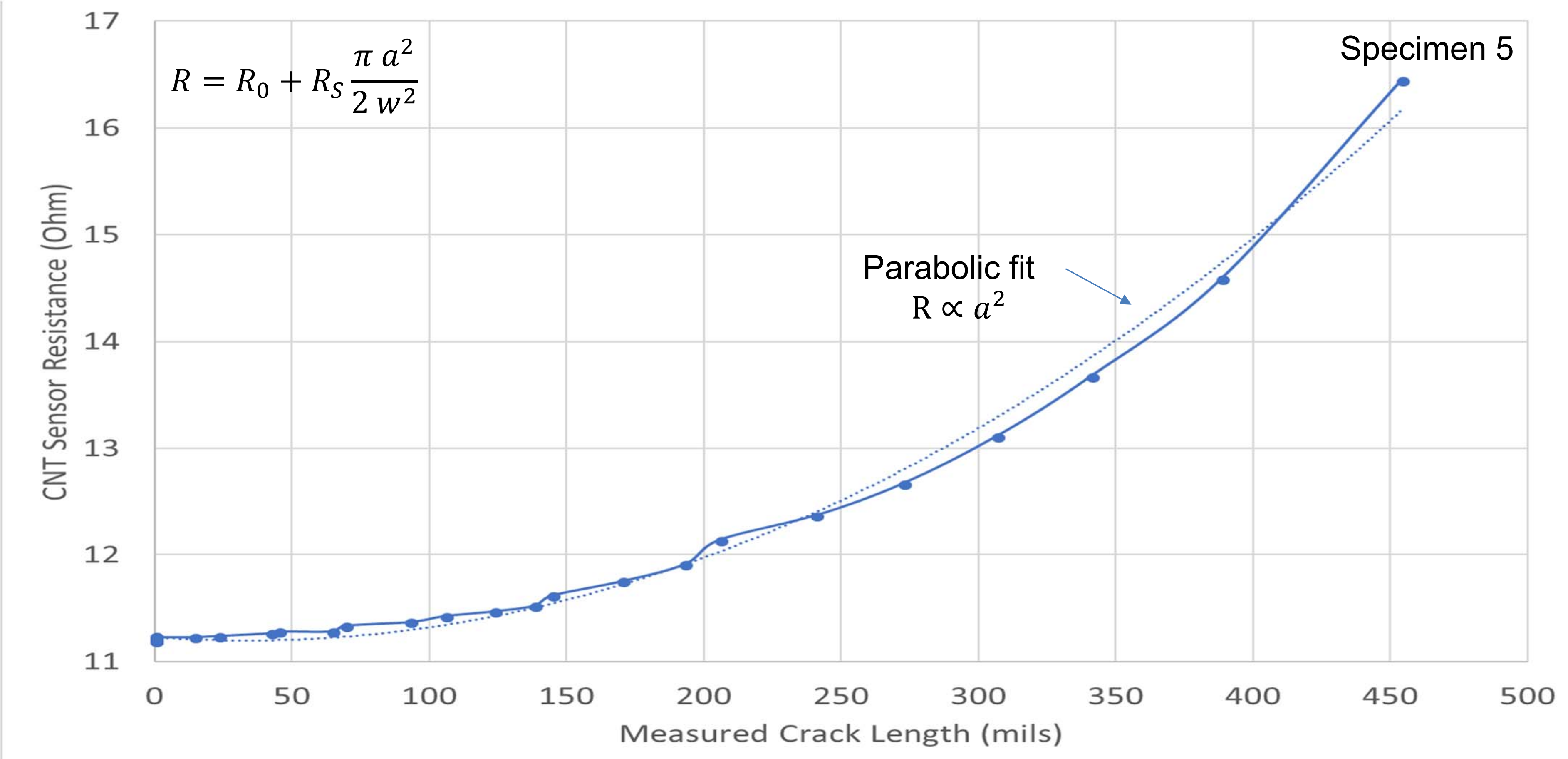
Resistance vs Measured Crack Length



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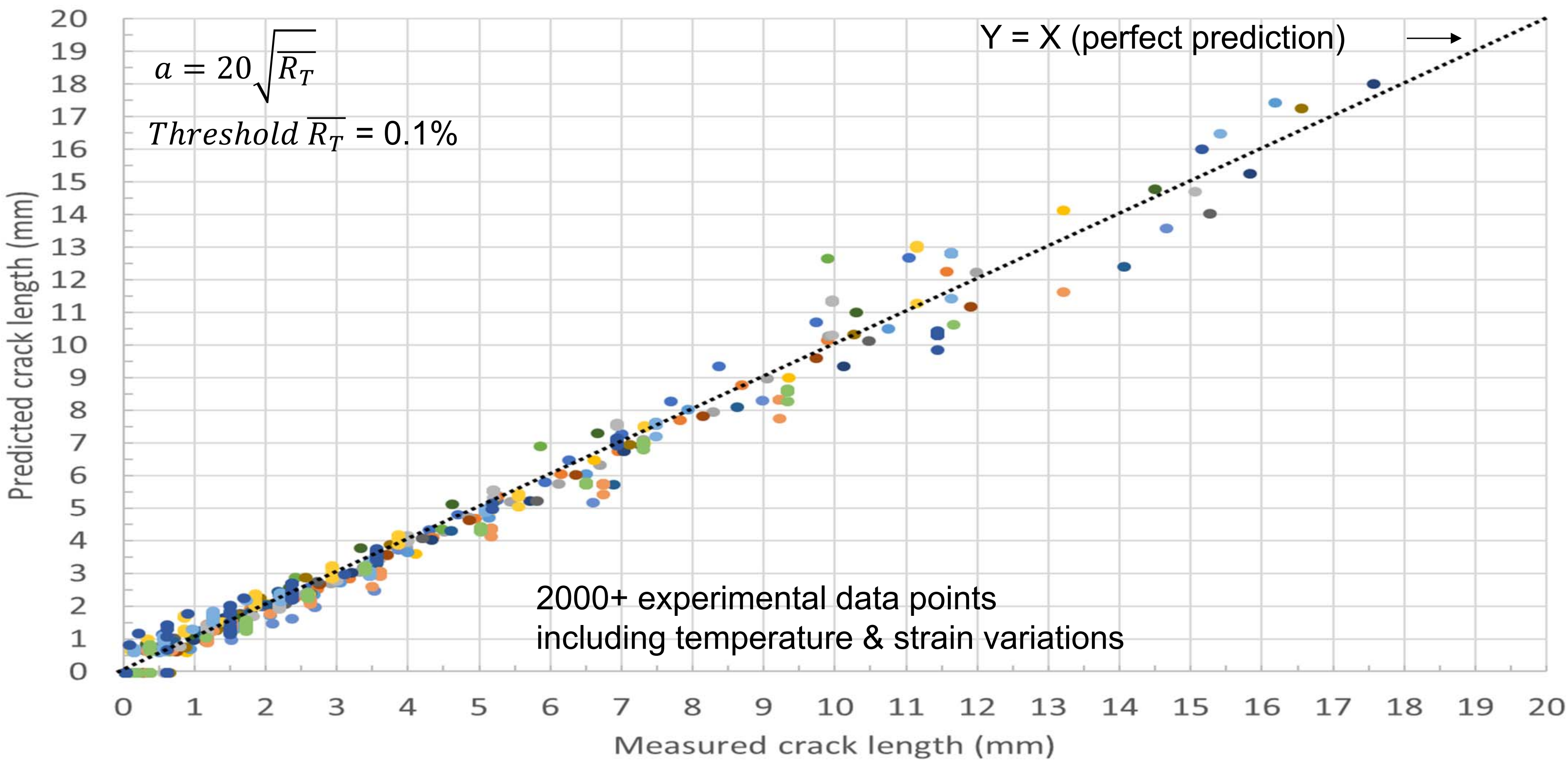
Predicted Crack Length vs Measured Crack Length



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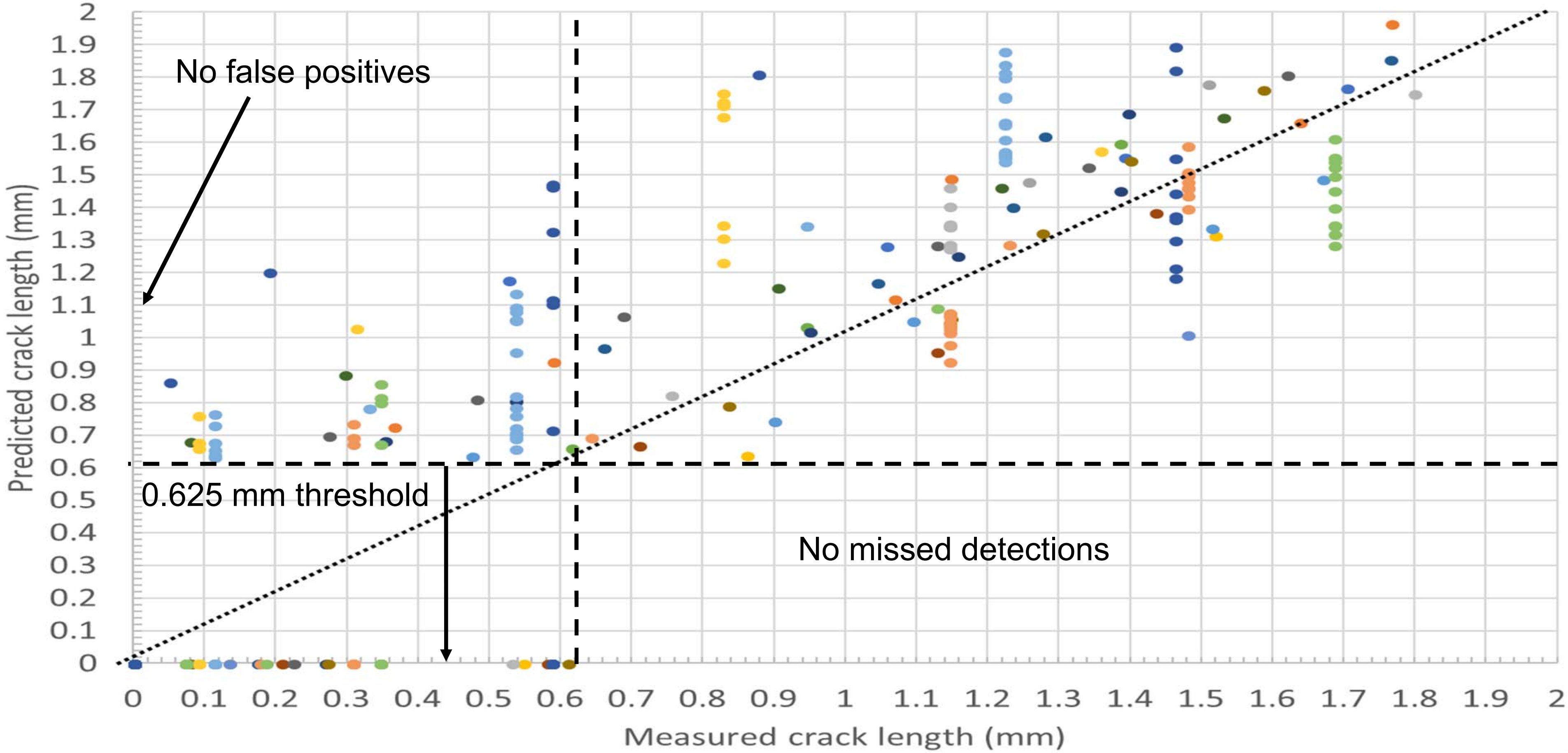
Zoomed Predicted Crack Length Comparison



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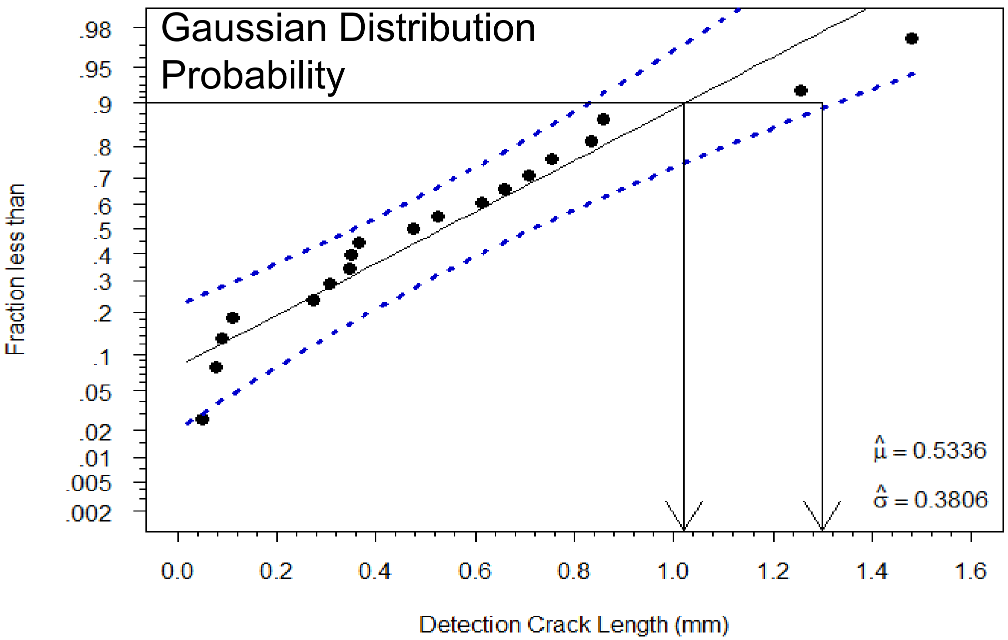
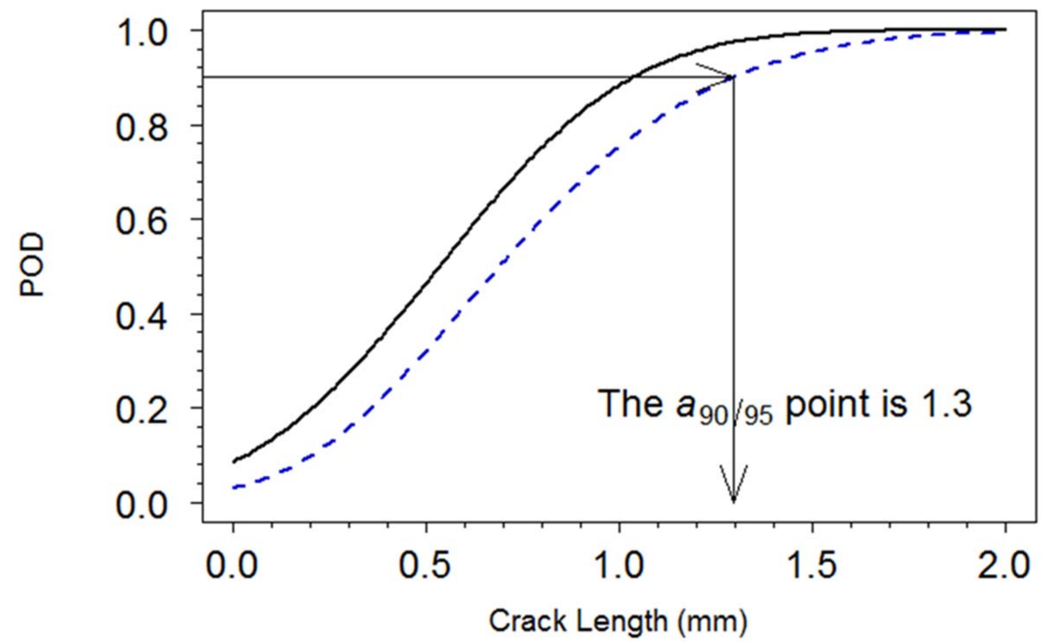
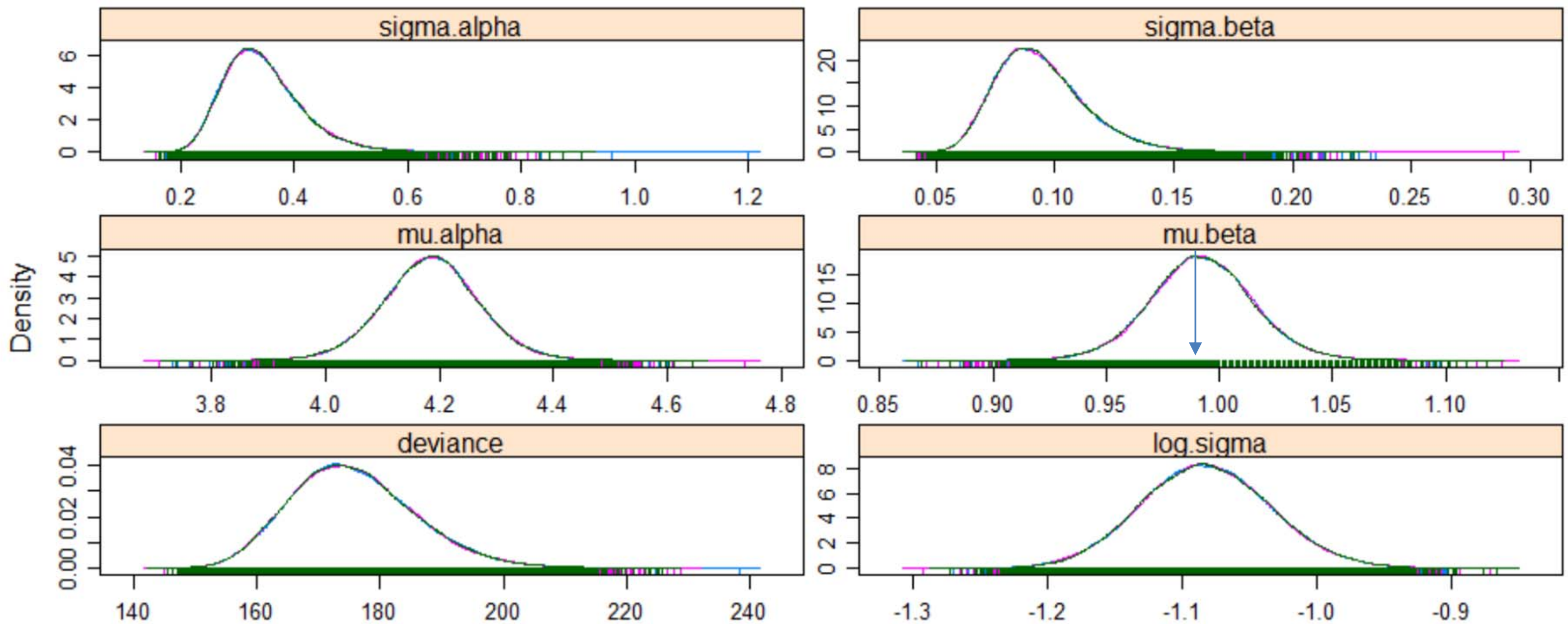
PD Method Detection Sensitivity using Length at Detection Method





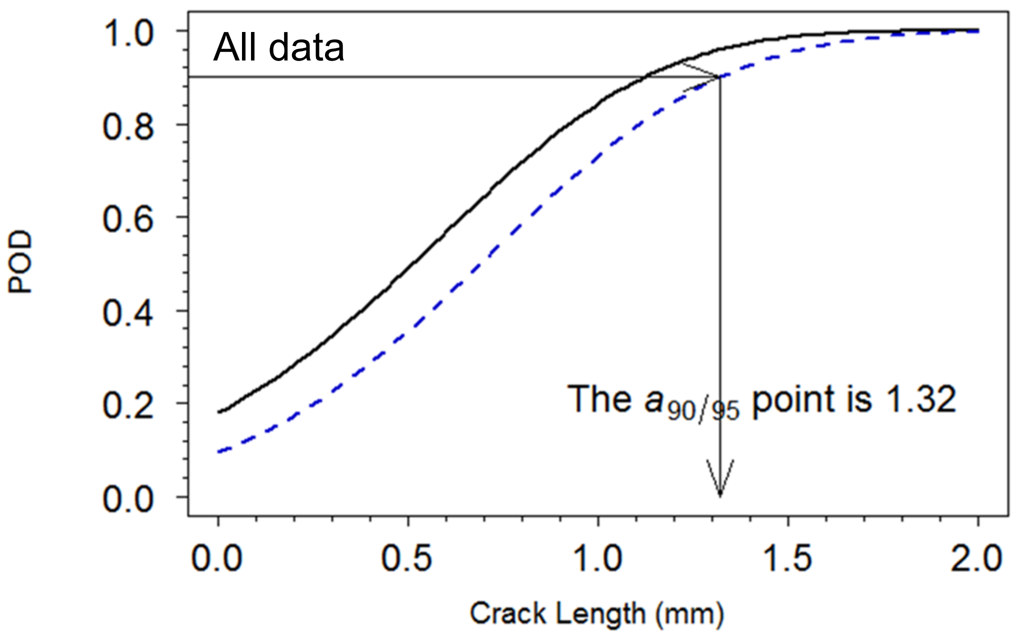
- **PD detection data is best fit by a gaussian distribution**
- **LaD provides an $a_{90/95}$ of 1.3 mm based on data *up until detection***
- **Statistical analysis performed by Prof. Meeker @ ISU as consultant under AFRL SBIR**

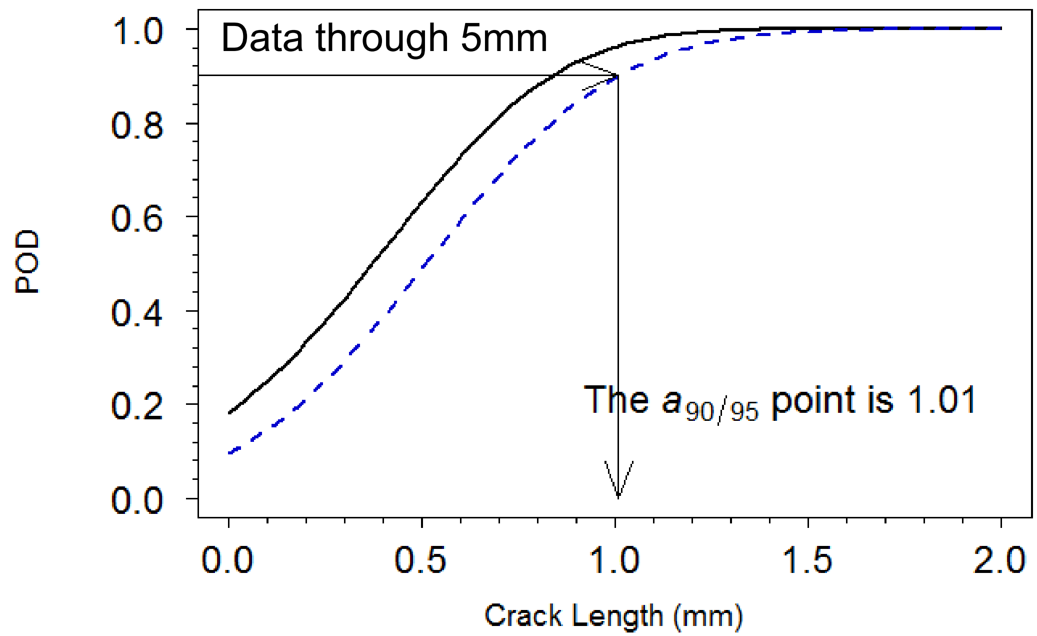
PD Method Detection Sensitivity using Random Effects Model



- Density Plots of Bayesian Estimation Results
- “mu beta” parameter indicates a mean slope of 0.99 (perfect = 1)
- Prediction error of ±5% for 2 standard deviations

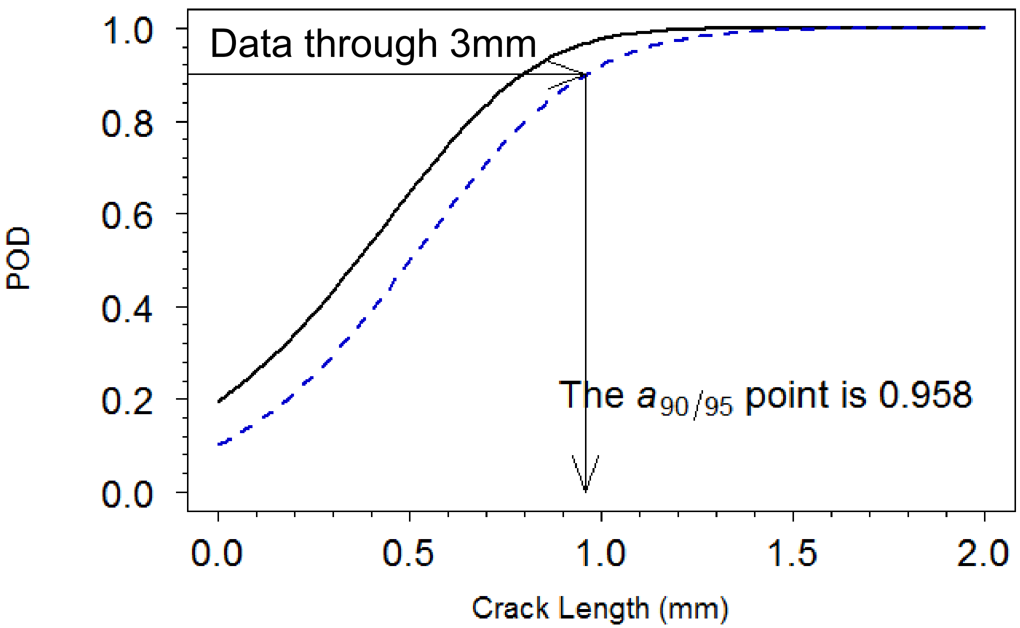
PD Method Detection Sensitivity using Random Effects Model (cont)

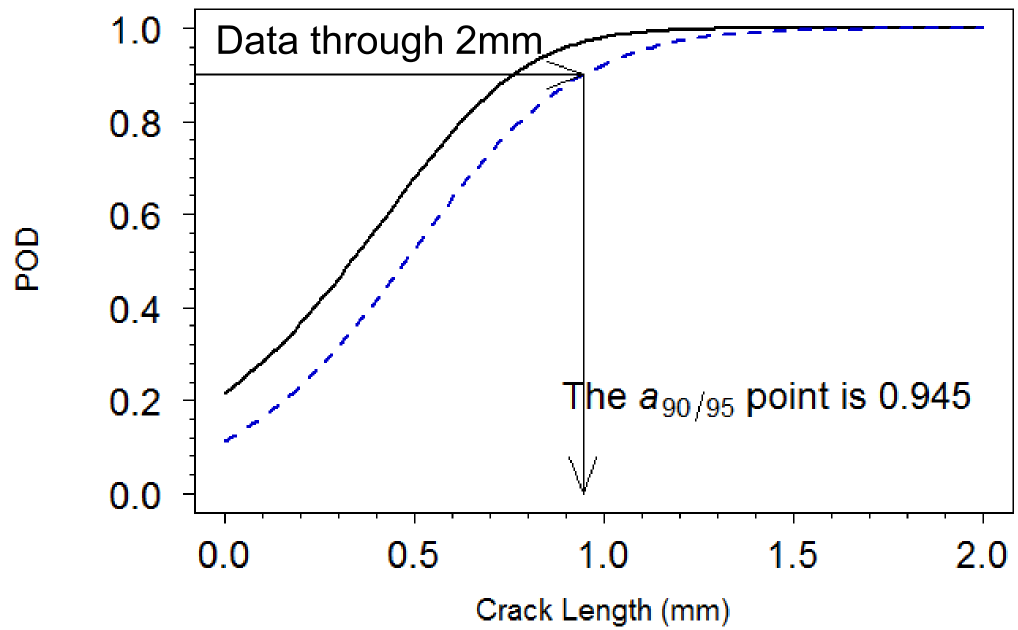




- **REM[2] provides an $a_{90/95}$ of 1.32 mm based on all data (up to 18 mm)**
- **$a_{90/95}$ improves to 1.01 mm when only considering data up through 5 mm**
- **Statistical analysis performed by Prof. Meeker @ ISU as consultant under AFRL SBIR**

PD Method Detection Sensitivity using Random Effects Model (cont)





- **$a_{90/95}$ improves to 0.958 mm when only considering data up through 3 mm**
- **$a_{90/95}$ improves to 0.945 mm when only considering data up through 2 mm**
- **Still considering appropriate approach for determining how much data to consider**

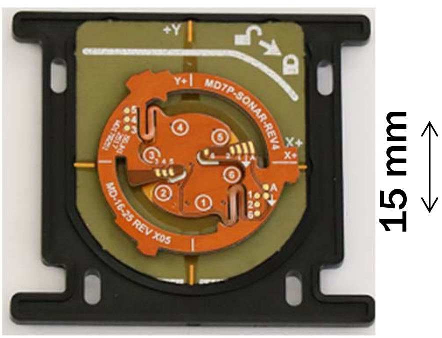
Comparison of PoD Approaches

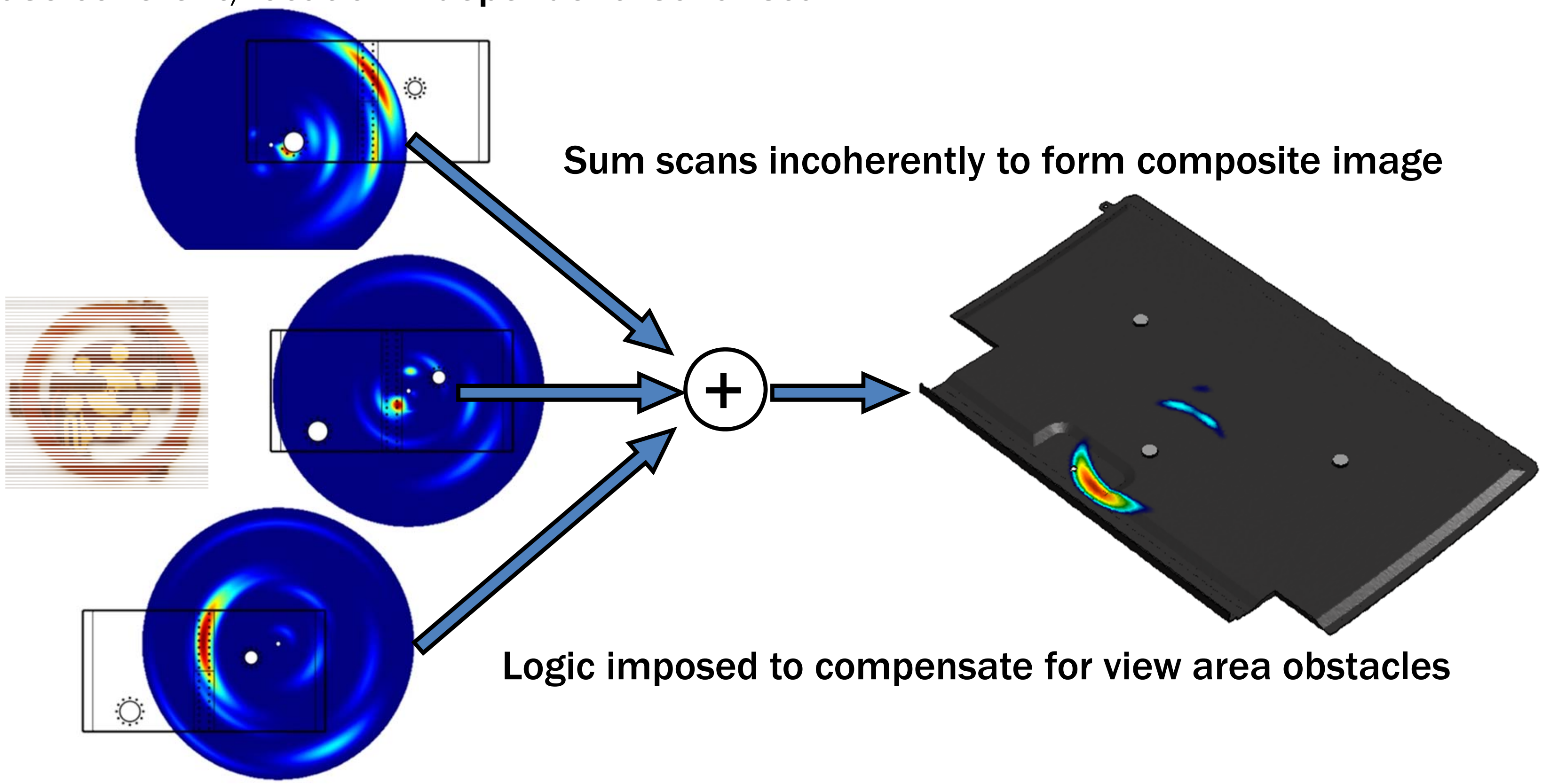
- Length-at-Detection (LaD) method
  - Computationally simple
  - Requires a minimal amount of data (just until first detection)
  - Requires assumption about distribution of detectable crack sizes (e.g., normal or lognormal), with little information to discriminate among different assumptions that might give vastly different $a_{90/95}$ values
  - $a_{90/95}$ of 1.3 mm calculated for data at first detection

- REpeated-measures random-effects model (REM^2) method
  - Uses available data more efficiently
  - More information to check model assumptions
  - More robust to departures from model assumptions
  - Provides a framework for model-assisted probability of detection (MAPOD)
  - More complicated computational algorithms are needed
  - $a_{90/95}$ of 1.3 mm calculated with all data, improves to <1 mm for considering less data post-detection

GW Approach: Beamforming PZT Array for Guided Wave Detection

Each node processes phase-coherent, location independent "sonar-scan"





Sum scans incoherently to form composite image

Logic imposed to compensate for view area obstacles

Color represents # of standard deviations above mean of damage-free data

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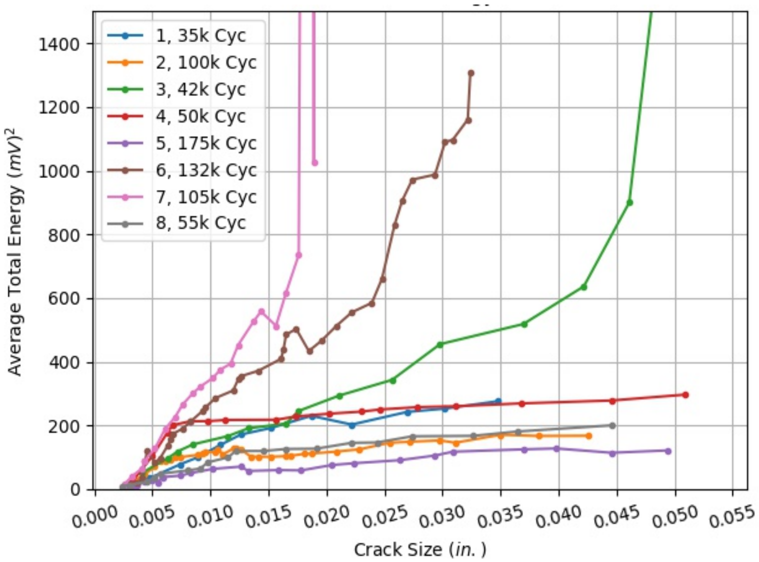
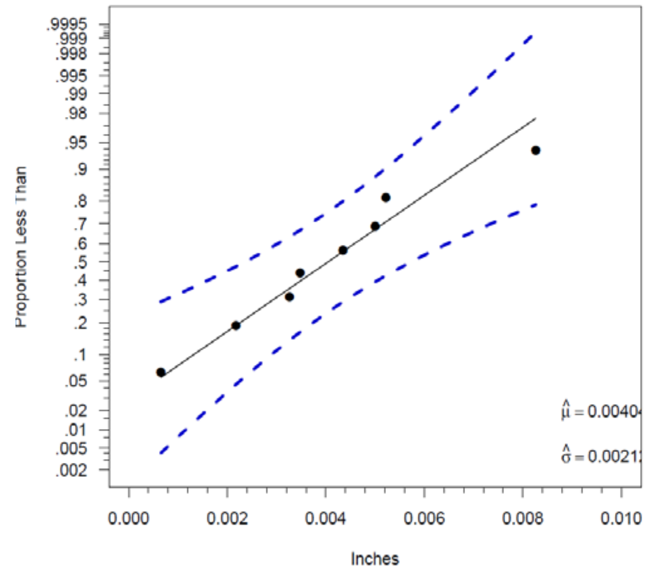
GW Method Detection Sensitivity using Length at Detection Method

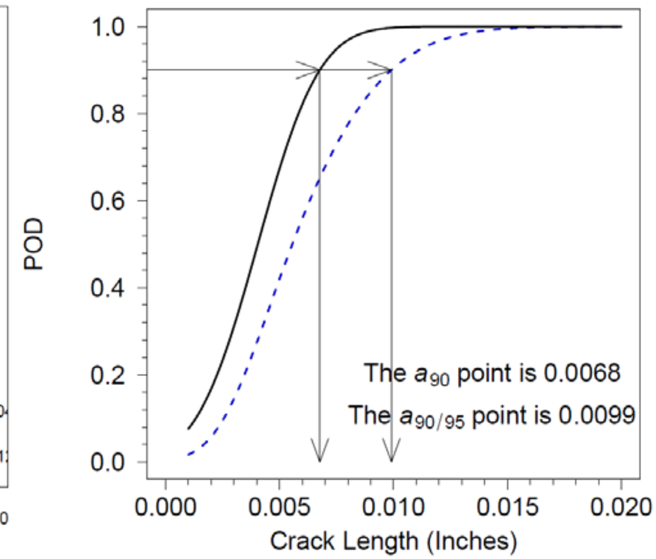
Pitch-Catch Energy Metric vs Crack Length



Normal Distribution Plot



Sensitivity using LaD



- **Identical sensitivity study performed using 2 GW sensors bonded at ends of Al beam**
- **GW detection data is best fit by a normal distribution**
- **LaD provides an $a_{90/95}$ of 0.25 mm based on data *up until detection***
- **Statistical analysis performed by Prof. Meeker @ ISU as consultant under AFRL SBIR**

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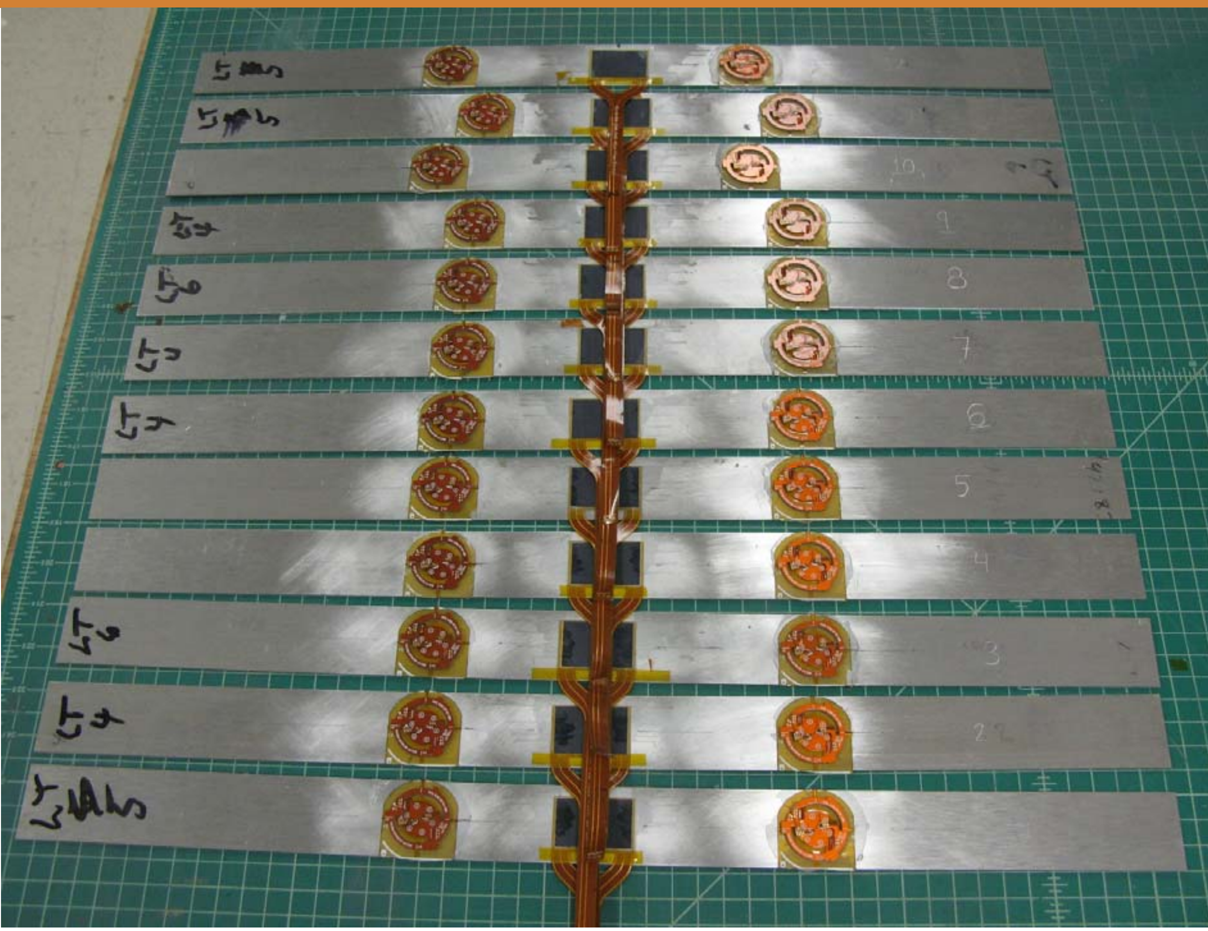
Blind Sensitivity Testing for PD & GW Methods at FAA Tech Center



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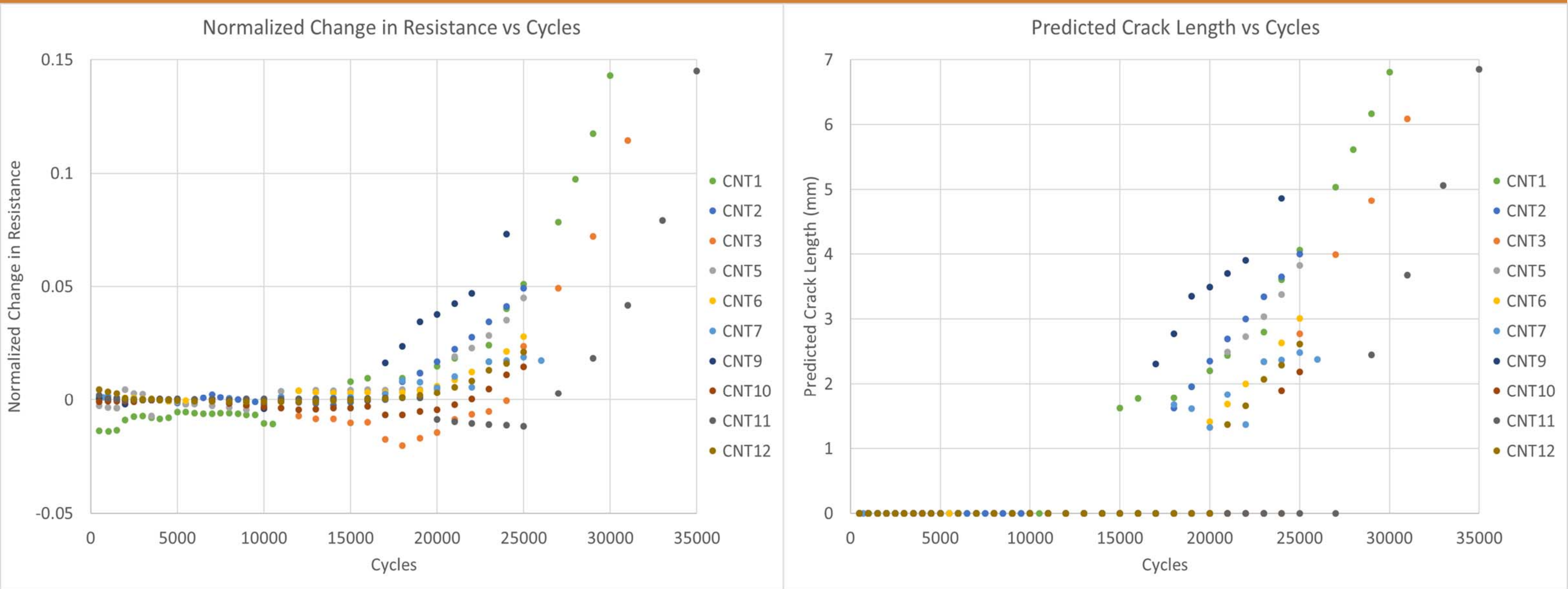
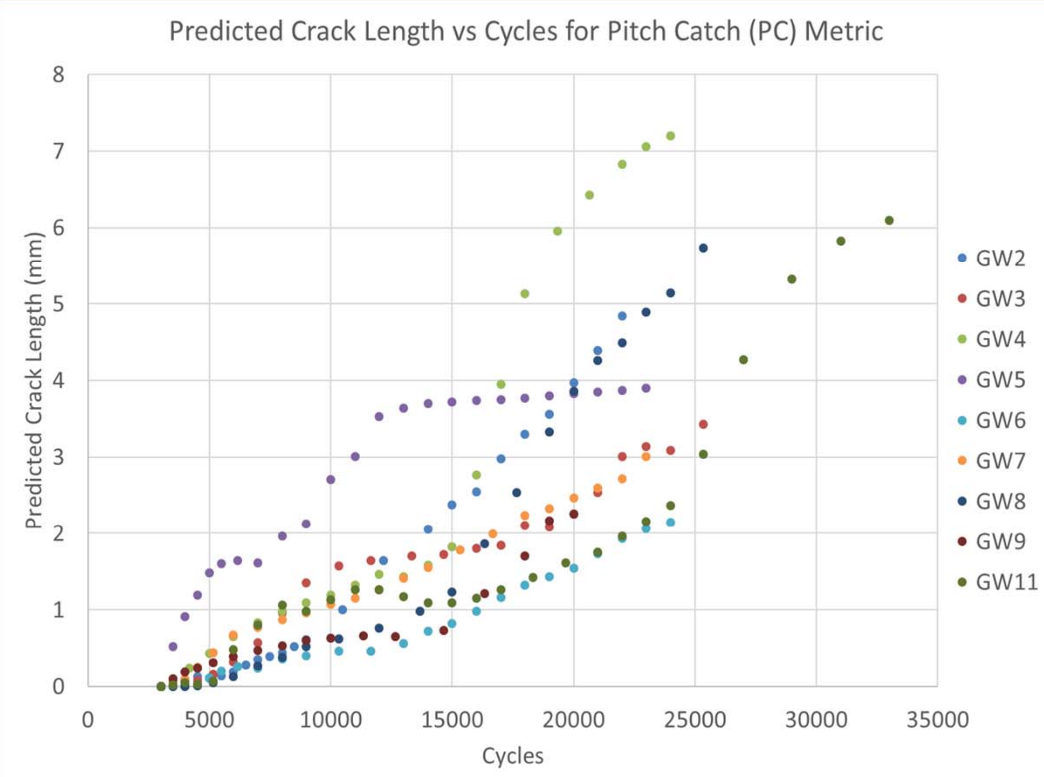
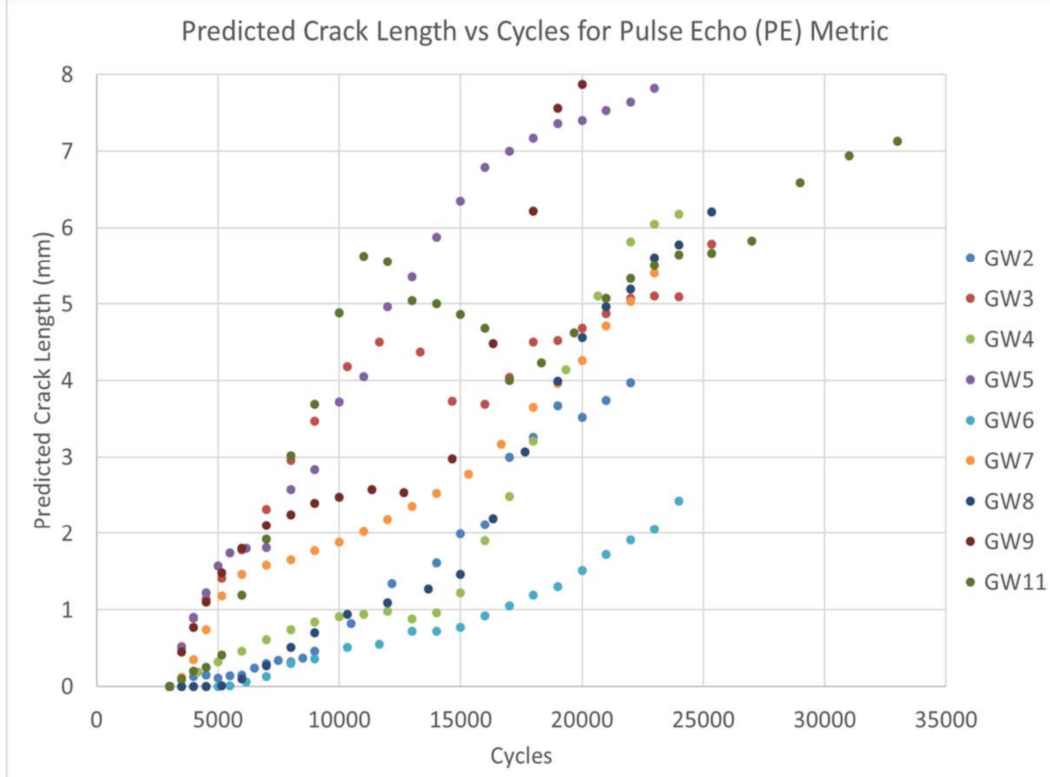
Initial PD Results from FAA Detection Sensitivity Study



- **Recently completed damage metric formulation for PD data from blind testing**
- **Next step is statistically analysis for sensitivity metric formulation by Prof. Meeker @ ISU**

Initial GW Results from FAA Detection Sensitivity Study





- Recently completed damage metric formulation for GW data from blind testing
- Next step is statistically analysis for sensitivity metric formulation by Prof. Meeker @ ISU

Summary & Future Work

- Recent work investigating detection sensitively for PD & GW SHM methods
  - Two programs using 4-pt bending fatigue of Al beams funded through AFRL WPAFB & WR-ALC
  - CRDA with FAA for tensile-tensile fatigue of Al/Li beams
  - Collaboration with Prof. Meeker at Iowa State University for statistical analysis
  - Two statistical approaches: Length at Detection and Repeated Measured Random Effects Model

- Initial detection sensitivity results have been produced for AFRL funded research
  - Results have been encouraging for LaD & REM^2 approaches as applied 2 very different sensor physics
  - FAA study results to be analyzed within the coming months, 2 other companies also participating

- Future work
  - Need to collect more data to be able to validate one or more alternative approaches vs MIL-1823A
  - Combining analytical/finite element for model-assisted probability of detection (MAPoD)

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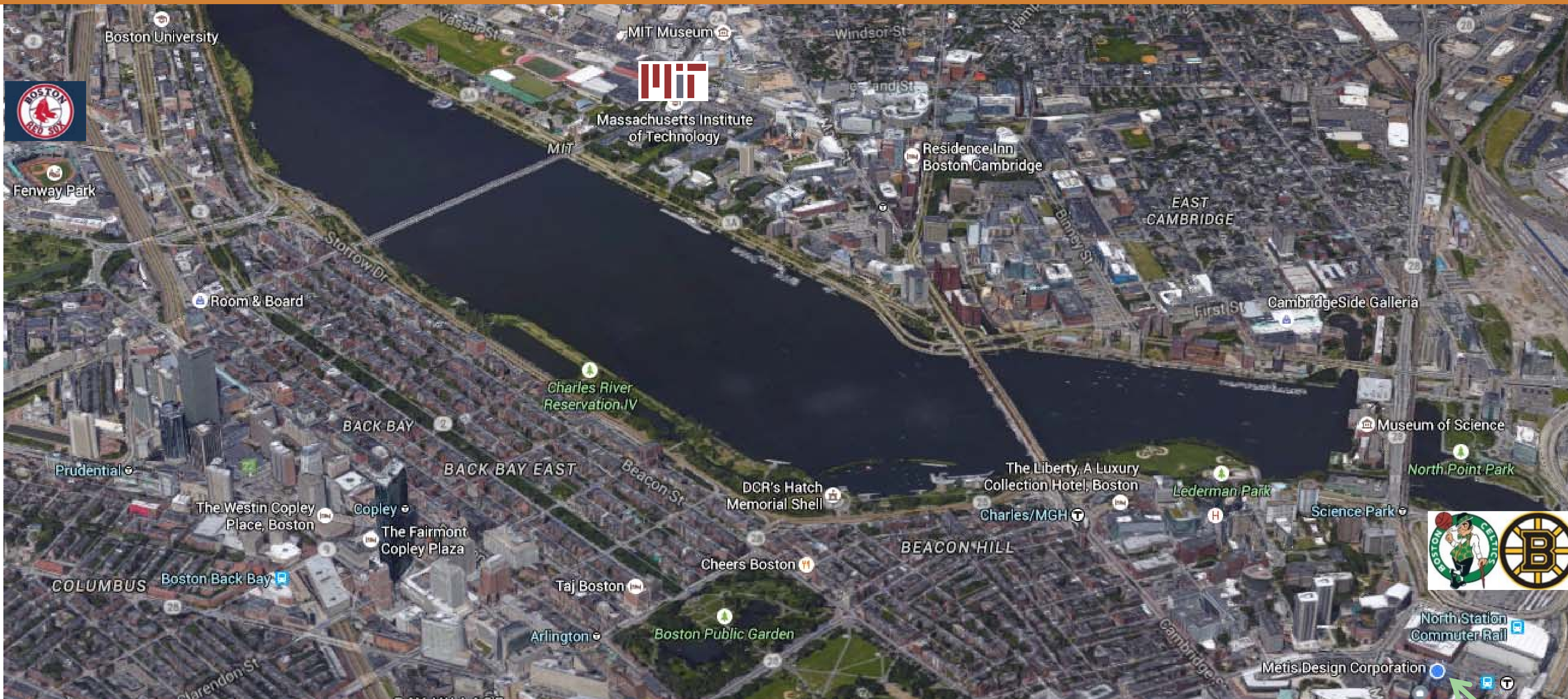

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