Detection Sensitivity Analysis for a Potential Drop (PD) Structural Health Monitoring (SHM) System

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structural health monitoring
multi-functional materials
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Introduction

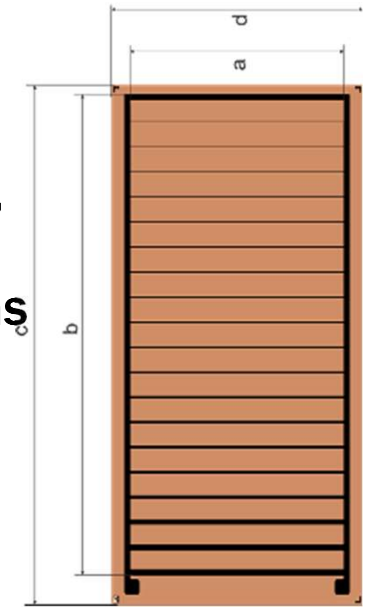
- SHM uses permanently integrated non-destructive sensors
  - Many viable strategies for measuring local or global damage
  - Potential Drop (PD) methods use change in resistance to indicate a flaw

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

- Challenging to obtain $a_{90/95}$ for SHM using traditional approaches
  - Expensive due to permanent sensor installation, need for many specimens
  - Length at Detection (LaD) developed at Sandia as an alternative approach
  - REpeated Measures Random Effects Model (REM^2) developed by Prof. Meeker at Iowa State University

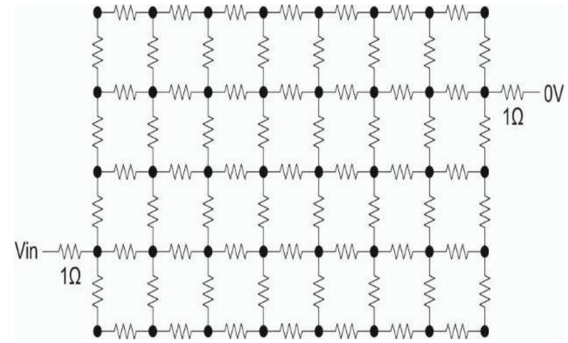
Carbon Nanotube Continuum Crack Gauge

- 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
  - ➢ Continuous response (as opposed to fixed gated response)
  - ➢ More mechanically durable under static & fatigue loads
  - ➢ Not susceptible to corrosion
  - ➢ Easy to fabricate in custom sizes and shapes, including cutouts
  - ➢ Capable of indicating crack orientation & length (w/2 electrode pairs)

CNT Crack Gauge Characteristics

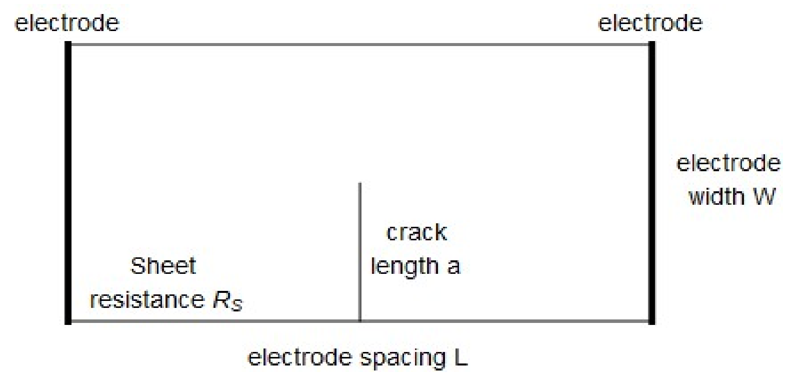


- Physical characteristics
  - ➢ Thickness ~ 100 micron
  - ➢ Mass ~10 mg/cm^2
  - ➢ Bend-radius ~ 5 mm
  - ➢ Footprint ~2x2 cm demonstrated
    - — Ideally length of sensor >2x desired crack measurement
    - — Ideally width between electrodes >1x length of sensor

- 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 με

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

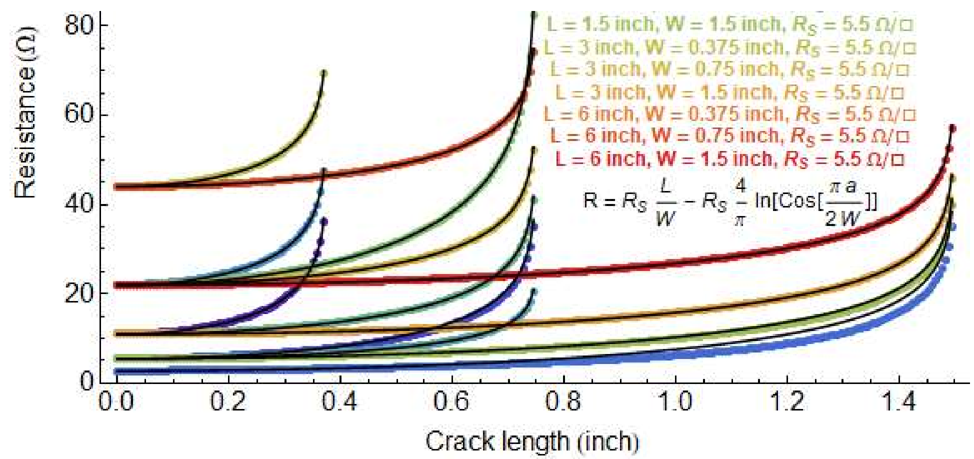


- **R fitted to:**

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

- **R_0 is resistance without crack:**

$$R_0 = R_S \frac{L}{W}$$



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

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Simple Crack Length Estimation Algorithm

- **Solving for crack length as a function of normalized resistance change**

$$a = \sqrt{\left(\frac{R}{R_0} - 1\right)\left(\frac{2\,wL}{\pi}\right)} \quad \textit{small } a/w$$

$$\bar{R} = \left(\frac{R}{R_0} - 1\right) \text{ and } \mathrm{G}_f = \sqrt{\left(\frac{2\,wL}{\pi}\right)} = \sqrt{\left(\frac{2*18\text{ mm}*38\text{ mm}}{\pi}\right)} = \text{~20 mm gauge factor}$$

$$a = \mathrm{G}_f\sqrt{\bar{R}} \quad \textit{for cracks that are less than half the gauge width}$$

- **However resistivity is a function of temperature (inversely)**

$$R_S = R_{S0}(1 - \gamma\Delta T) \text{ where } R_{S0} = R_0\frac{W}{L} \text{ at } \Delta T = 0$$

$$a = \sqrt{\left(\frac{R}{R_0(1 - \gamma\Delta T)} - 1\right)\left(\frac{2\,wL}{\pi}\right)} \quad \textit{small } a/w$$

$$\overline{R_T} = \left(\frac{R}{R_0(1-\gamma\Delta T)} - 1\right) \quad \textit{where } \gamma \textit{ is the thermal sensitivity coefficient}$$

$$a = \mathrm{G}_f\sqrt{\overline{R_T}} \quad \textit{for cracks that are less than half the gauge width}$$

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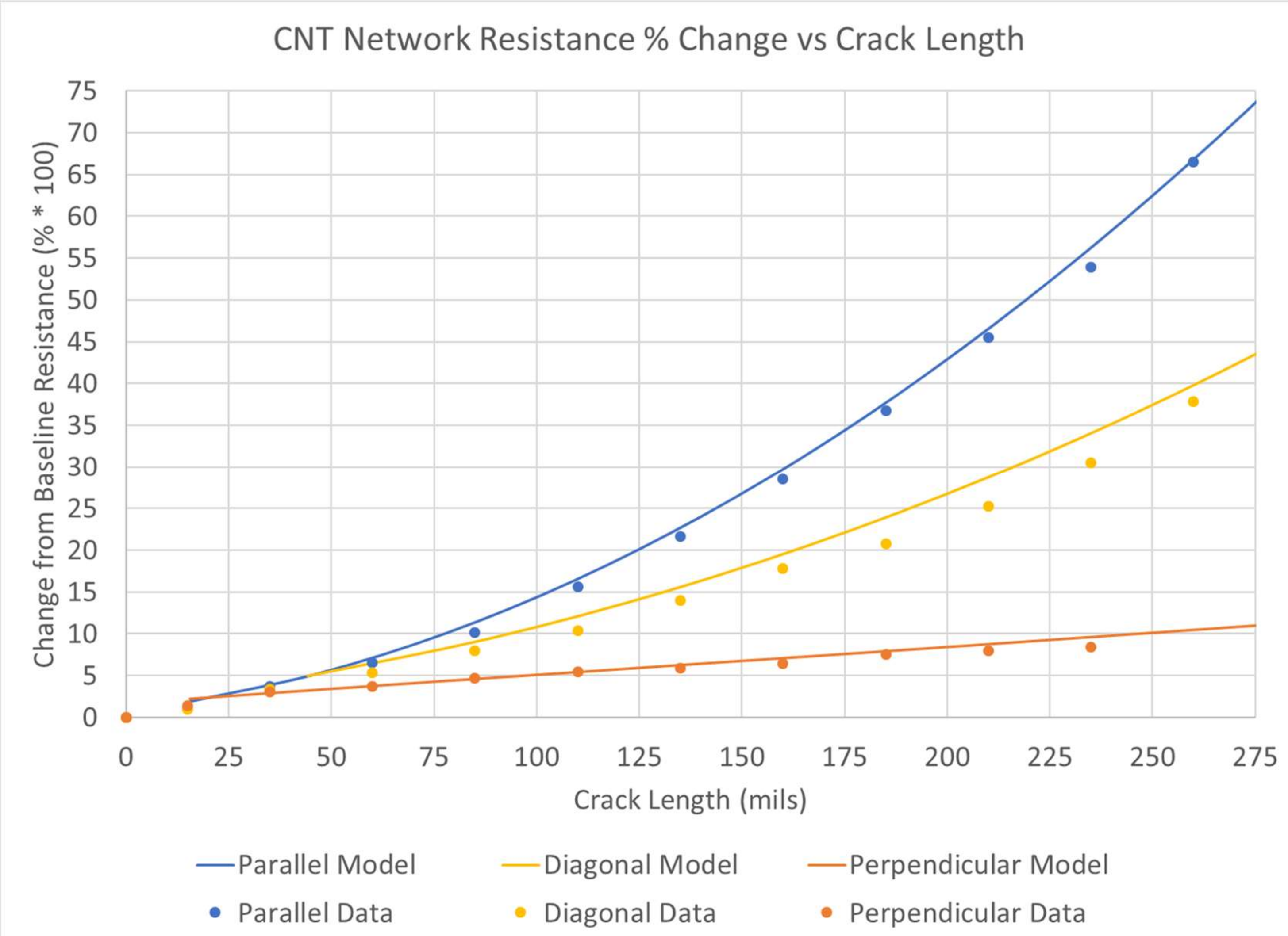
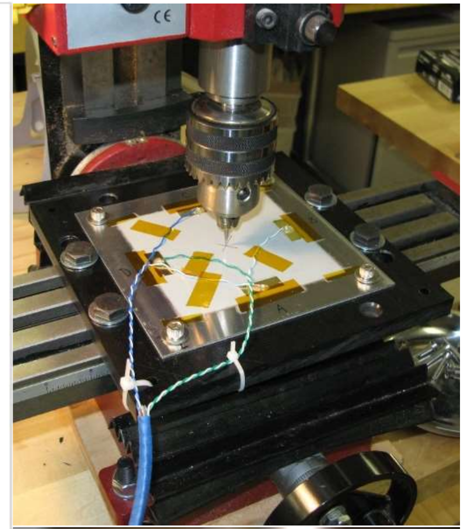
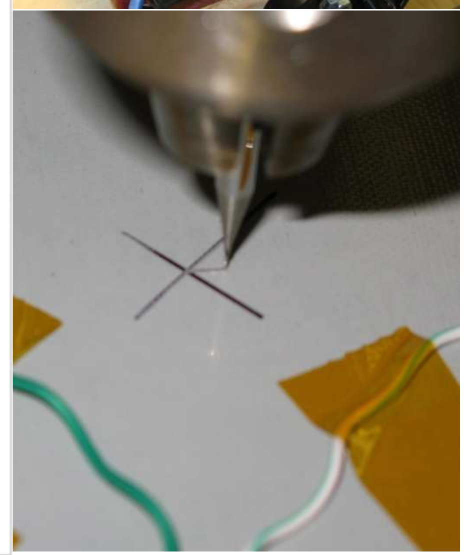
CNT Crack Gauge Model 2D Validation

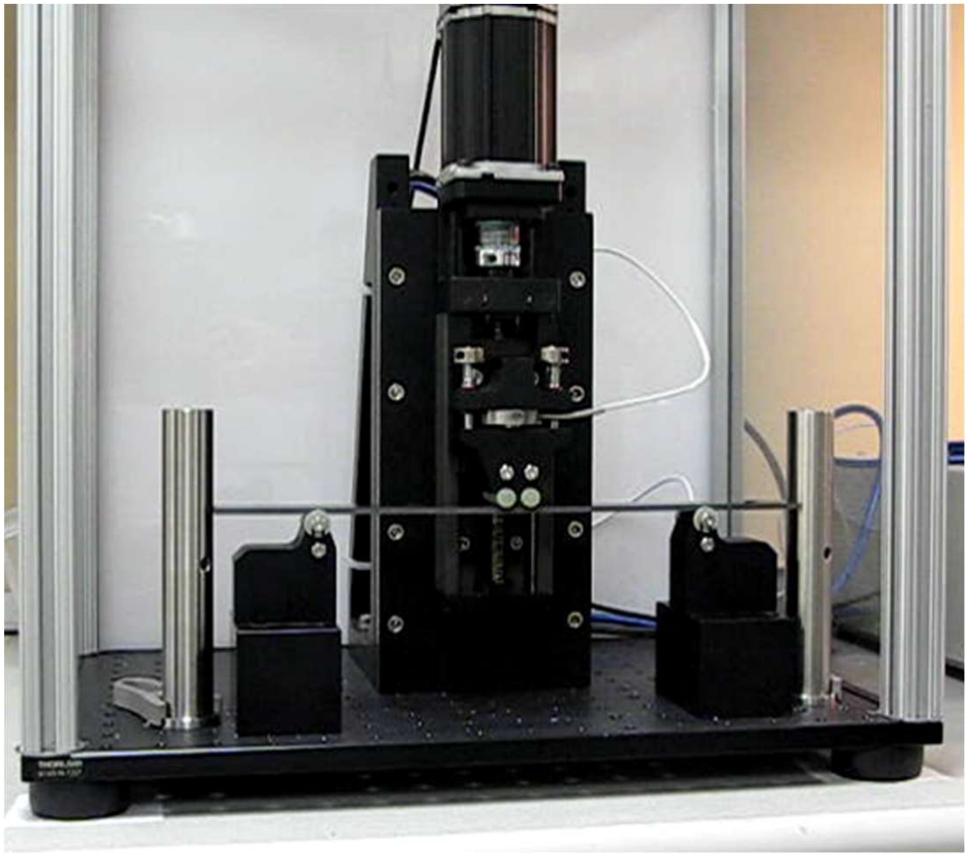


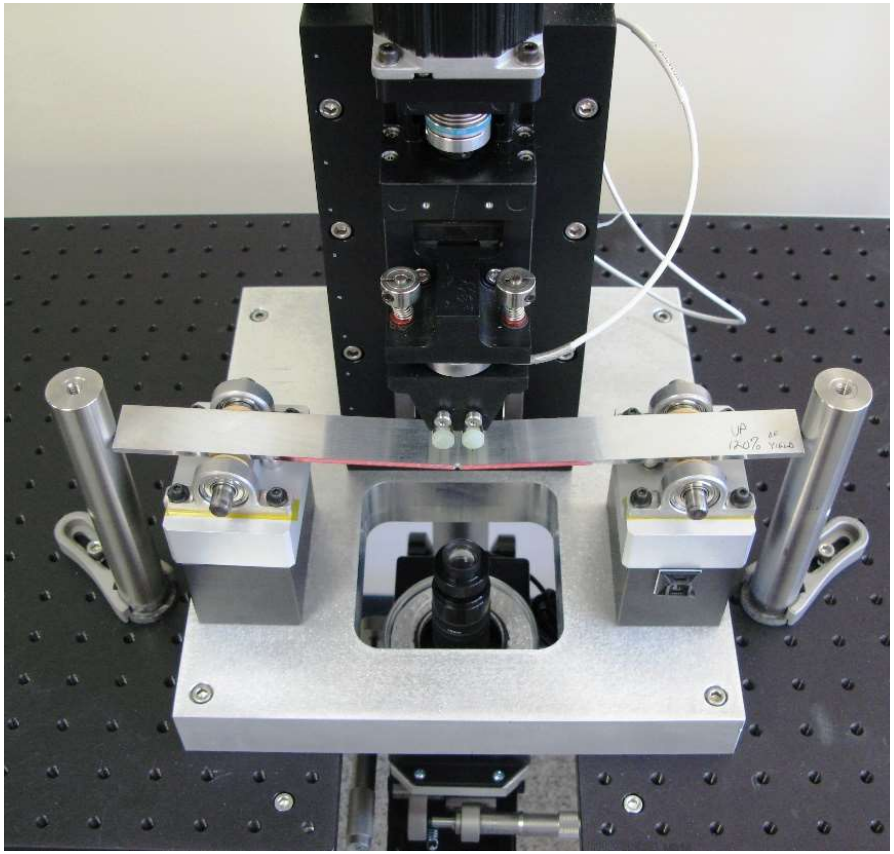




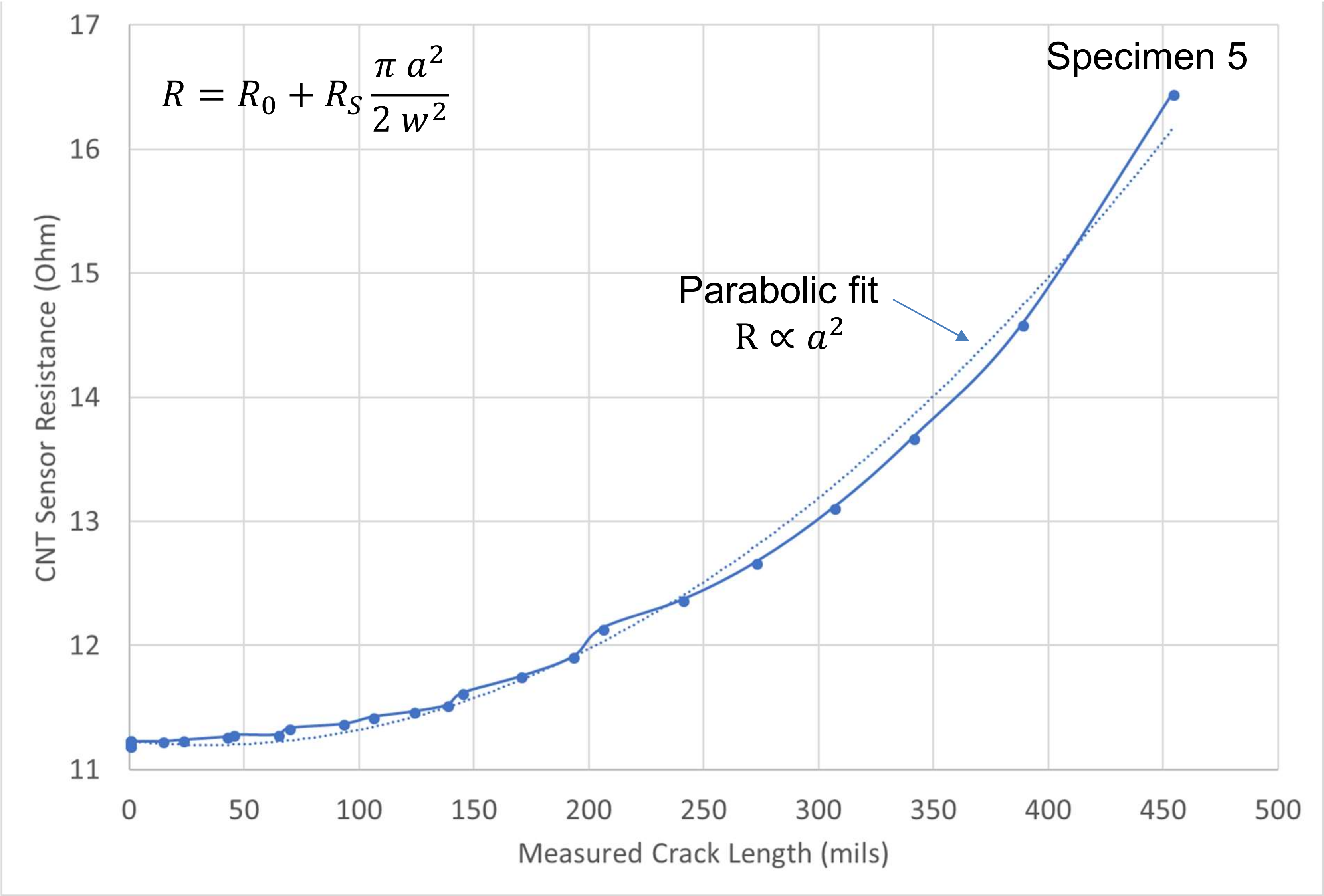
Automated 4-Point Test Bending Rig

- 25 mm between inner rollers, 200 mm between outer rollers
- Constant moment between inner rollers, 3300 $\mu\varepsilon$ (80% yield)
- Cycles at 1Hz while collecting load, stroke, temp, CNT resistance





Resistance vs Measured Crack Length Example



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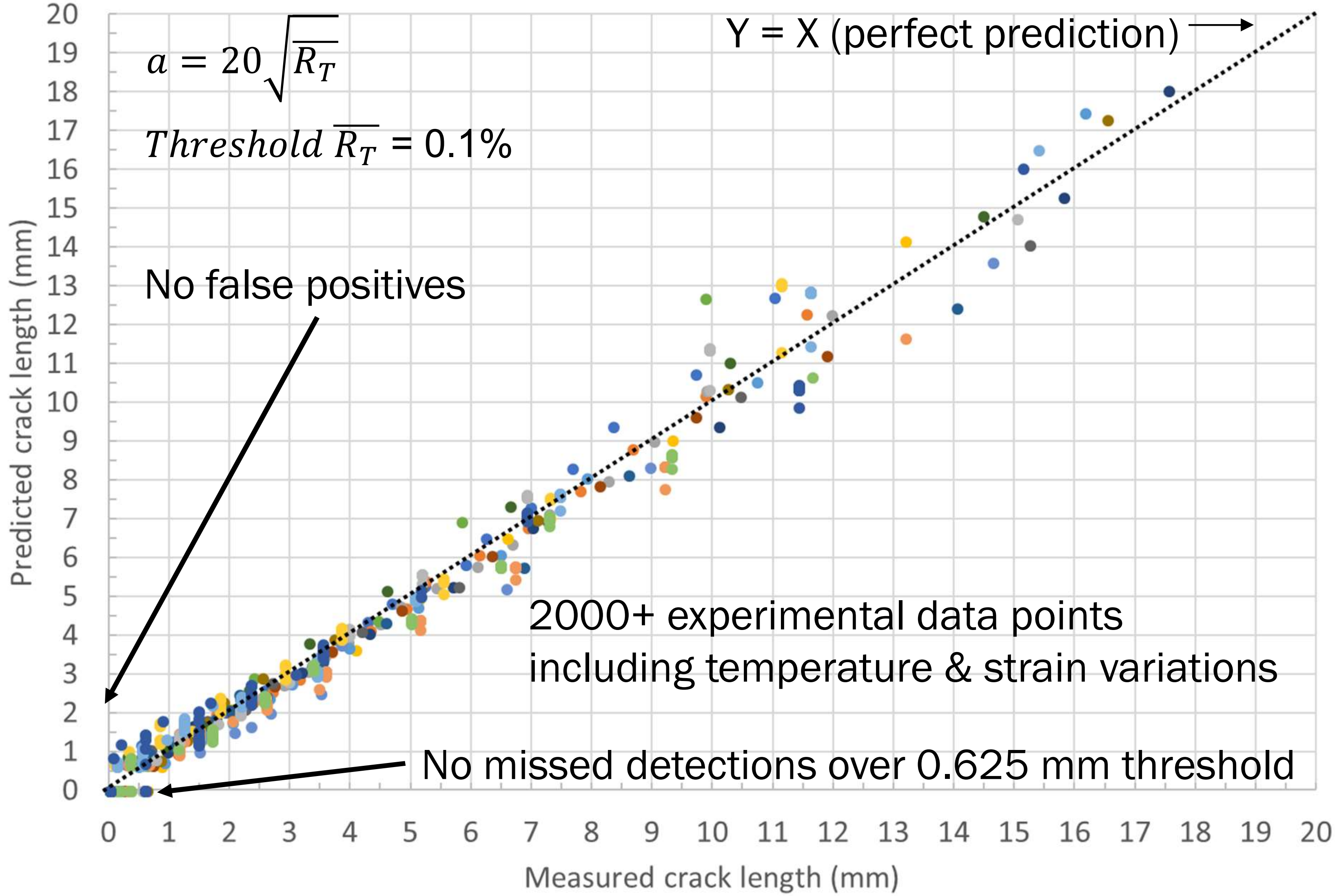
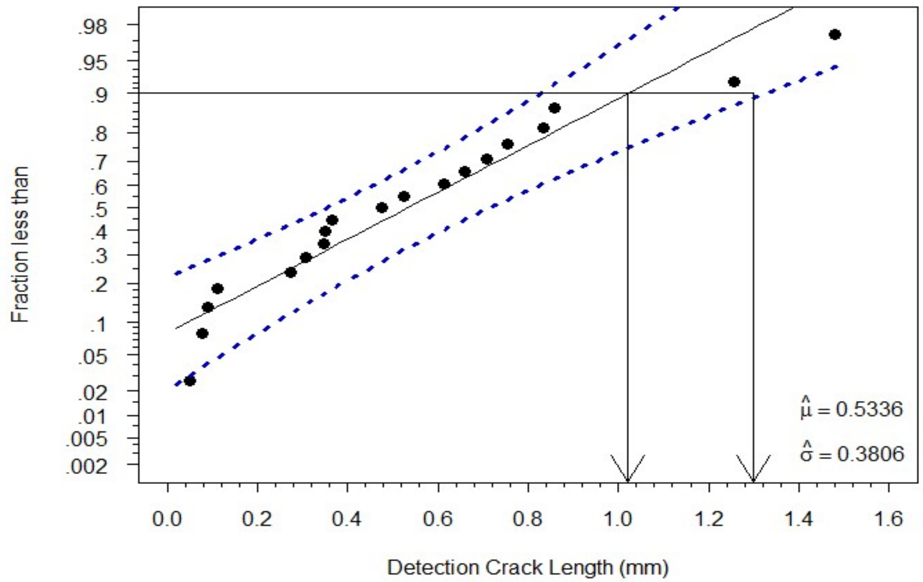
Predicted Crack Length vs Measured Crack Length

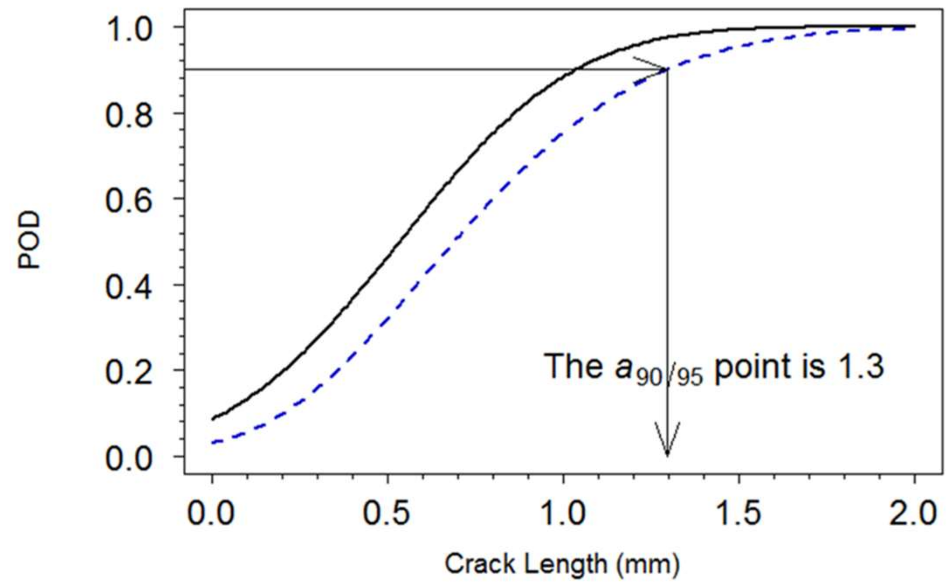


Detection Sensitivity: Length at Detection Method

Gaussian Distribution Probability



$a_{90/95}$ using LaD Model



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

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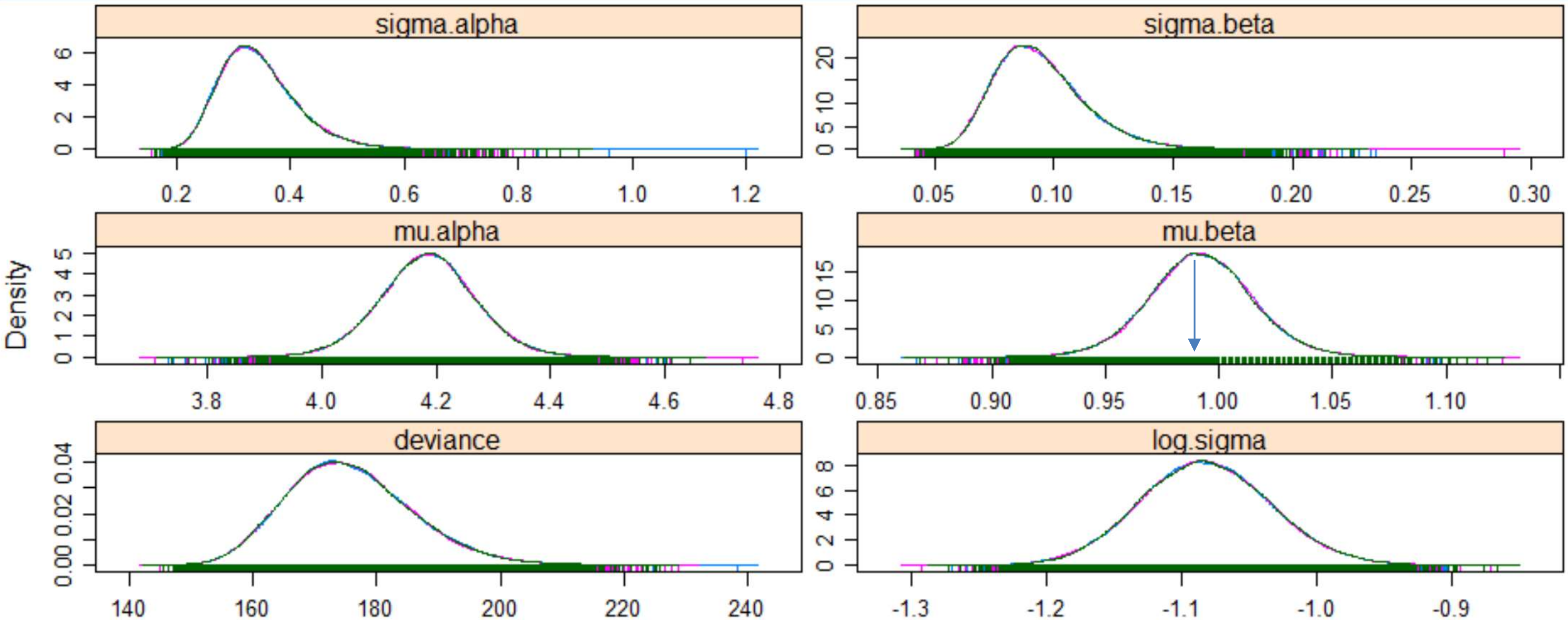
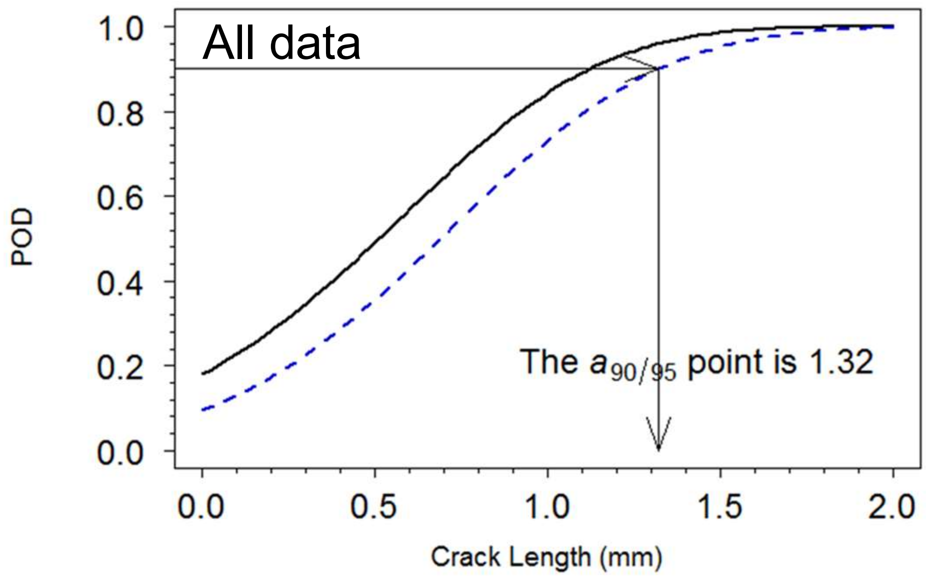
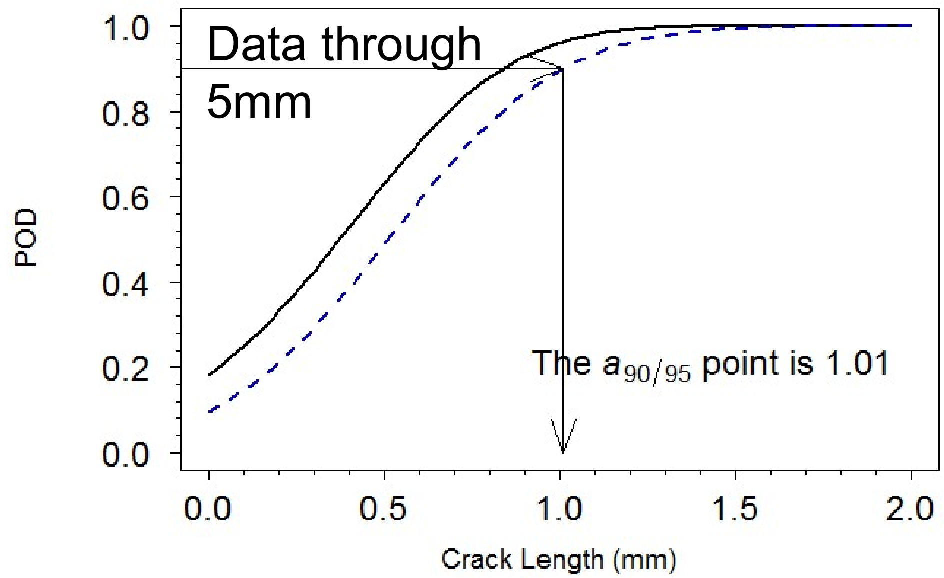
Detection Sensitivity: Random Effects Model



- 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

Detection Sensitivity: Random Effects Model (cont)





- **REM^2 provides an $a_{90/95}$ of 1.32 mm using all data (up to 18 mm)**
- **$a_{90/95}$ improves to 1.01 mm when only considering data < 5 mm**
- **Statistical analysis performed by Prof. Meeker @ ISU**

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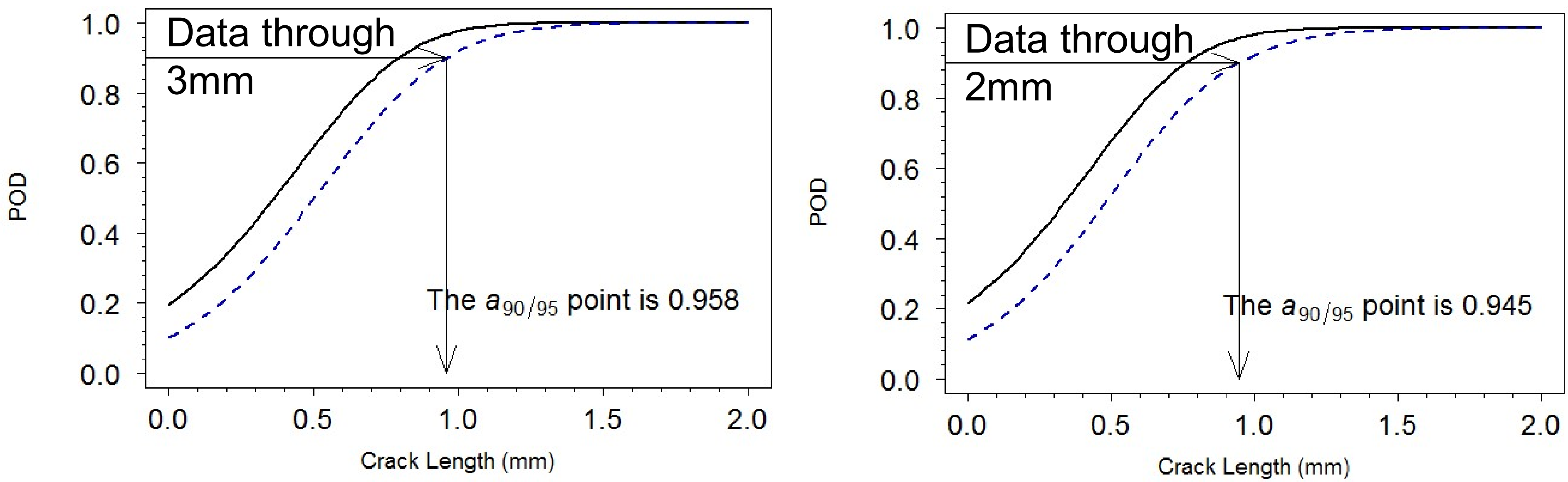
Detection Sensitivity: Random Effects Model (cont)



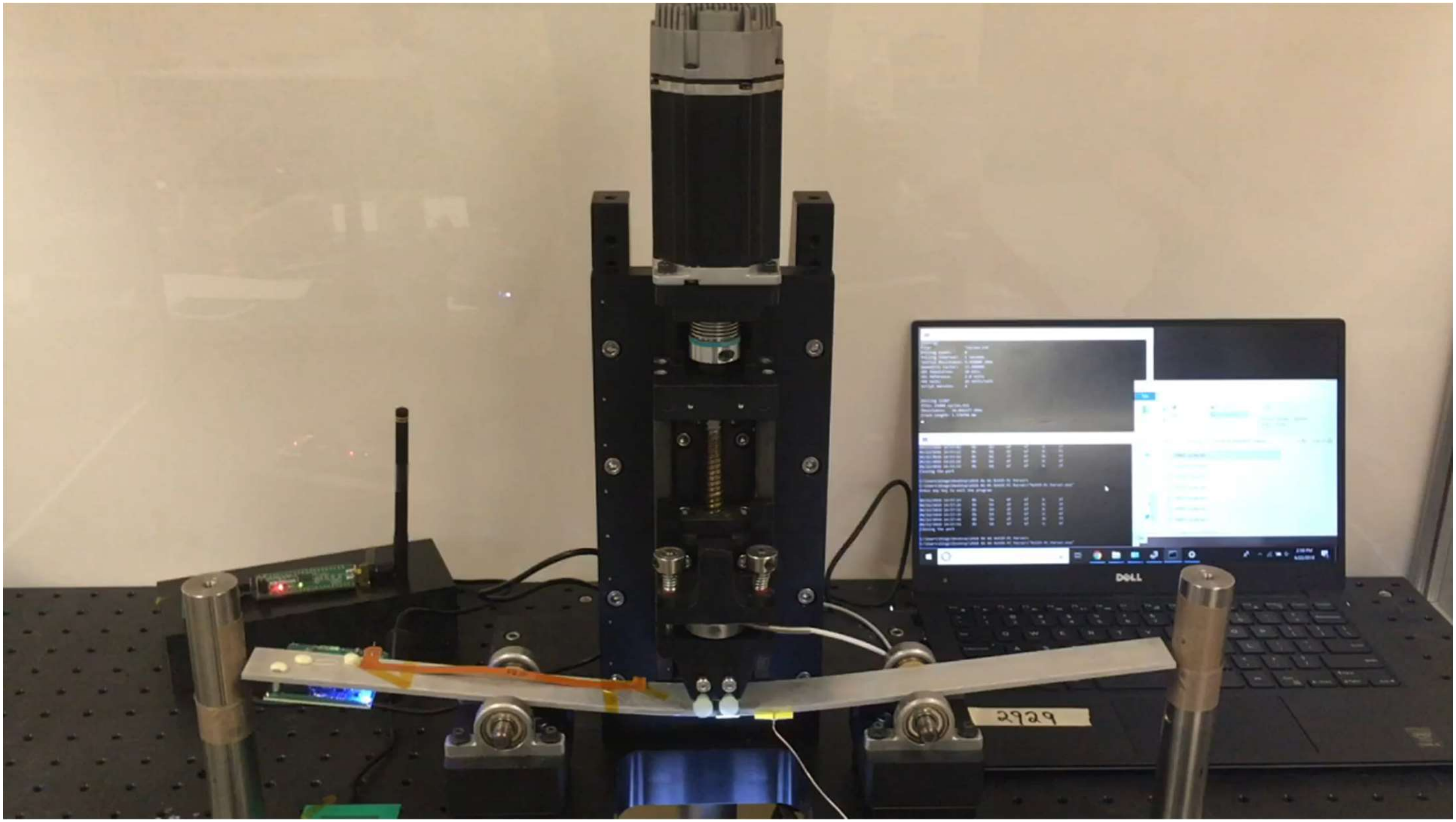
- $a_{90/95}$ improves to 0.958 mm when only considering data < 3 mm
- $a_{90/95}$ improves to 0.945 mm when only considering data < 2 mm
- Considering approach for determining how much data to consider

Comparison of PoD Approaches

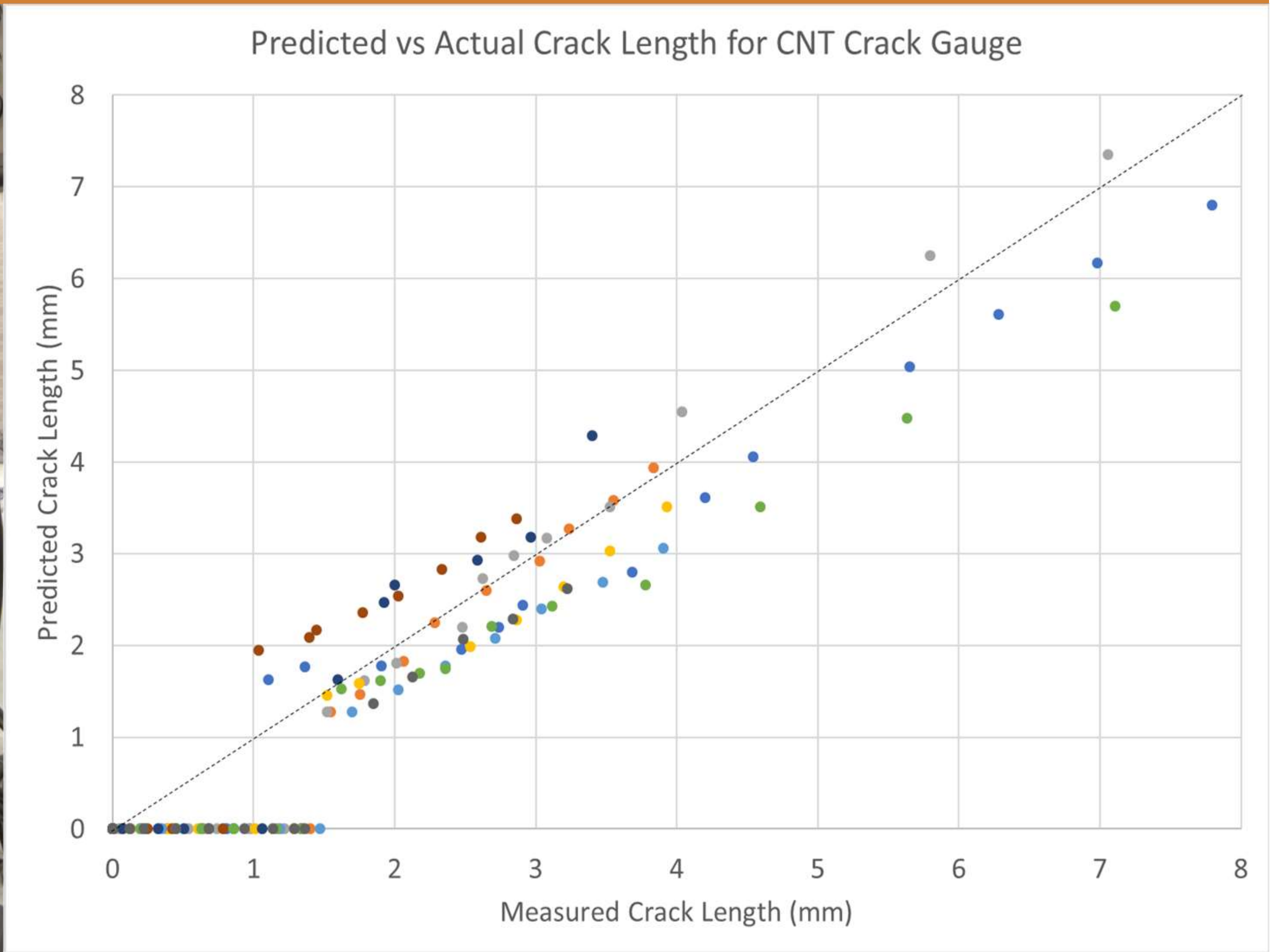
- Length-at-Detection (LaD) method
  - Computationally simple
  - Requires a minimal amount of data (just until first detection)
  - Requires assumption about distribution of detectable crack sizes (e.g., normal or lognormal), with little information to discriminate among different assumptions that might 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 (all data), <1 mm for considering less data

Wireless Power/Data Transmission (Hyperlapse)

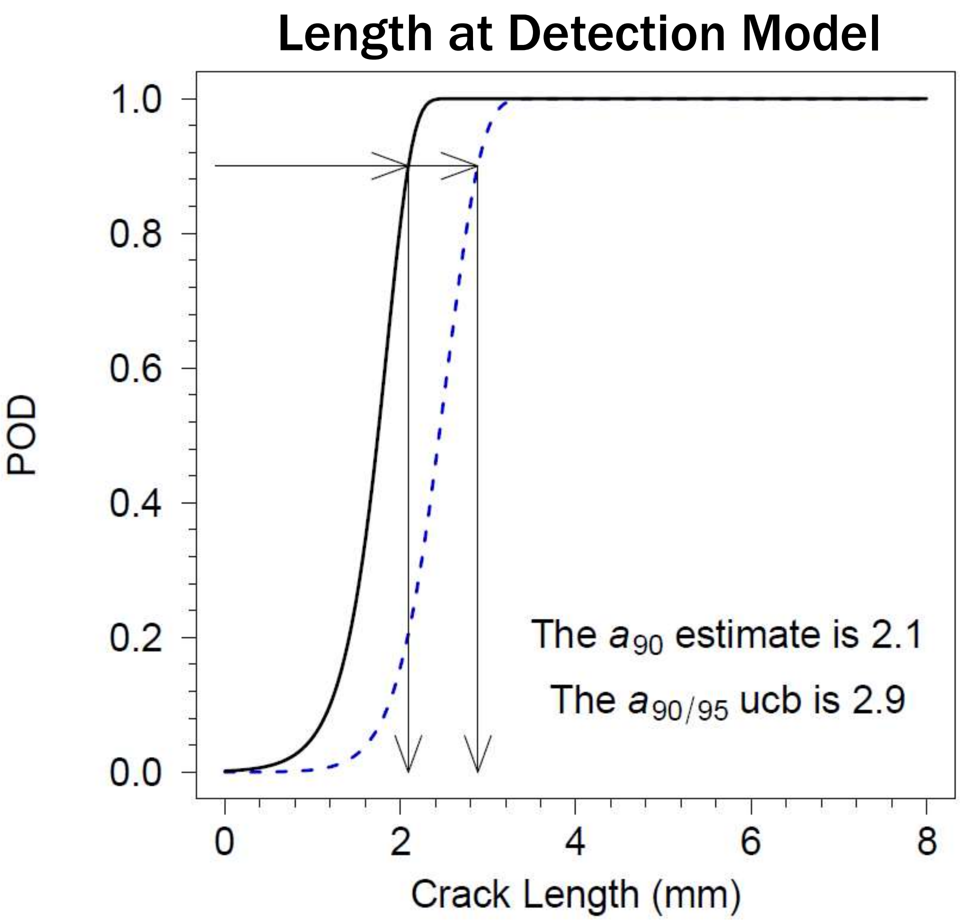


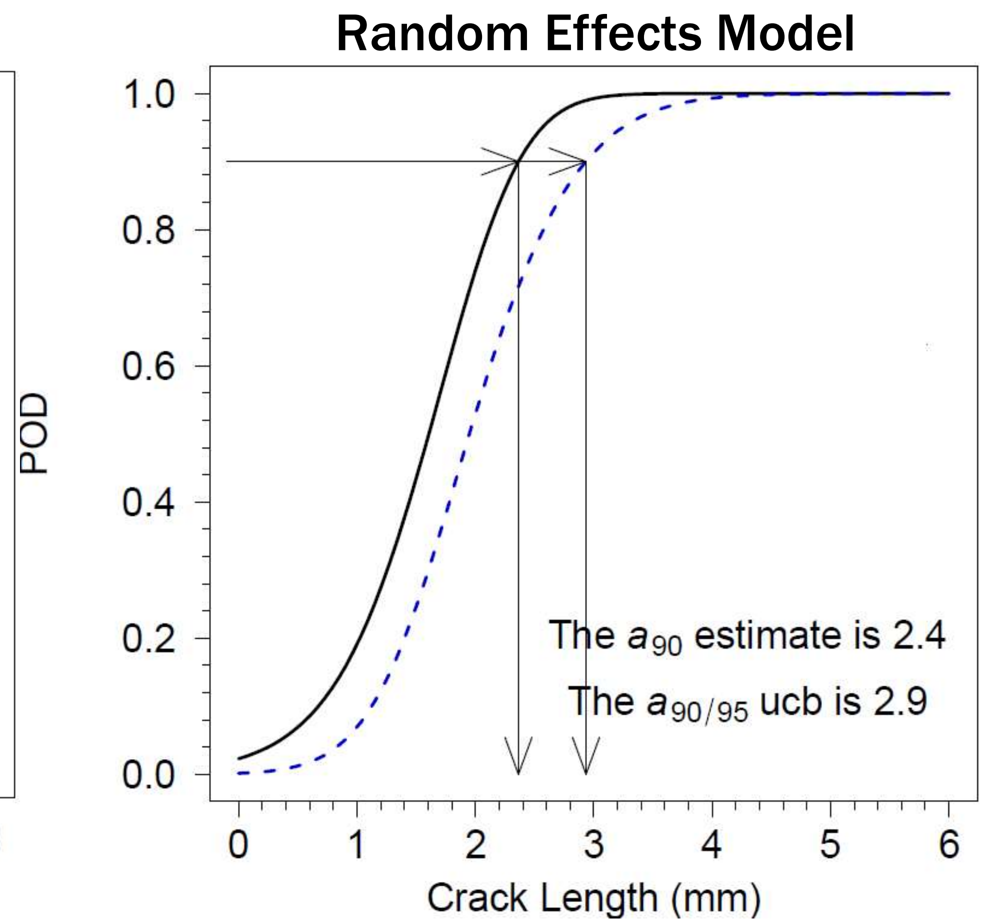
Blind Sensitivity Testing at FAA Tech Center



- **Tensile-tensile fatigue tests on aircraft Al-Li bars with EDM notch**
- **RFID response + visual crack data sent to ISU for PoD analysis**

Blind FAA Detection Sensitivity Results





- **RFID response + visual crack data sent to ISU for PoD analysis**
- **$a_{90/95}$ slightly higher than lab results, variability of fatigue heating**

Summary & Future Work

- Investigation of detection sensitively for PD SHM method
  - 4-pt bending fatigue of Al beams funded through AFRL SBIR
  - CRDA with FAA for tensile-tensile fatigue of Al/Li beams
  - Collaboration with Prof. Meeker (Iowa State) for statistical analysis
  - 2 statistical approaches: Length at Detection & Repeated Measured Model

- Initial detection sensitivity results encouraging
  - Results have been consistent between LaD & REM^2 approaches
  - $a_{90/95}$ value of 1.3 mm for laboratory 4-pt bending fatigue
  - $a_{90/95}$ value of 2.9 mm for blind tensile-tensile fatigue (temp variations)

- Future work
  - Need much more data to validate alternative approaches vs MIL-1823A
  - Analytical/FEA for model-assisted probability of detection (MAPoD)
  - Issue being investigated by AISC-SHM sub-committee, new SBIR topic

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