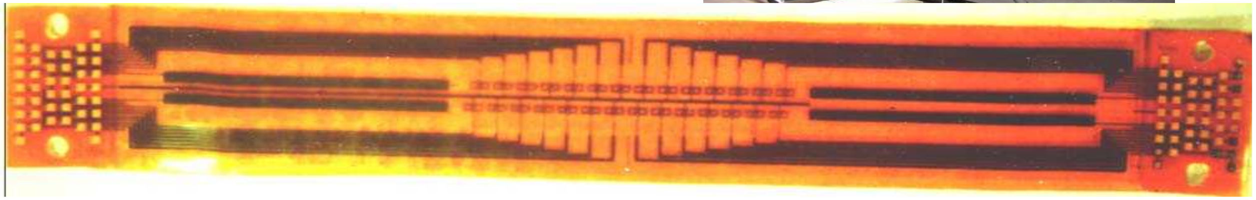
Presented to the University of New Mexico

SAND2008-7832P

Manually-Deployed Nondestructive Inspection vs. In-Situ Structural Health Monitoring: Advantages, Disadvantages, and Limitations



Dennis Roach
Sandia National Labs
FAA Airworthiness Assurance Center

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia Labs Has Distributed Facilities to Meet National Needs

Approx 4600 engineers, 3000 other technical people (chemistry, physics, math, computing, etc) across the entire technical spectrum

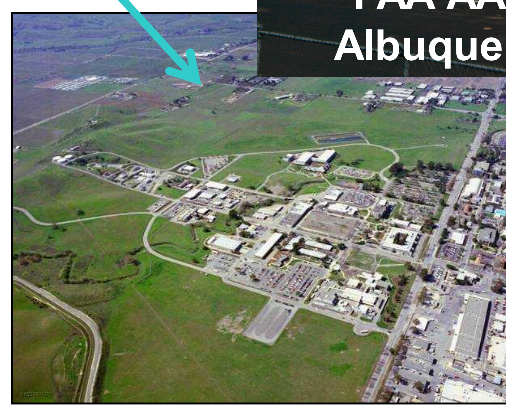
Kauai Test Facility, Hawaii

Albuquerque, New Mexico

WIPP, New Mexico

Tonopah Test Range, Nevada

Pantex, Texas



Livermore, California

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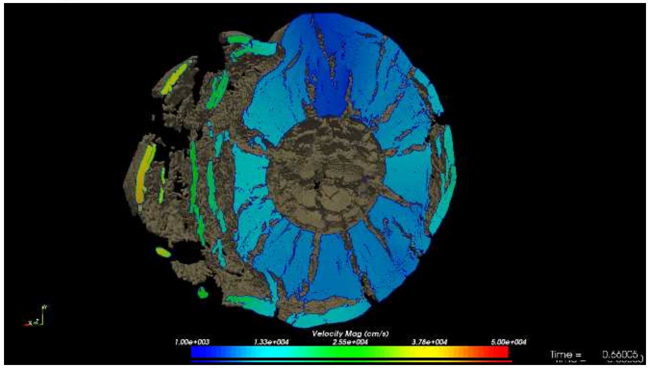
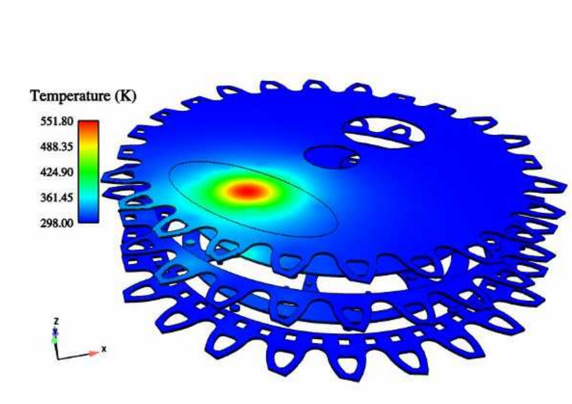
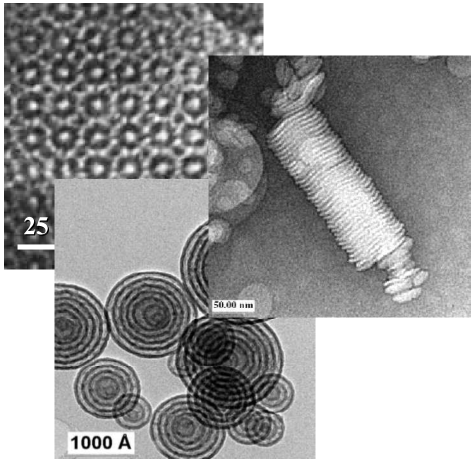
Sandia's Mission Focus Relies on Strong Science and Engineering



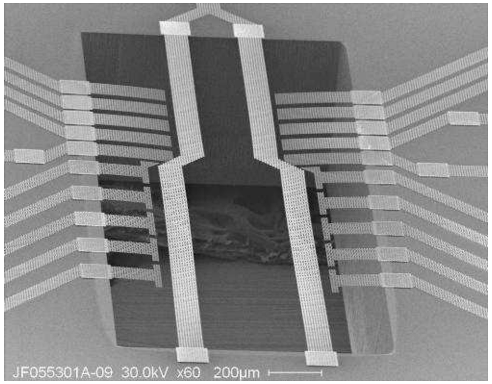
Computational and Information sciences



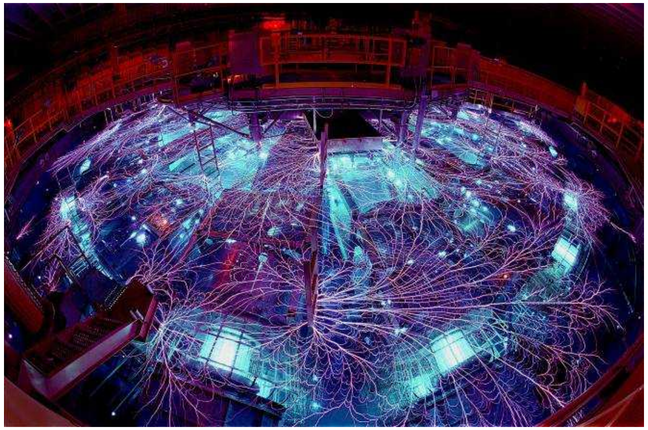
Engineering Sciences



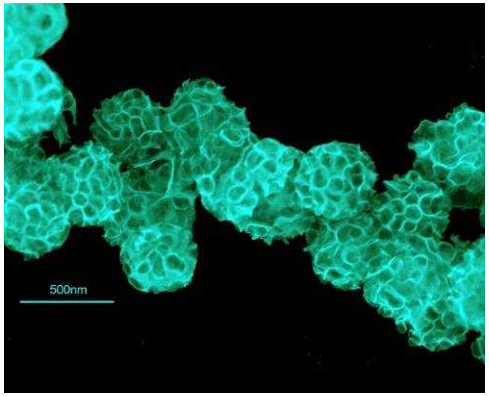
Materials Science and Technology



Microelectronics and Photonics



Pulsed Power



Biotechnology

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FAA Airworthiness Assurance Center (AANC) at Sandia National Laboratories

- Initiated in 1988 under the Aviation Safety Act
- Provides a mechanism to develop, evaluate, and bring new aircraft technologies to market
- Partner with industry, academia, and government
- Develop and implement solutions to pressing problems

B737-200
Test Bed

Fairchild Metro II
Test Bed

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AANC Teaming with FAA, DoD, NASA & Private Industry

USCAR

Department of the Air Force · United States of America

Bell Helicopter TEXTRON
A SUBSIDIARY OF TEXTRON INC.

EXXON

LOCKHEED MARTIN

KLM
Royal Dutch Airlines

Alaska Airlines

BOEING

Department of the Navy · United States of America

United States Coast Guard 1790

NORTHWEST AIRLINES

UNITED

U·S AIRWAYS

FedEx

NASA

U.S.ARMY

GM

Delta

Syncrude

Forest Service U S Department of Agriculture

AIR FRANCE

AA

SAIC

SR Technics

BRITISH AIRWAYS

Cessna

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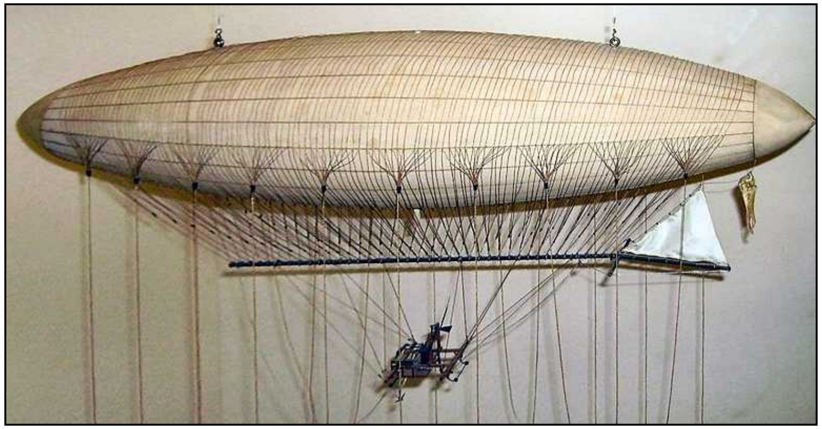
First flight?

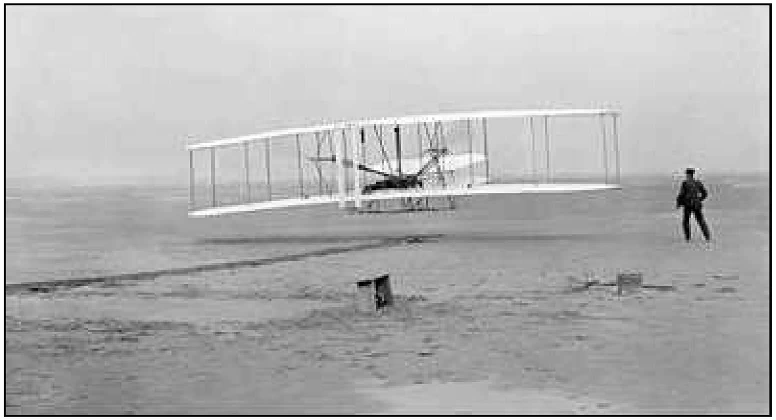
1852 - First powered, controlled flight; Henri Giffard flew 15 miles with a steam engine mounted on a dirigible



First heavier-than-air flight?

1894 - First heavier-than-air, non-powered flight; Otto Lilienthal, who flew more than 600 ft. in his glider

First manned, powered, heavier-than-air, controlled flight?



1903 - Wright Brothers 120 feet in 12 seconds, at a speed of only 6.8 mph

1908 (first fatality of an airplane accident); Army lieutenant Thomas Selfridge

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CARAVAN I
FALK
KOREAN AIR CARGO

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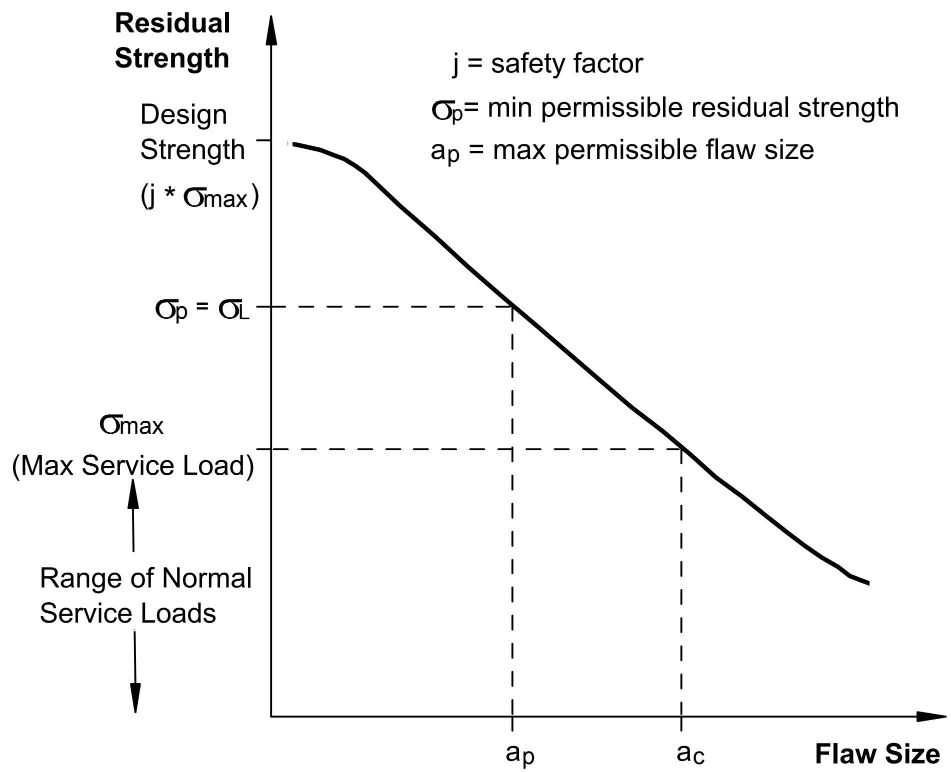
Damage Tolerance Philosophy

Damage tolerance is the ability of an aircraft structure to sustain damage, without catastrophic failure until such time that the component can be repaired or replaced.

FAR - residual strength shall not fall below limit load, P_L, (establishes the minimum permissible residual strength $\sigma_P = \sigma_L$)

Residual Strength Curve

relates this minimum permissible residual strength, σ_P , to a maximum permissible flaw size a_P



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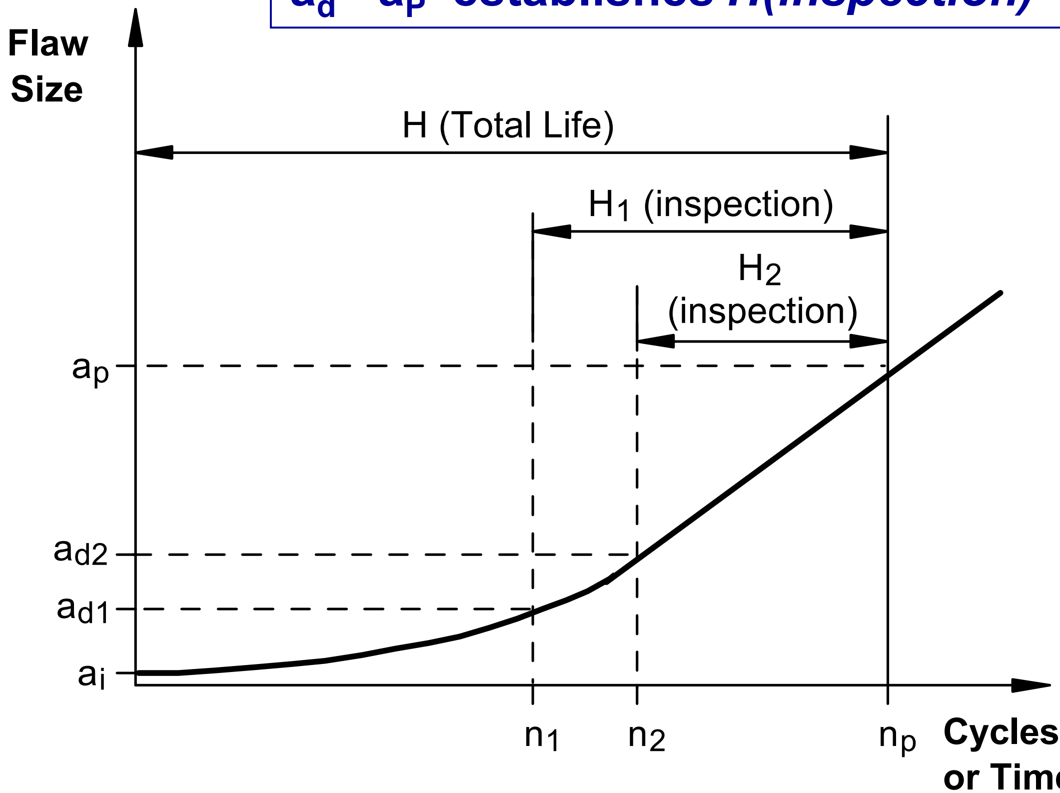
Fracture Control Plan

Nondestructive inspection is the tool used to implement the fraction control plan – detect the flaws.

n_P = cycles, required to reach a_P
a_d = minimum detectable flaw size
a_d - a_P establishes *H(inspection)*

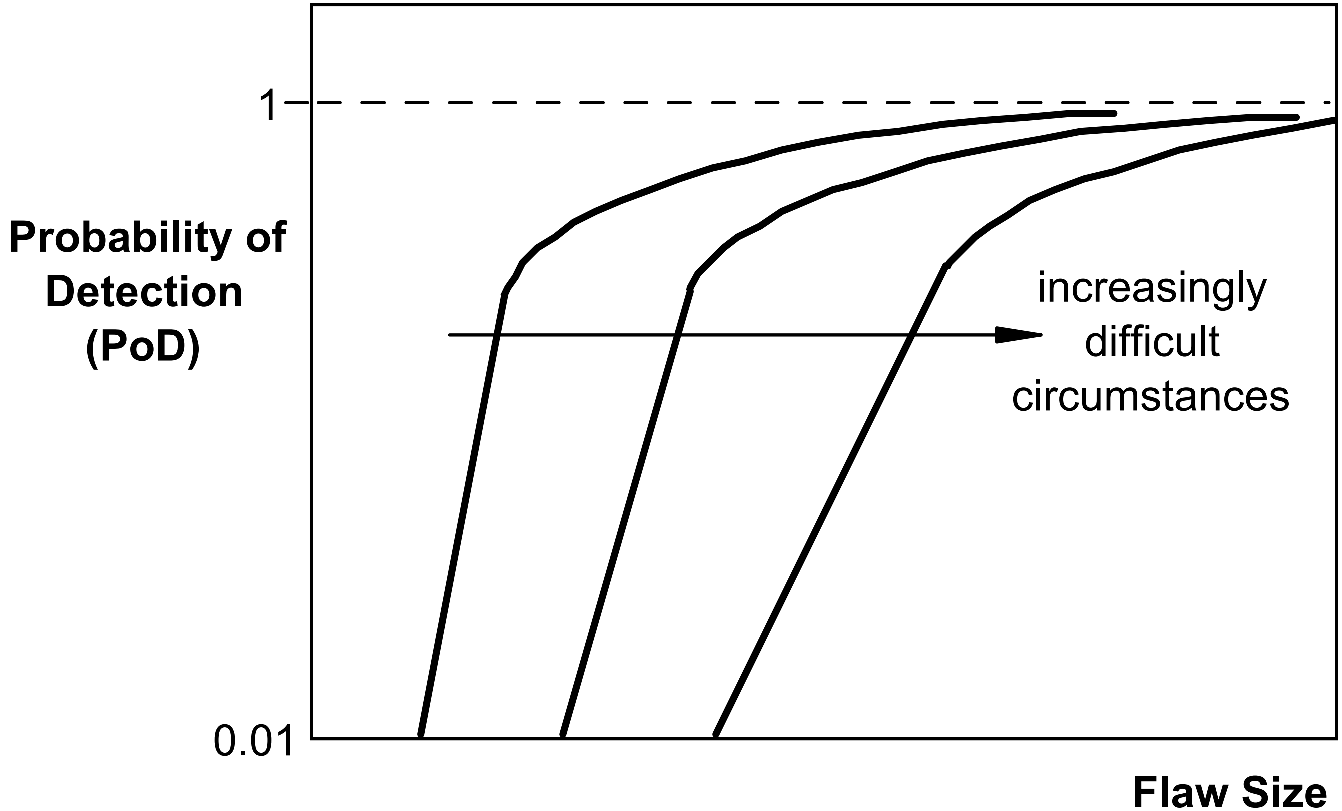
Note effect of NDI sensitivity on required inspection interval



Crack Growth Curve Showing Time Available for Fracture Control

Quantifying NDI Performance

Probability of Detection (POD) - quantitative measures of flaw detection for each NDI technique



Effect of Circumstances on Probability of Detection

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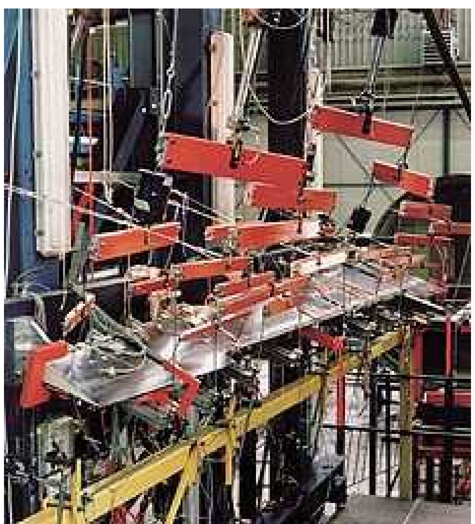
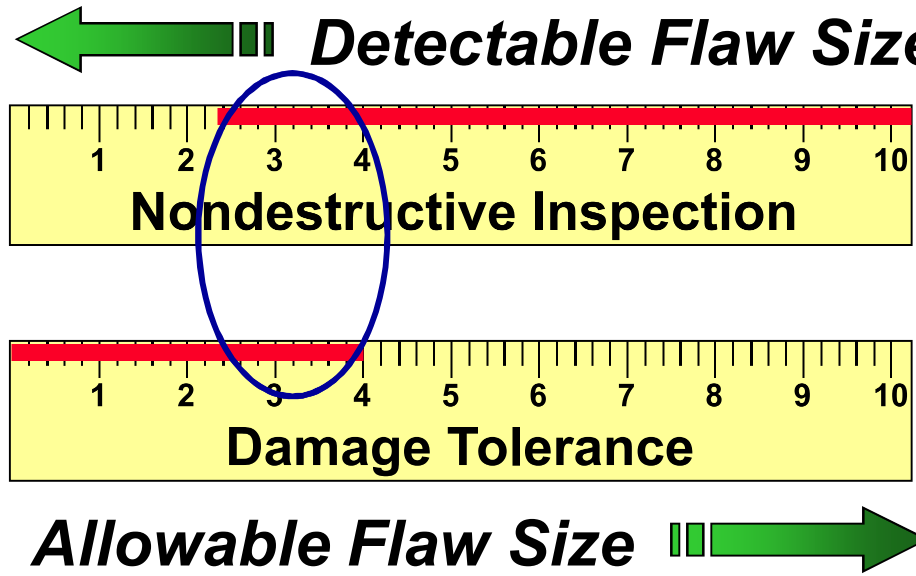
Required Relationship Between Structural Integrity and Inspection Sensitivity





Fundamentals of Damage Tolerance

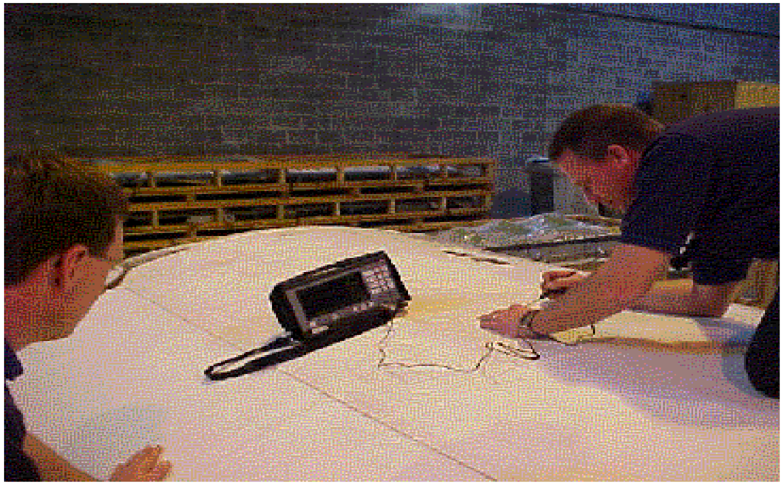
FRAMEWORK-

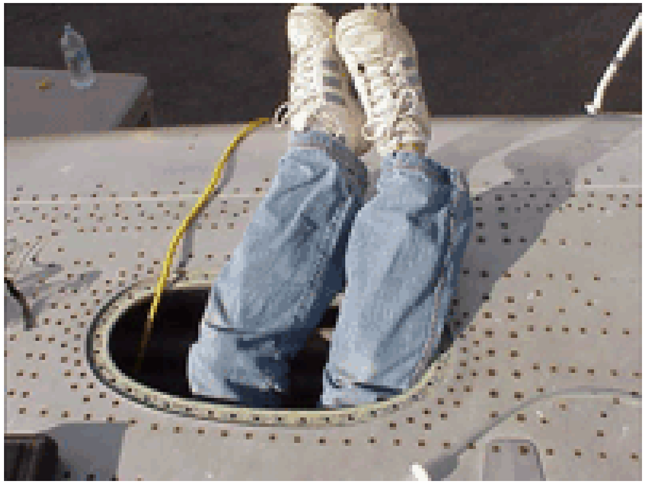
WHAT to look for (damage specific),	←	Structures Person
WHERE to look (SSI, ETC),	←	Structures Person
HOW to look,	←	NDI Person
WHEN to look,	←	Both People
HOW OFTEN to look,	←	Both People
What is the POD and the	←	NDI Person
DETECTION THRESHOLD	←	NDI Person

D. S. Forsyth, T. B. Mills, "Inspection, Health Monitoring, Probability of Detection, and Structural Integrity", a short course presented at the 11th Joint NASA/FAA/DOD Conference on Aging Aircraft

Math, Glorious Math or…..
How do we calculate DT ??

- **Fatigue guy:** Brilliant! I've calculated K to within 0.5%!
- **Stress guy:** Splendid! I've calculated stress to within 10%!
- **Loads guy:** WOOHOO! I think I got the sign right!
- **NDI guy: You want me to find a crack how small??**





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Nondestructive Inspection vs. Structural Health Monitoring

Nondestructive Inspection (NDI) – examination of a material to determine geometry, damage, or composition by using technology that does not affect its future usefulness

- High degree of human interaction
- Local, focused inspections
- Requires access to area of interest (applied at select intervals)
- Portable and applied to numerous areas; numerous inspection needs

Structural Health Monitoring (SHM) – "Smart Structures;" use of NDI principles coupled with in-situ sensing to allow for rapid, remote, and real-time condition assessments; goal is to reduce operational costs and increase lifetime of structures

- Greater vigilance in key areas – address DTA needs
- Overcome accessibility limitations, complex geometries, depth of hidden damage
- Eliminate costly & potentially damaging disassembly
- Minimize human factors with automated data analysis

Wide Range of Potential Uses

- Extended service life
- Thick & Large Structures
- Harsh, Long-Term Environments
- Need to Accommodate Changes in Use
- Current Repair & Monitoring Problematic

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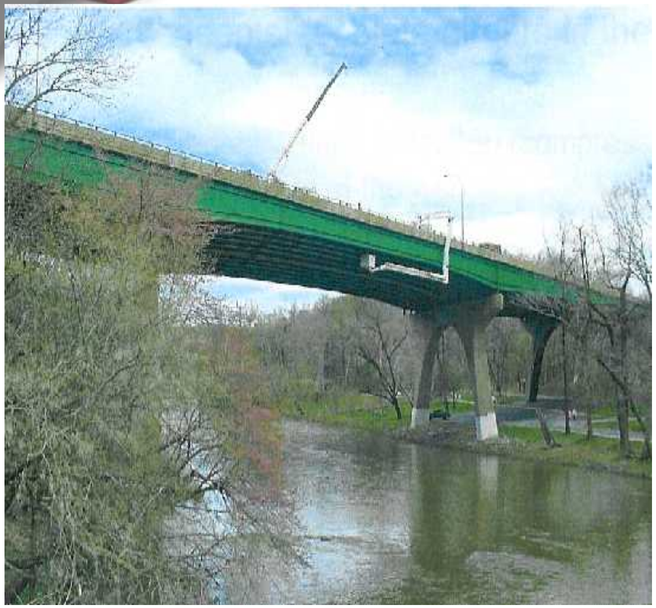
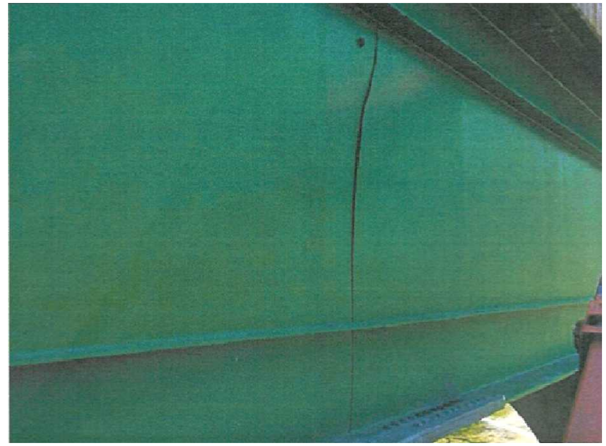
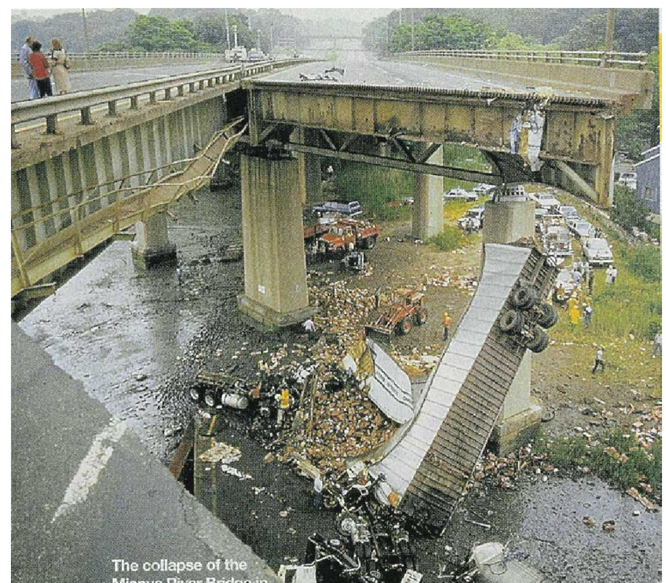
Sample Infrastructure Health Monitoring Needs





30% of 600,000 bridges in U.S. are listed as "structurally deficient" (Fed. Highway Admin. Nat. Bridge Inventory)

Brandywine River Bridge
Interstate Highway 95



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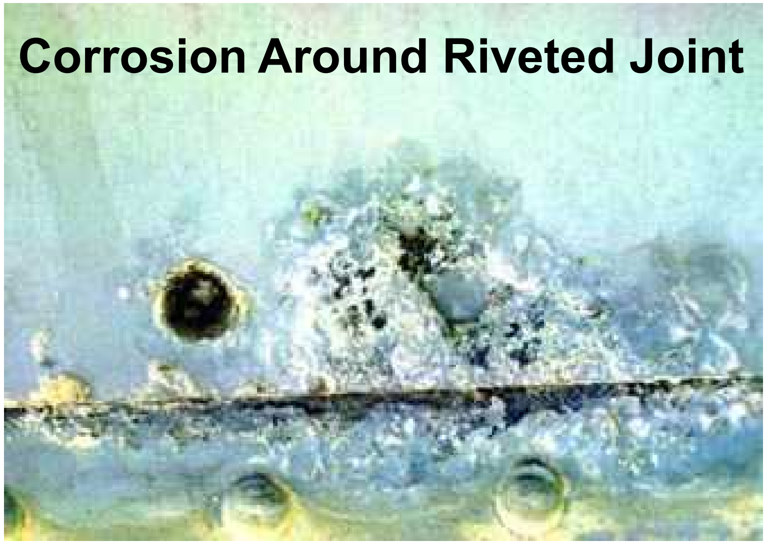
Typical Aircraft Flaw Scenarios



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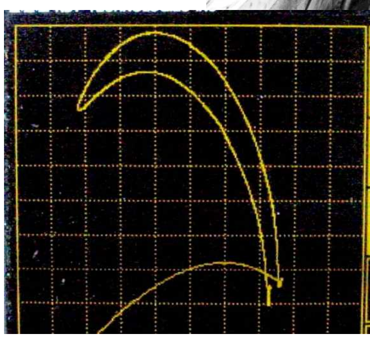
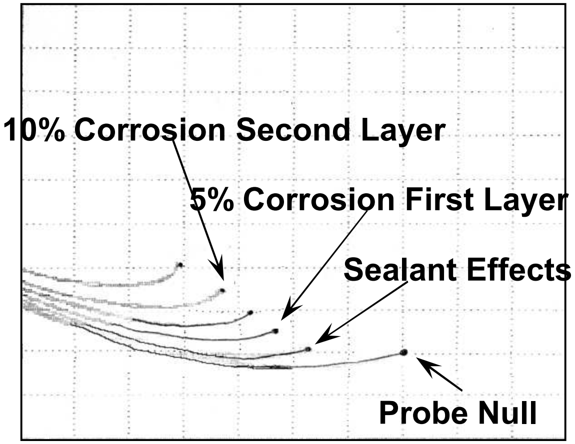
Typical A-Scan Signals Used for Flaw Detection with Hand-Held Devices

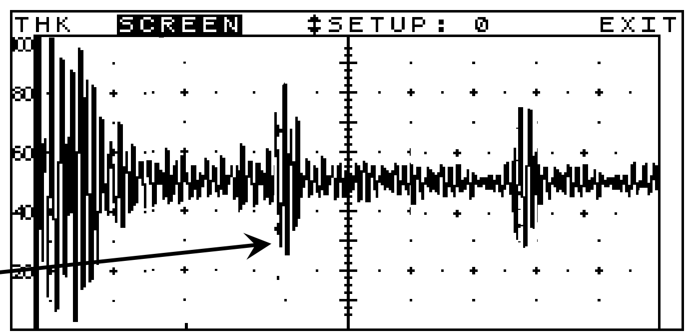


Eddy Current Signal at Crack Site



Corrosion Detection with Dual Frequency Eddy Current

Intermediate Echo Caused by Delamination



Ultrasonic Pitch-Catch UT Signals Comparing Flawed and Unflawed Signatures

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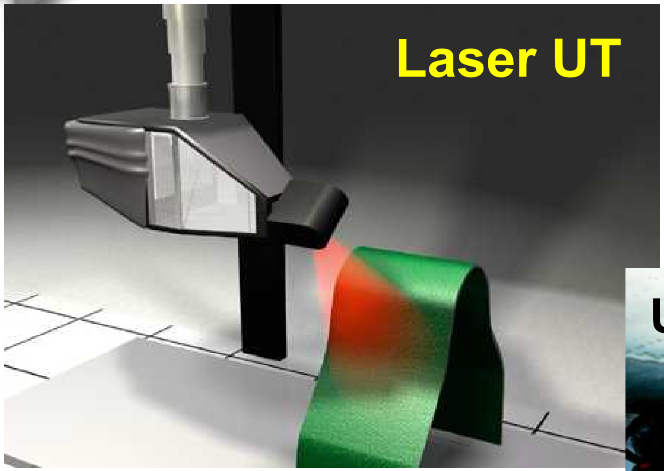
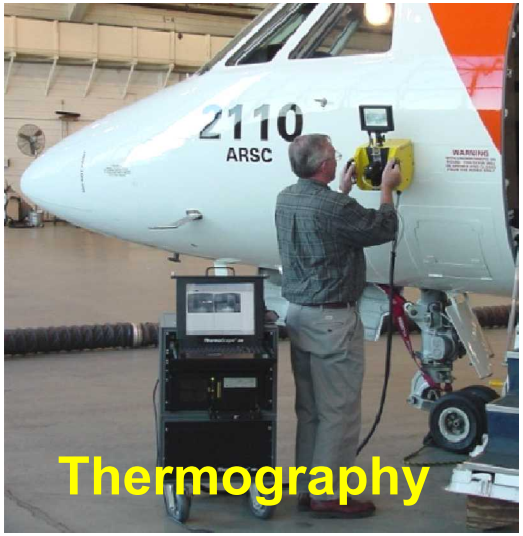
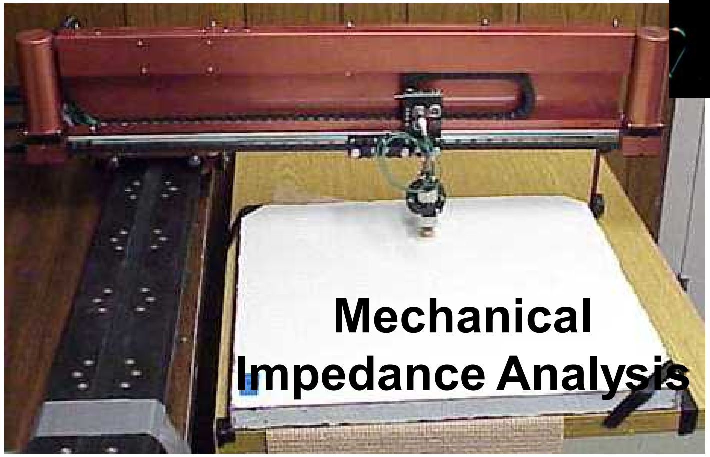
Wide Area and C-Scan Inspection Methods







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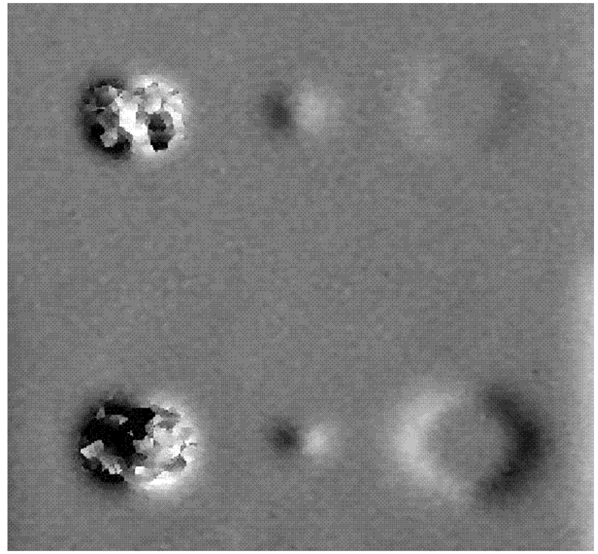
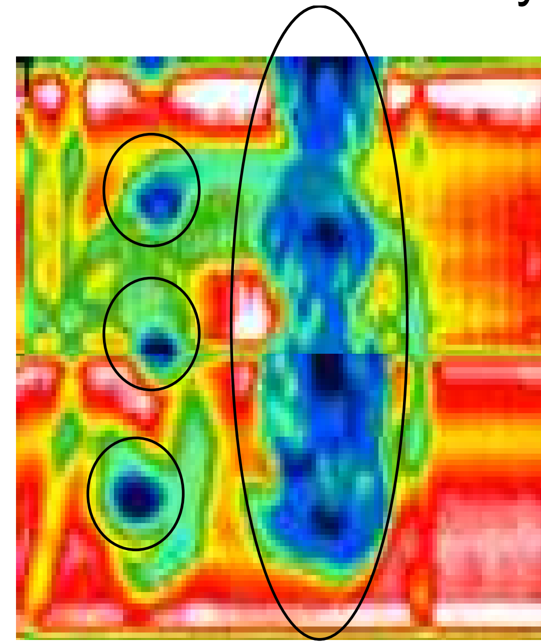
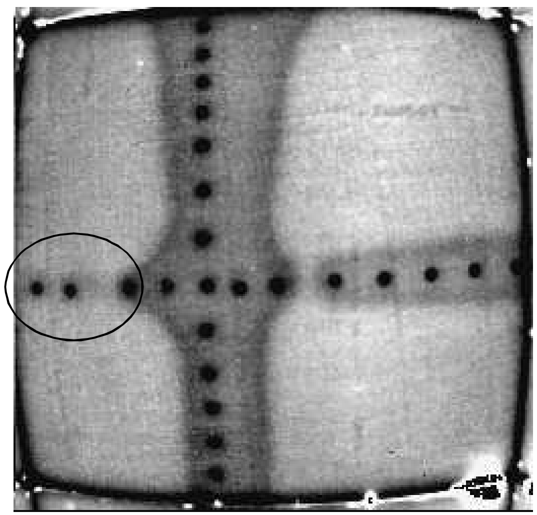
Shearography (LTI) Image

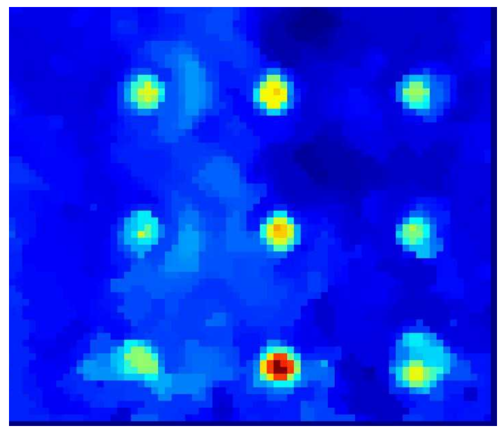


Ultrasonic Wheel Array

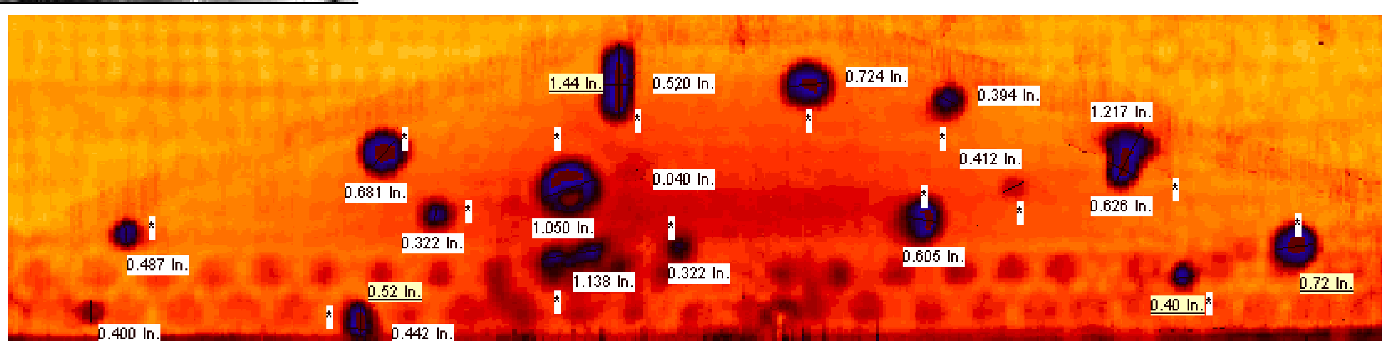


Thermography (TWI) Image





SAM Image



MAUS Image

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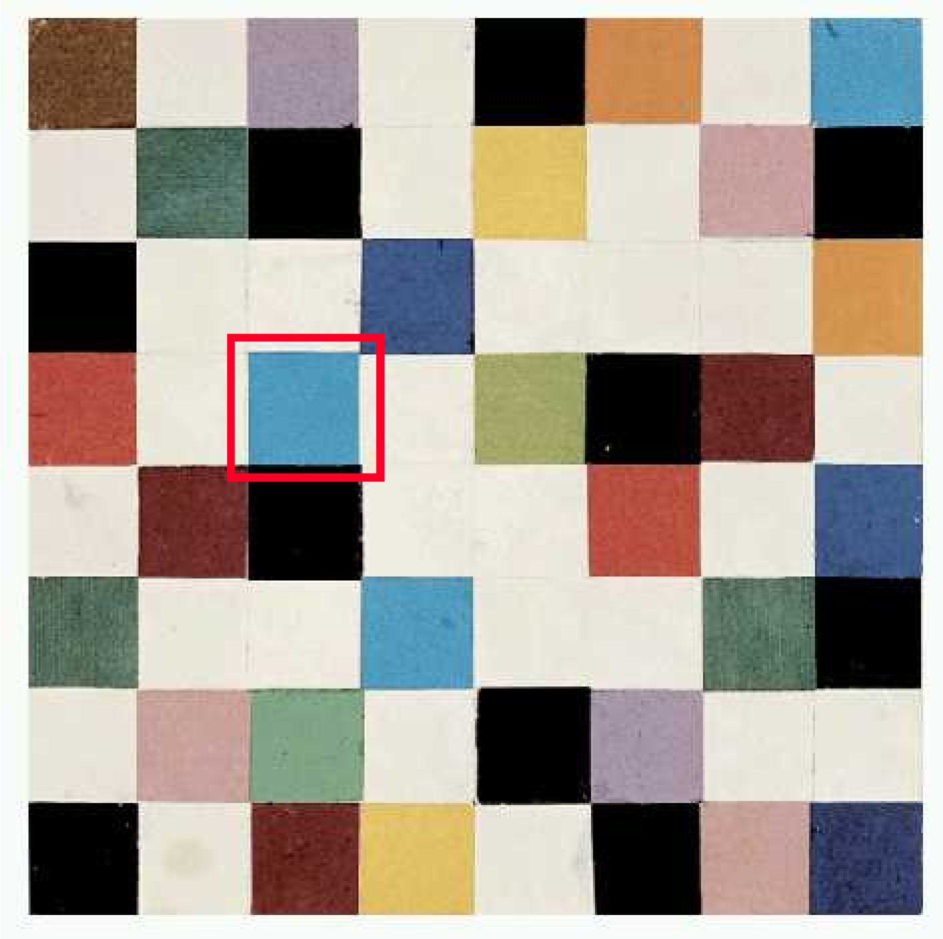
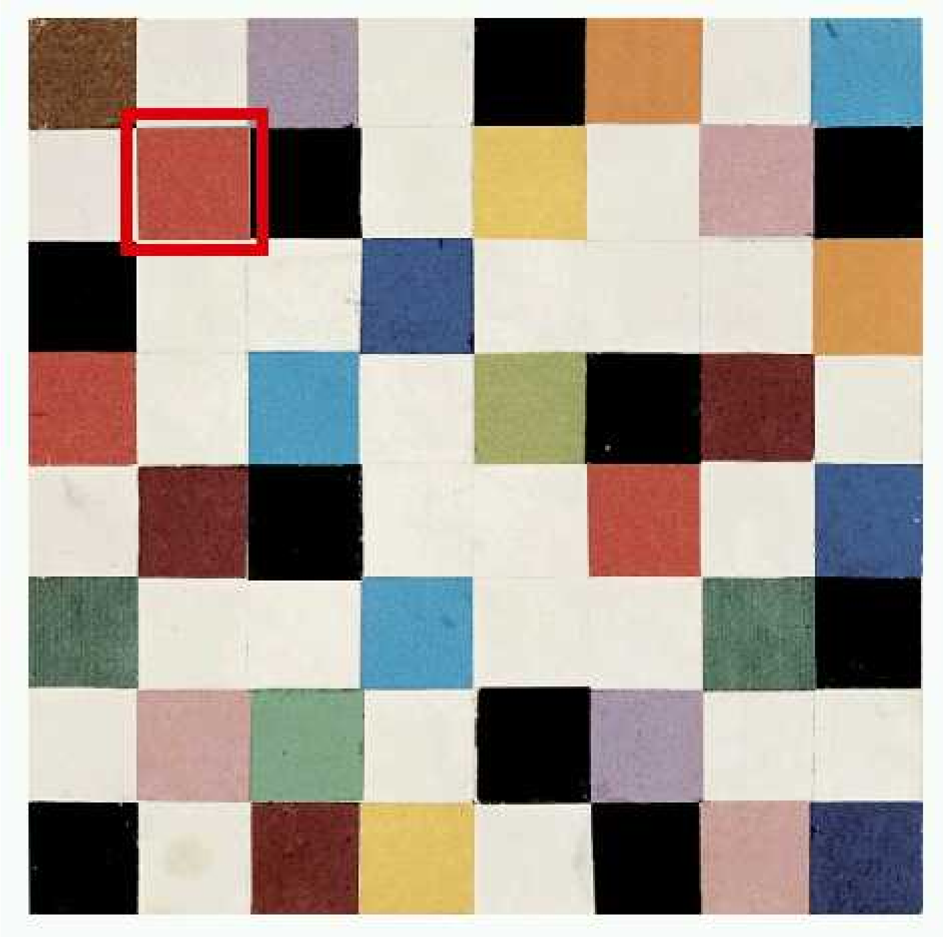
You as the Inspector – Performance Assessment



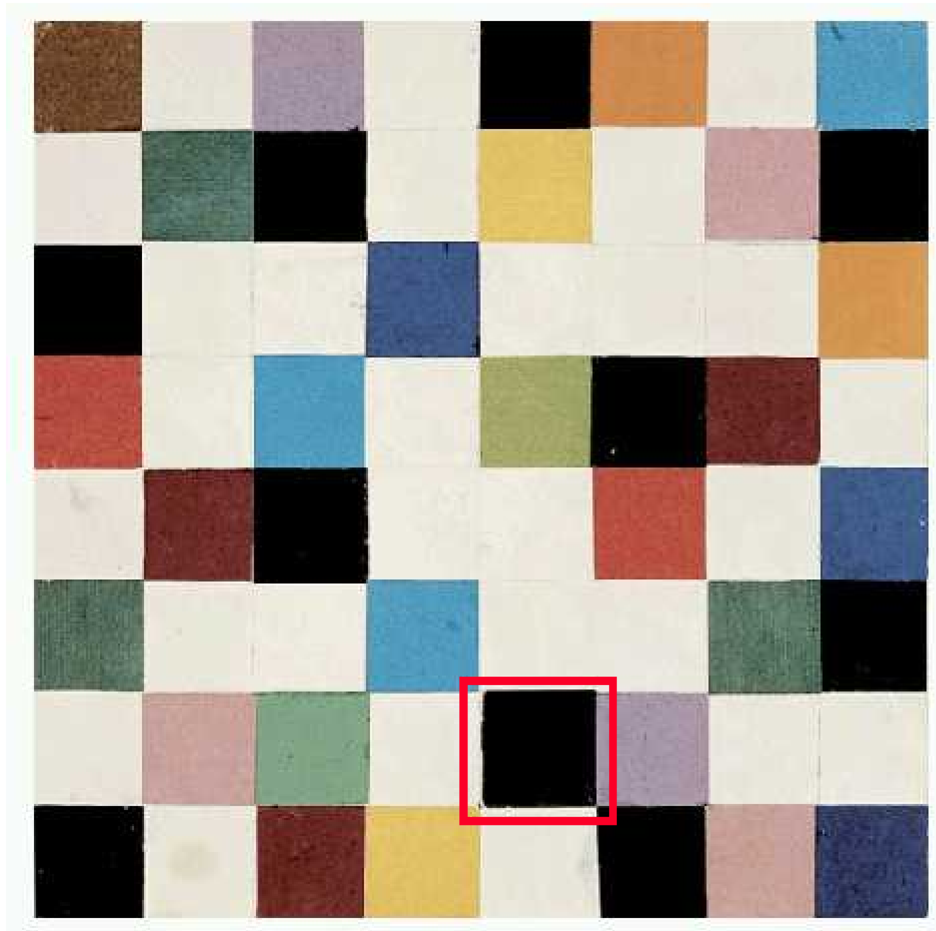
NO CHANGE

Did the selected square change color?



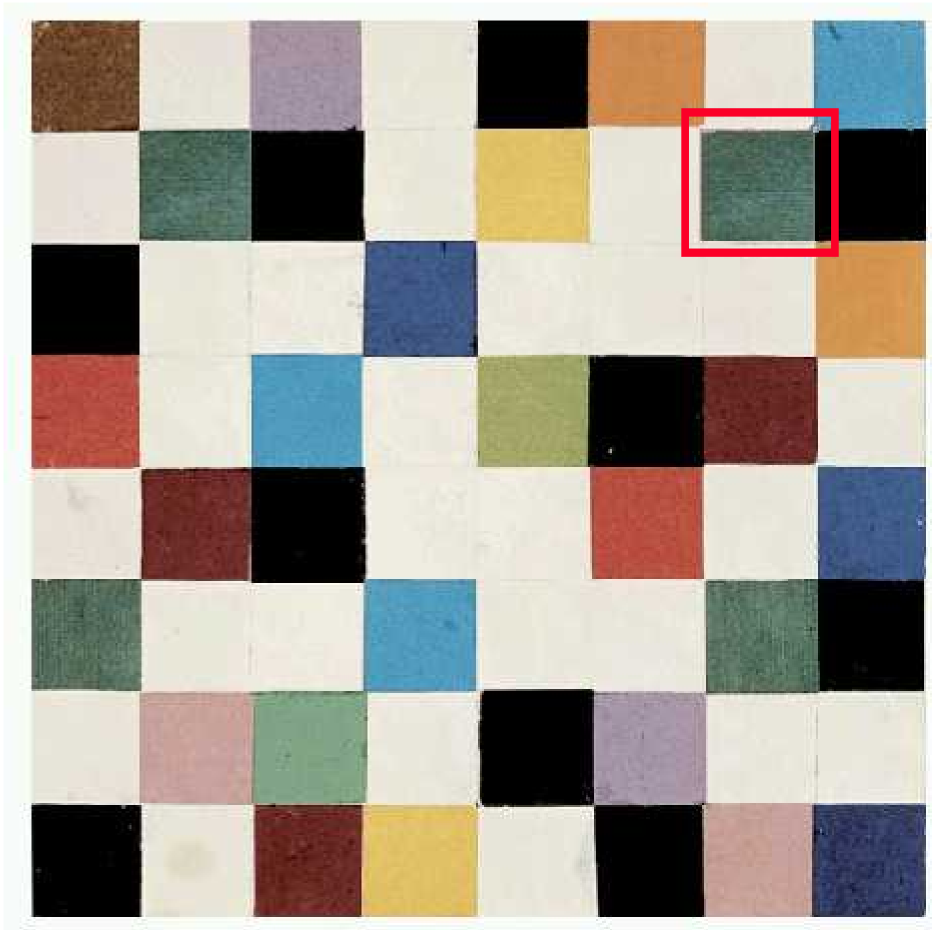
YES CHANGE

Did the selected square change color?



NO CHANGE

Did the selected square change color?



YES CHANGE

Did the selected square change color?

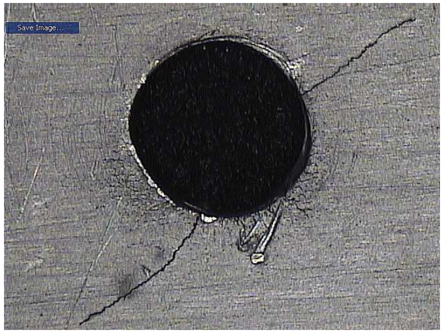
How did you do?

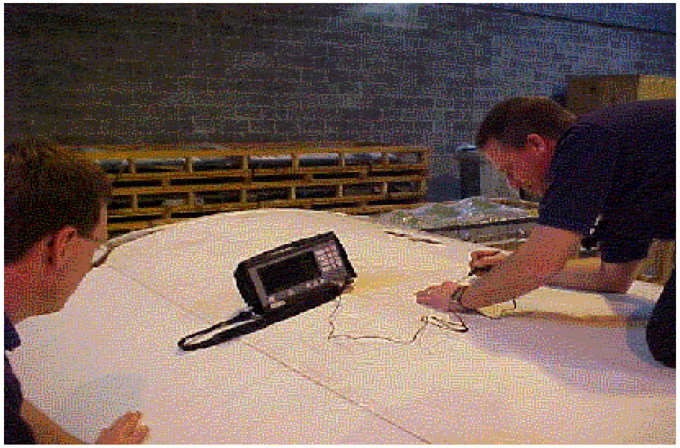
- Did you try to game the system?
  - FACT: inspectors do better where they expect to find cracks

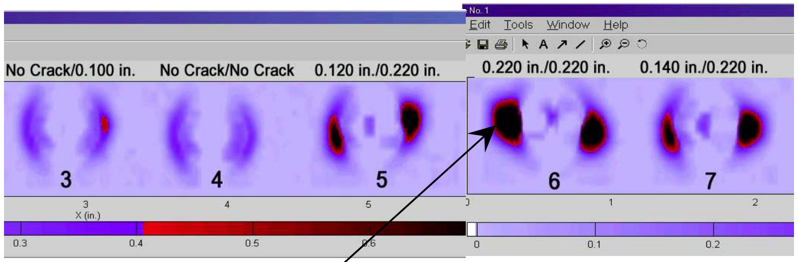
- Did you have the same level of concentration from the beginning to the end?
  - There is significant research on how fatigue and difficulty of tasks affect performance.

Widespread Fatigue Damage

- Understand WFD phenomena through lab and field studies; aging aircraft teardown inspections
- Advanced NDI has produced order of magnitude improvements to create risk management options
- Program is producing guidelines for assessing continued airworthiness







Fatigue Cracks

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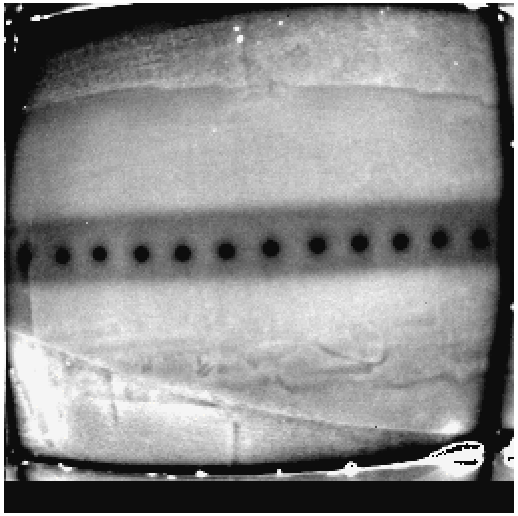
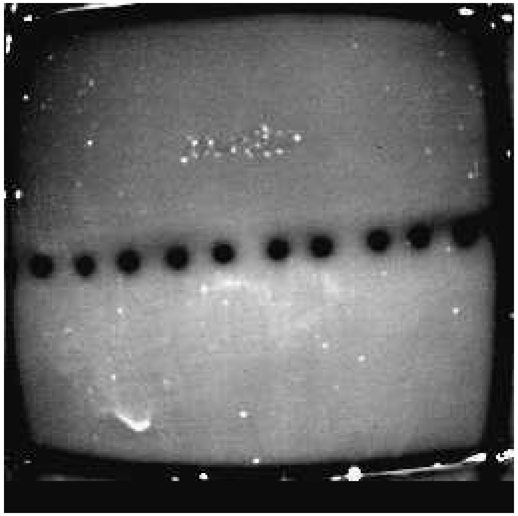
Fuselage Disbond Inspection Using Pulsed Thermography

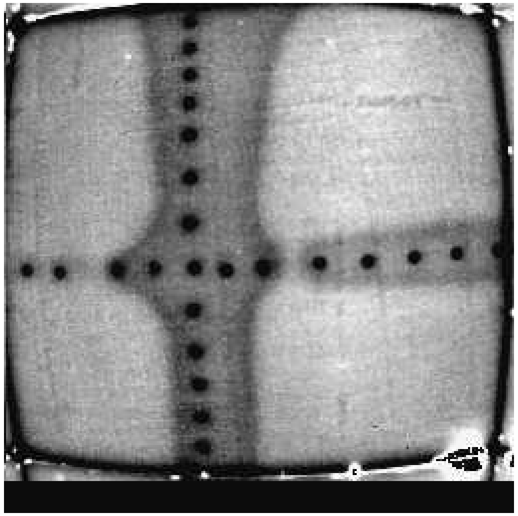
Thermography Inspection



Bonded Doubler



Disbonded Doubler



Disbonded/Bonded Doubler

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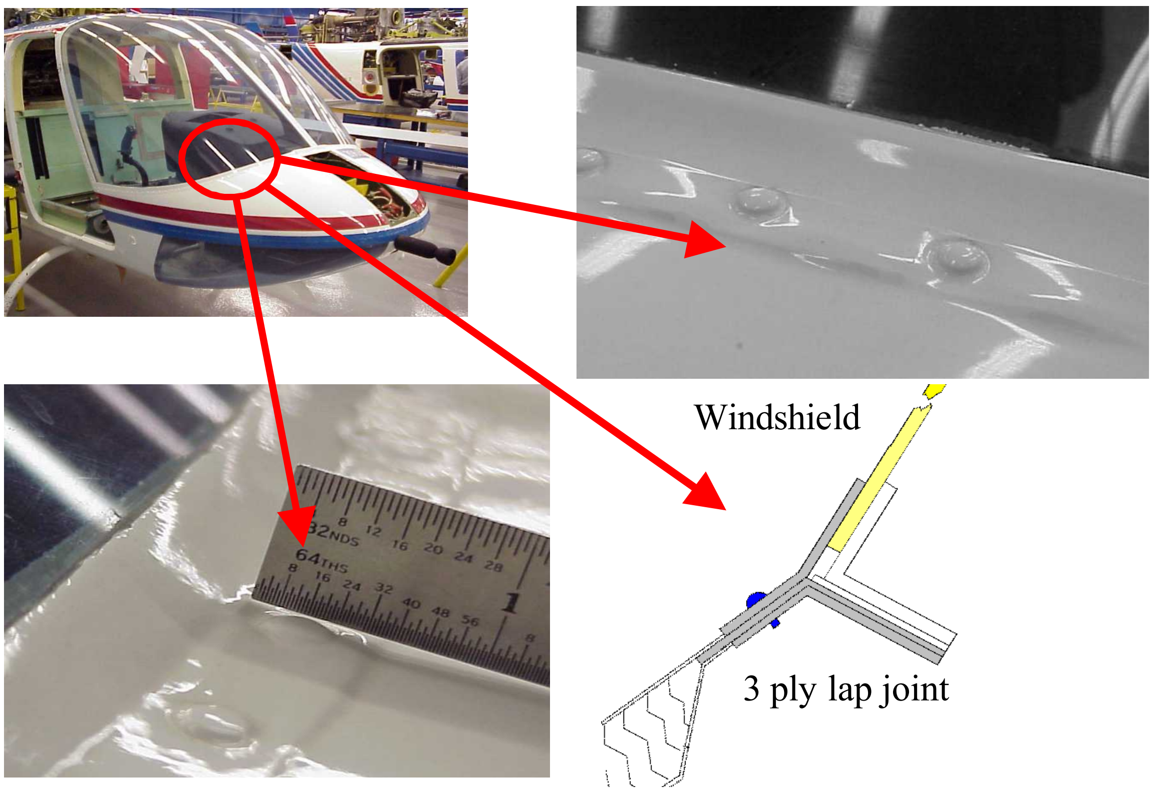
Corrosion Inspection of Multi-Layer Rotorcraft Joints

Approach: use single and dual frequency techniques to determine total corrosion in assembly and provide insights into corrosion levels in different layers



Typical Joints - two and three layers of thin skin material separated by sealant of varying thickness

Inspections must contend with narrow inspection areas, uneven surfaces, & raised fastener heads

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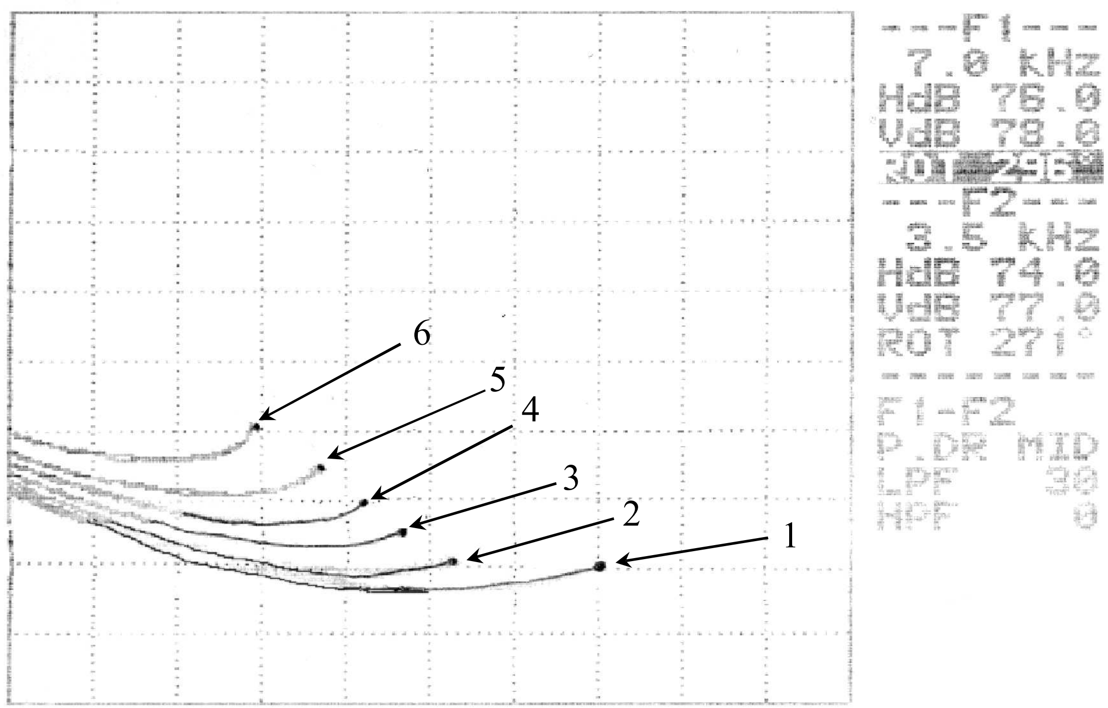
Sample Eddy Current Signals From Corrosion Sites

Two Layer Stack Up; 1st & 2nd Layer Corrosion



(1) Probe Null (over air gap between plates)

(2) Sealant Effects (0.007" th. Teflon between Plates)

(3) 5% Corrosion First Layer

(4) 5% Corrosion Second Layer

(5) 10% Corrosion Second Layer

(6) 15% Corrosion Second Layer

- **Dual frequency EC can resolve thickness variations of 0.002" (5% corrosion in 0.016" th. skin)**
- **Success demonstrated on 206 & S-76 structures in the field**

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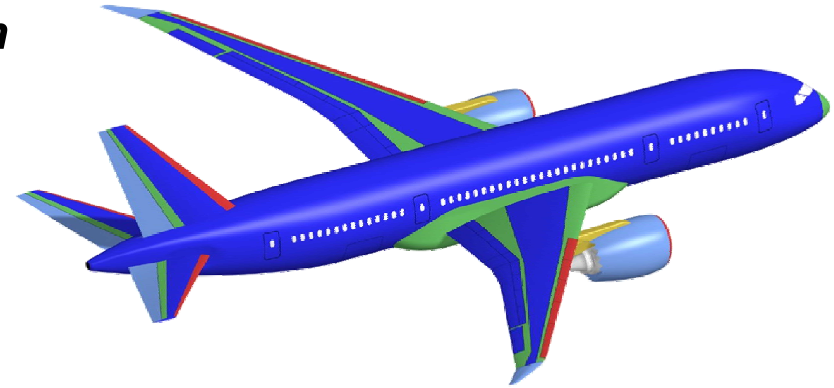
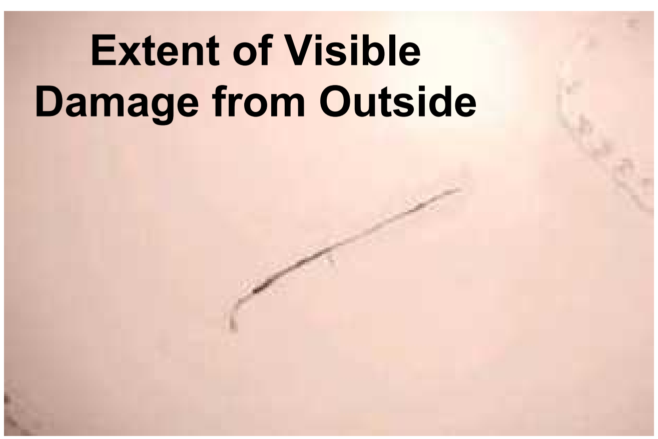
Composite Structures on Boeing 787 Aircraft

- Carbon laminate
- Carbon sandwich
- Fiberglass
- Aluminum
- Aluminum/steel/titanium pylons



Damage from ground vehicle



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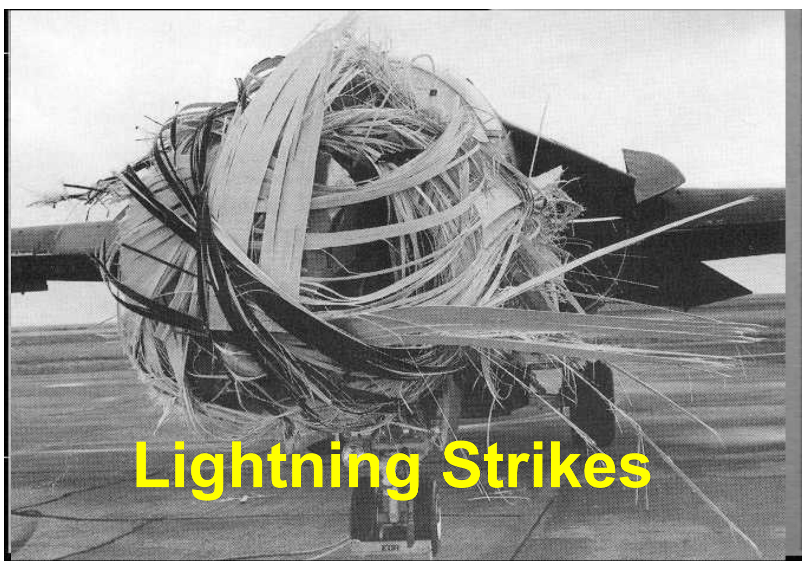
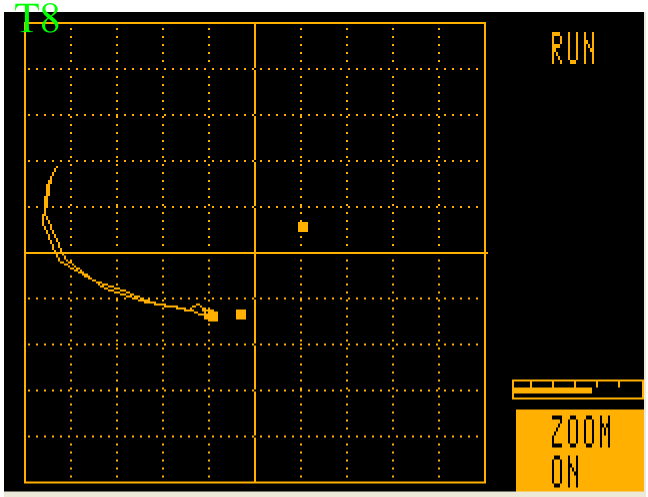
Jackstands

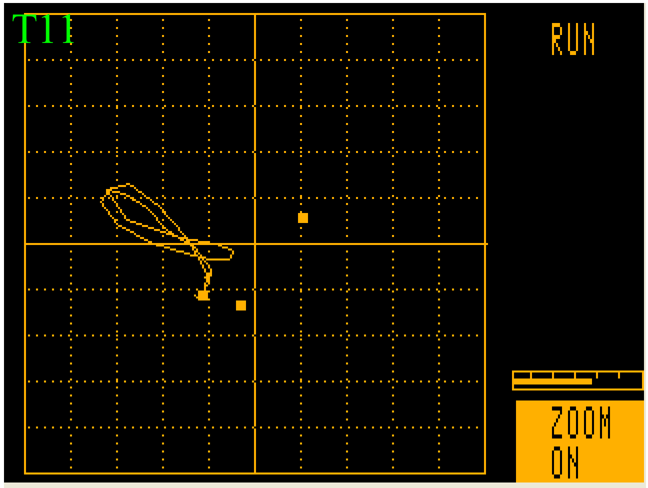

Ground Handling
Impact Damage


Lightning Strikes


Bird Strikes
5:34 PM

Bondmaster – Resonance Mode

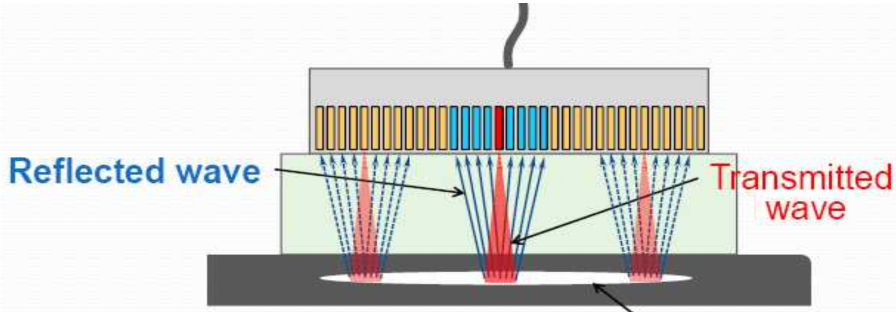


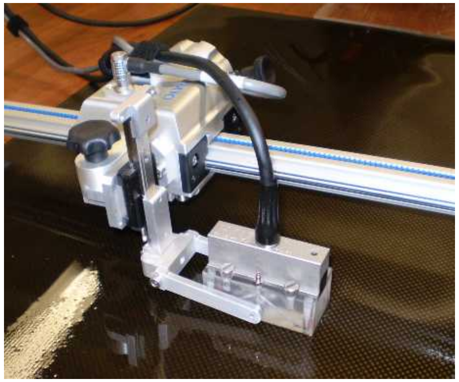


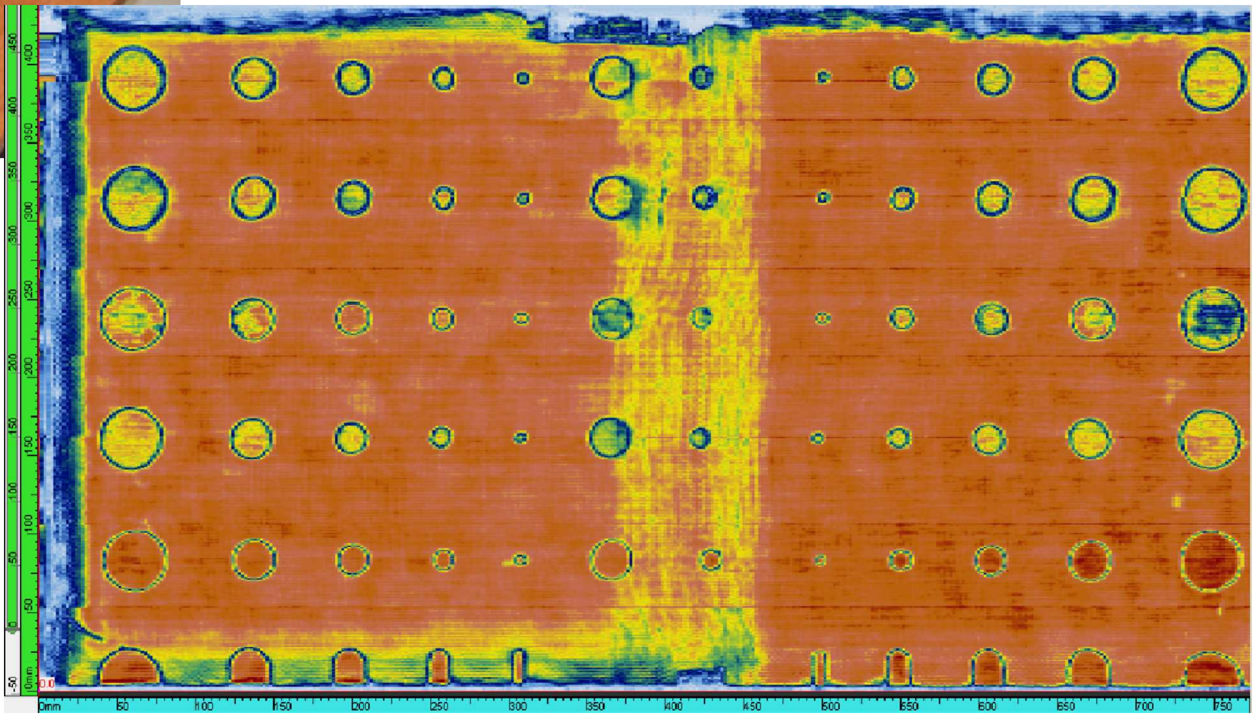
Challenge of flying dot interpretation, especially in areas of changing geometry

Advantages of Phased Array Ultrasonics

OmniScan MX with a Phased Array Module (5 MHz)





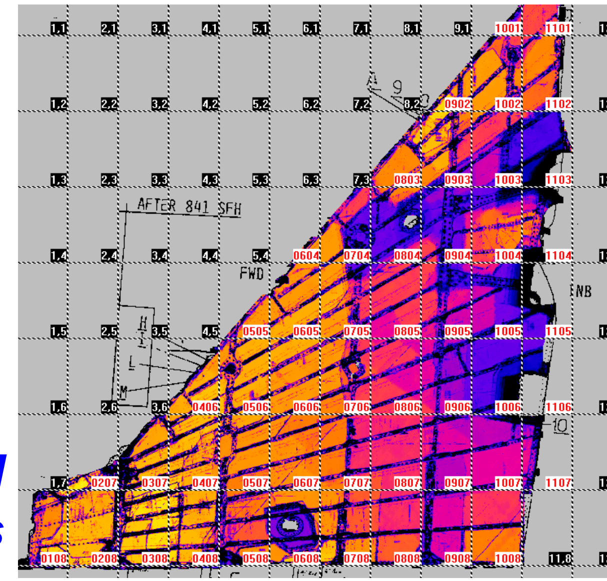


Reflected wave can be received by multiple sensors

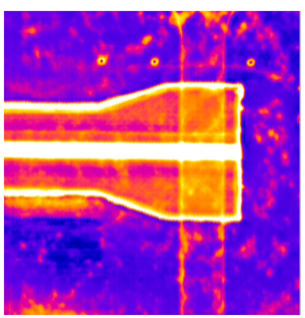
Ultrasonic Material Characterization

QinetiQ

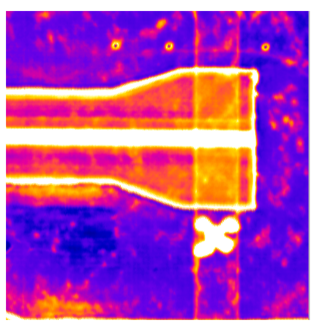
- **Automated analysis for characterizing defects**
- **Large area mapping where fingerprint scan can be used as reference for automated comparisons**
- **Enhance S/N**
- **Direct measurement of material properties from signal processing & spectral analysis of waveform data**



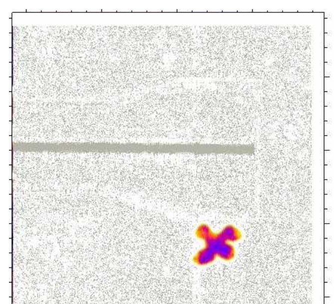
Single mosaic scan assembled from 'slave" scans



Original Structure



Scan After Impact



Damage Assessment C-Scan After Image Subtraction

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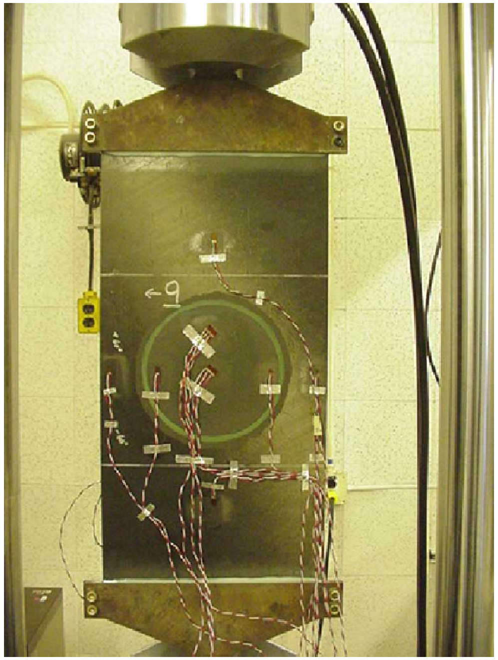
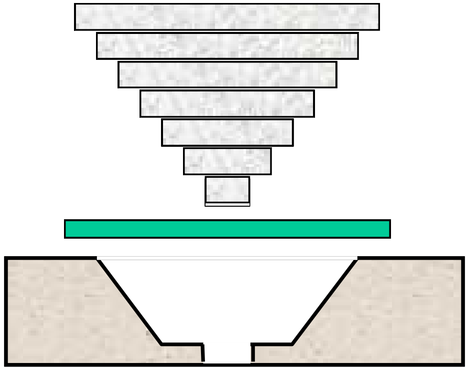
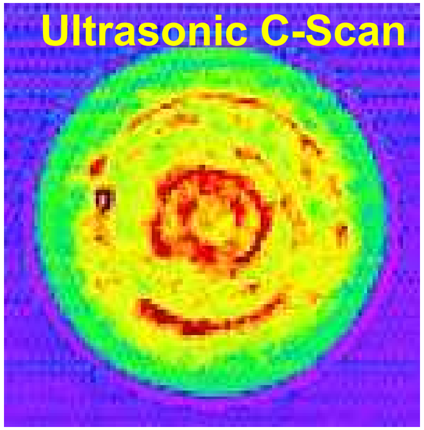
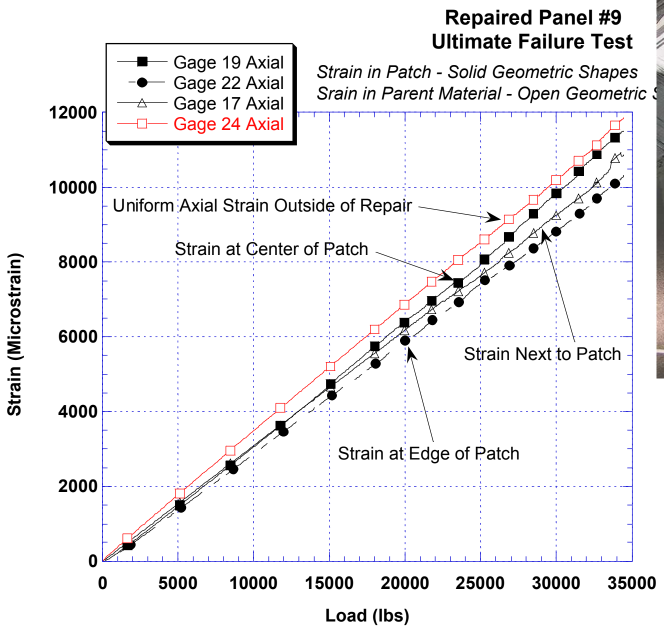
Evaluation of Laminate Repair Systems – Compare Mechanical & NDI Performance

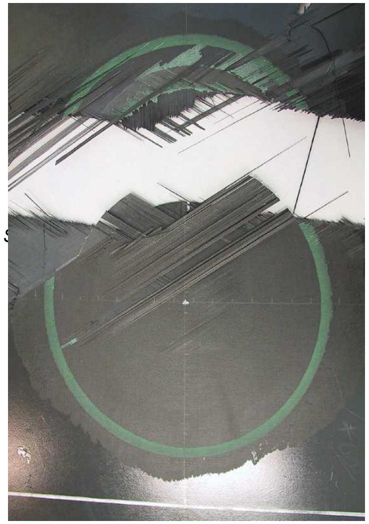






Strain field & repair efficiency assessment vs. NDI findings





Comprehensive evaluation of composite repair and associated NDI technology to ensure proper mesh between structural integrity & flaw detection

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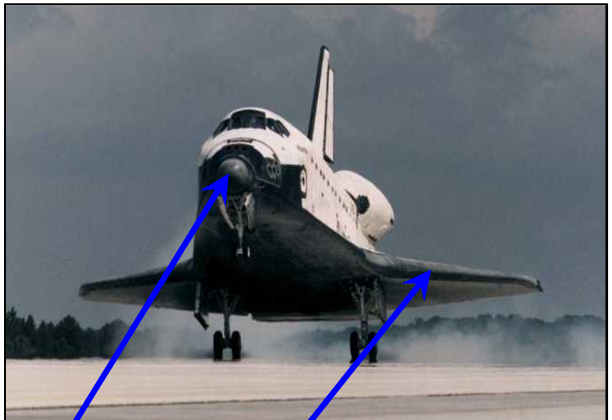
Pulse-Echo Ultrasonic Method for Health Monitoring of Space Shuttle Thermal Protection System

- **Example of FAA AANC expertise applied to solve NASA problem**
- **SNL-developed technique used prior to all missions to certify flight-worthiness**



Wing Leading Edge & Nose Cap Reinforced Carbon-Carbon Panels

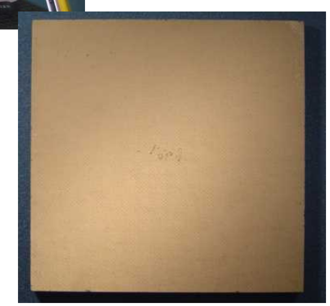
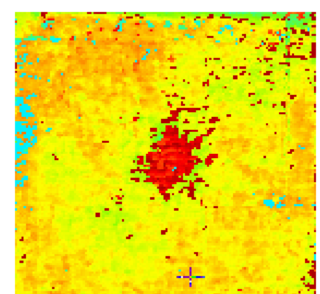
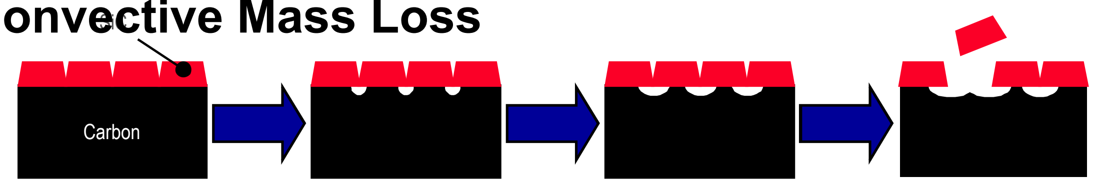


Photo of Impact - RCC Front Surface



UT Image of Flaw

SiC Coating Loss Mechanism via Convective Mass Loss



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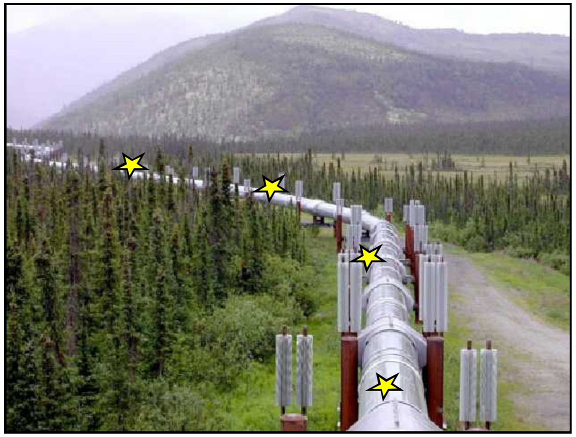
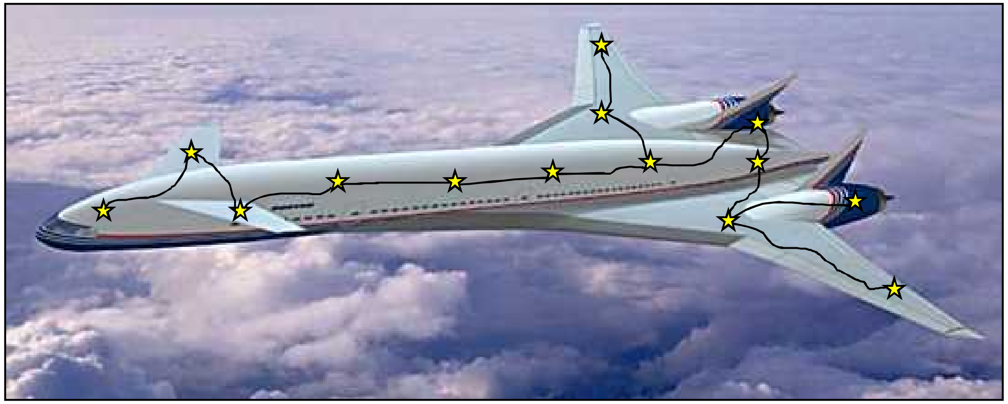
Distributed Sensor Networks for Structural Health Monitoring

Smart Structures: include in-situ distributed sensors for real- time health monitoring; ensure integrity with minimal need for human intervention



- **Remotely monitored sensors allow for condition-based maintenance**
- **Automatically process data, assess structural condition, & signal need for maintenance actions**



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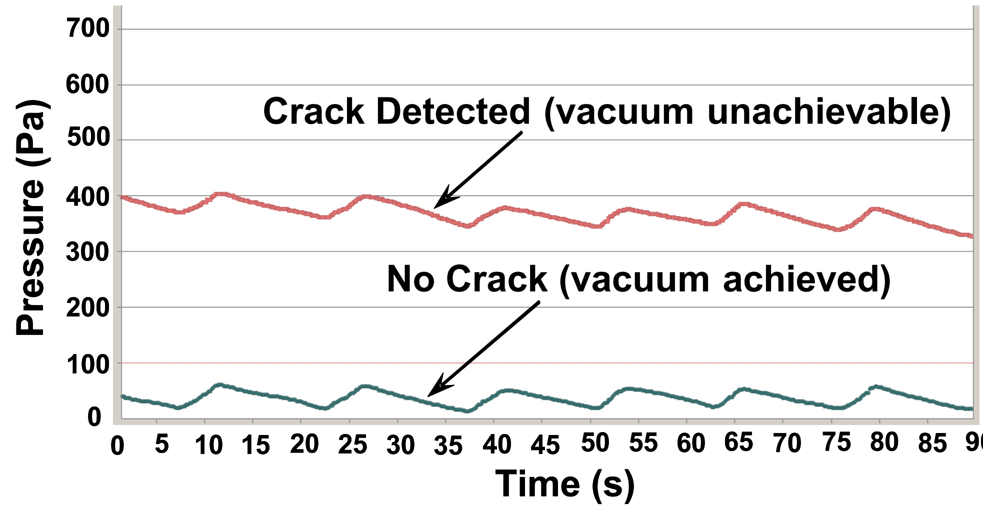
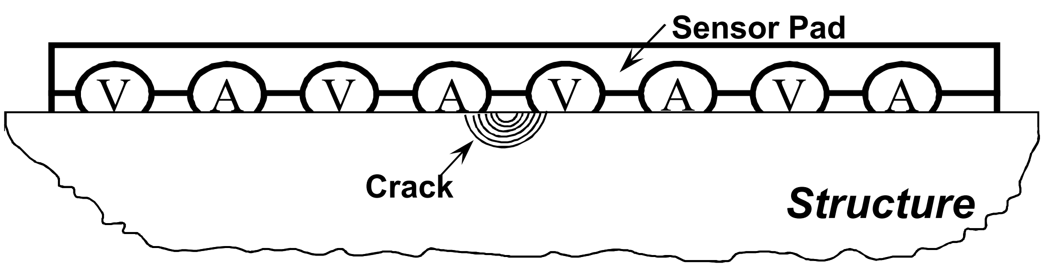
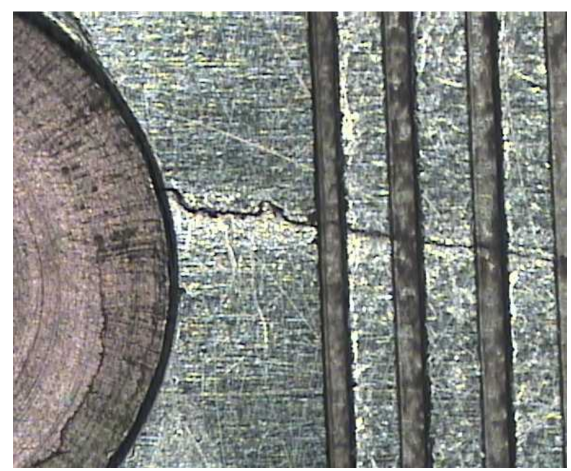
Comparative Vacuum Monitoring System

- Sensors contain fine channels - vacuum is applied to embedded galleries (crack detection ~ 0.1” to 0.5” L for thick steel)
- Leakage path produces a measurable change in the vacuum level
- Doesn’t require electrical excitation or couplant/contact

CVM Sensor Adjacent to Crack Initiation Site







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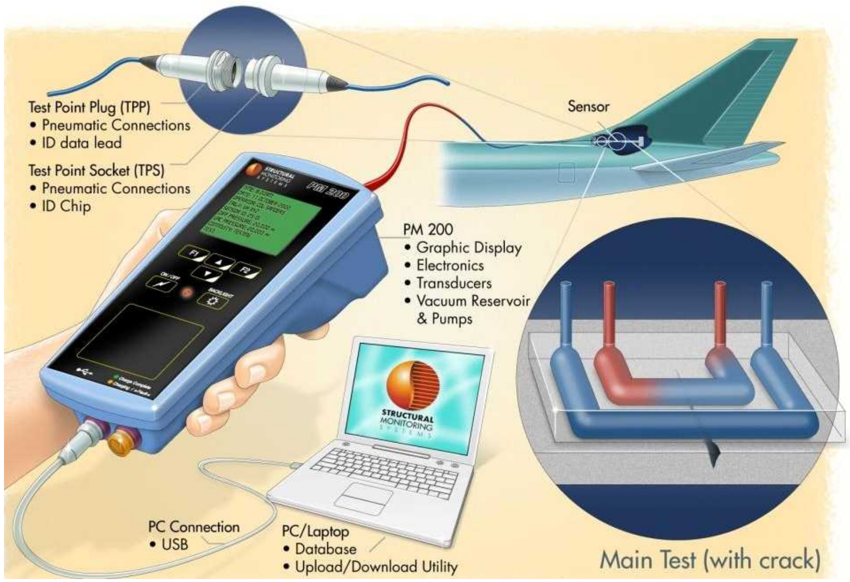
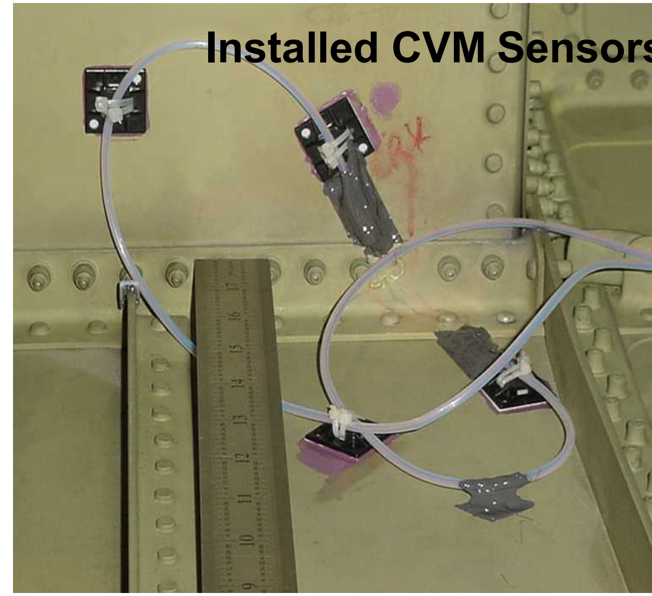
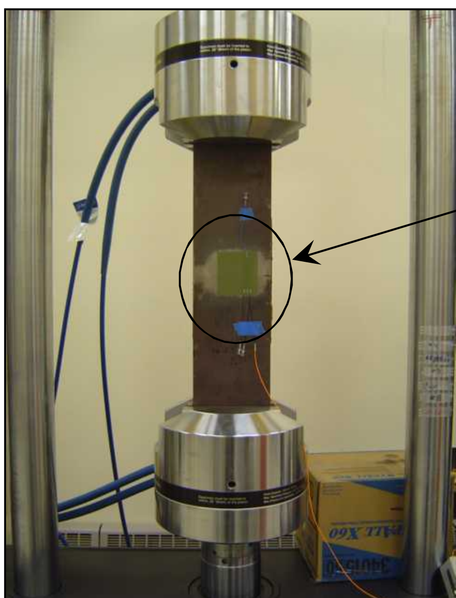
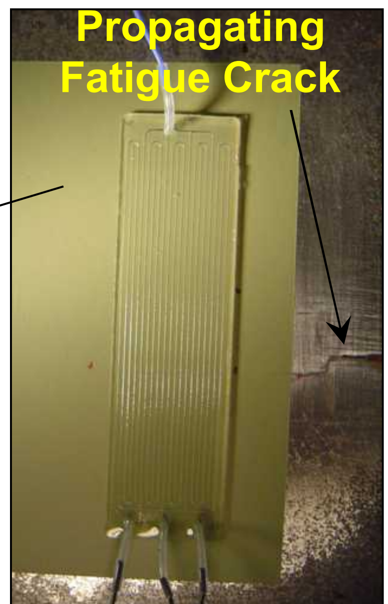
Crack Detection Via CVM System and Test Installation of Sensors









CVM Sensor Installation & Crack Growth Monitoring

For 0.040" th. Skins

90% POD Level	False Calls
0.021"	0

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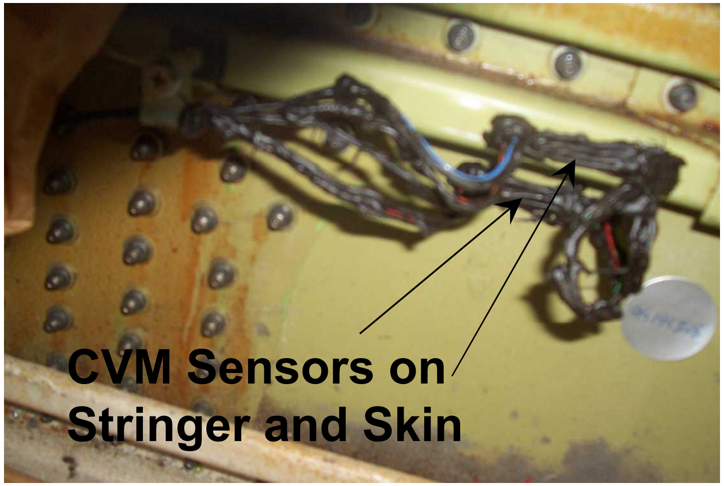
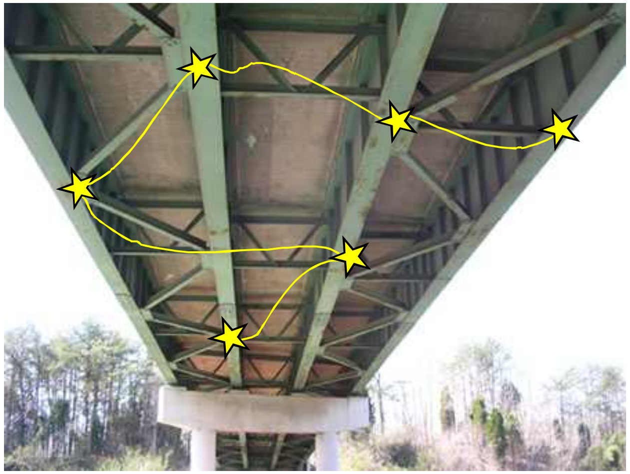
CVM Durability - NWA Aft Baggage Compartment Sensor (A/C 9968)

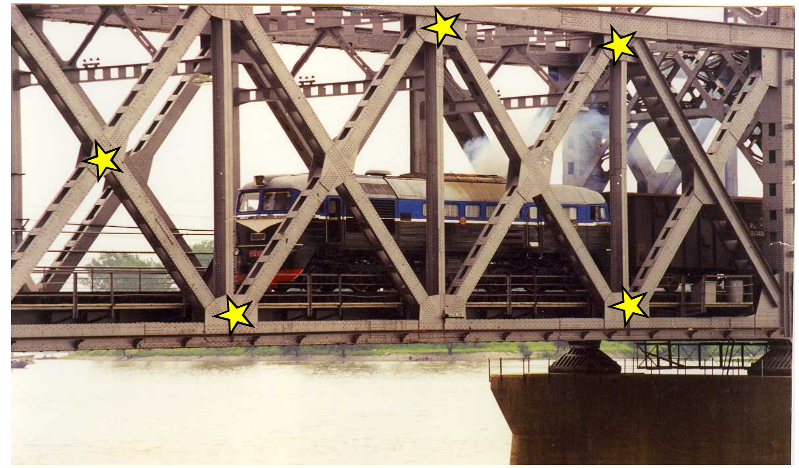


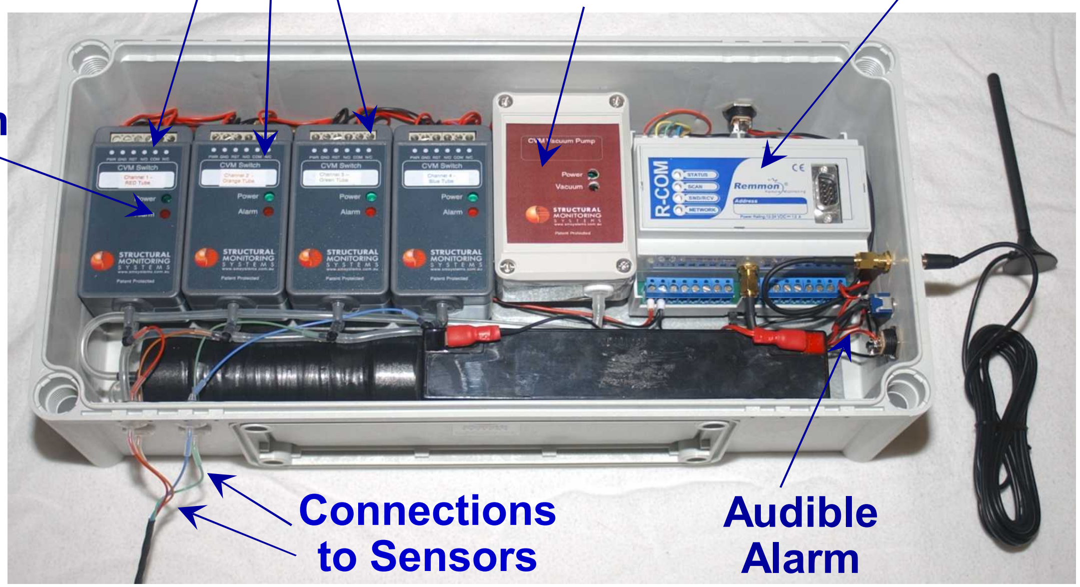
TPS connector routed to access panel

Monitoring CVM with PM-4 device

Real-Time Structural Health Monitoring Using Distributed CVM Sensor Networks







Real-Time, Remote Monitoring System for a Network of CVM Sensors

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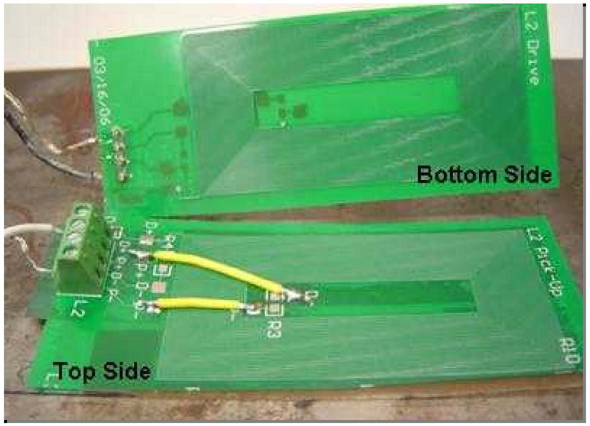
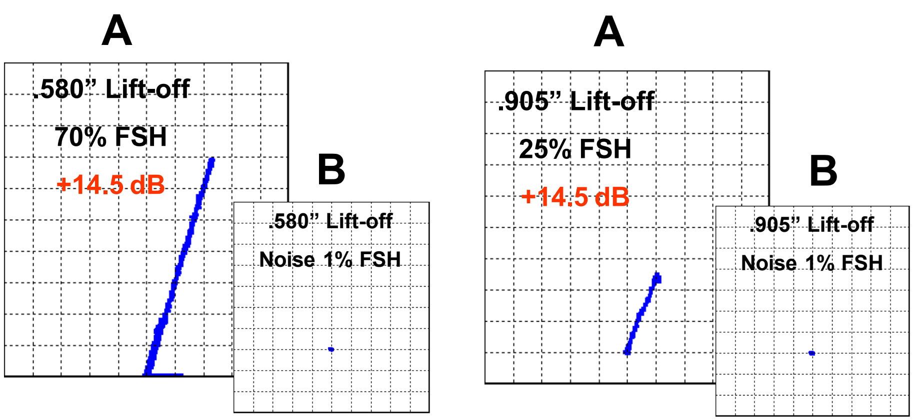
Smart Mountable Eddy Current Sensor (SMECS)

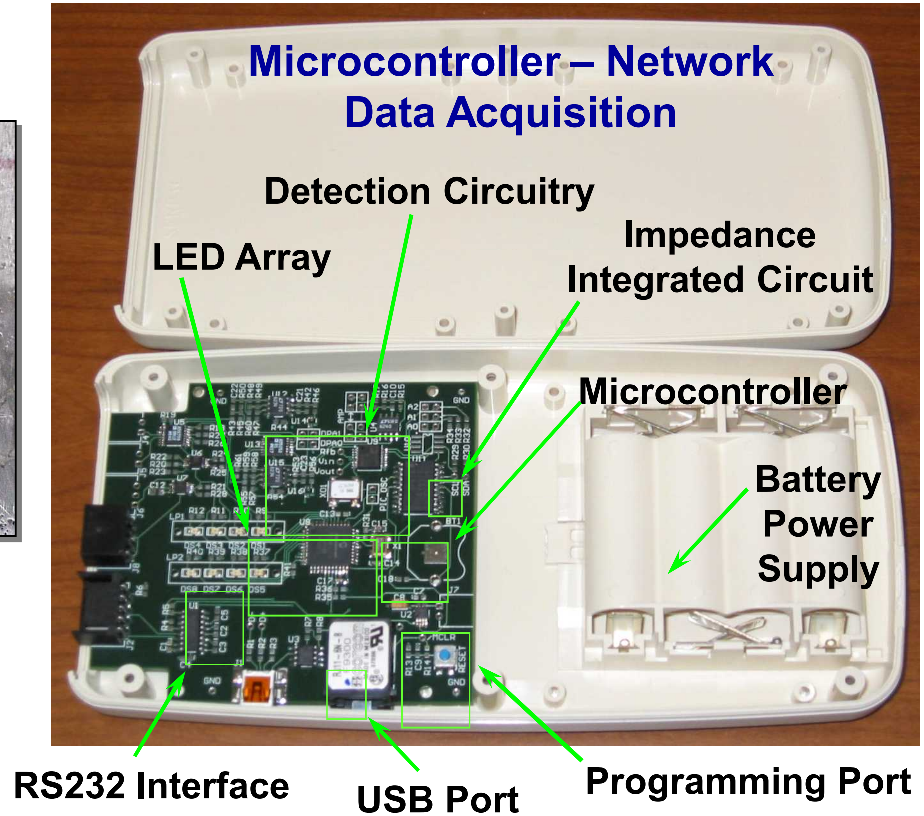
Self-Nulling Differential Coil Set-Up

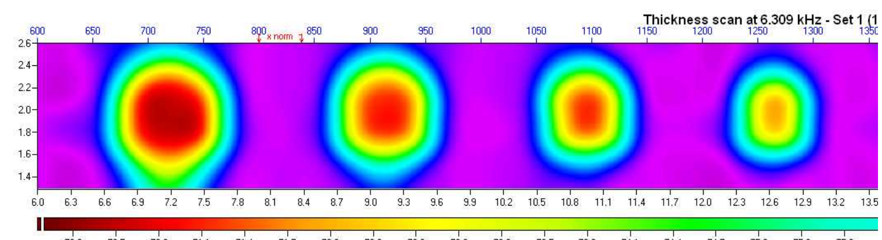


Subsurface Crack Detection Signals Produced Through Thick Surface Layers



Patent Pending





Corrosion Detection

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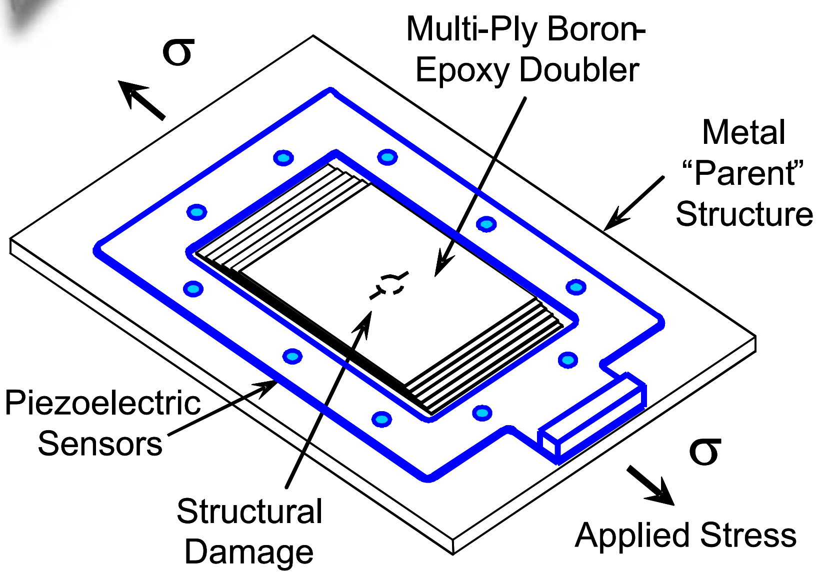
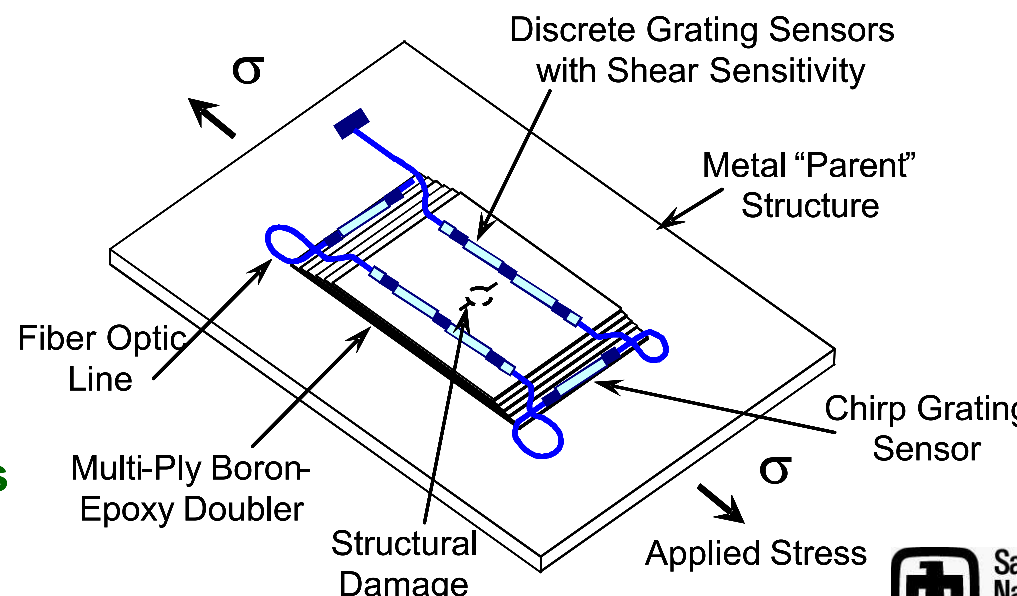
Fiber Optic and Piezoelectric Sensor Systems



Embedded and peripheral monitoring for cracks, corrosion, and disbonds

Piezoelectric Sensors

Fiber Optic Bragg Sensors



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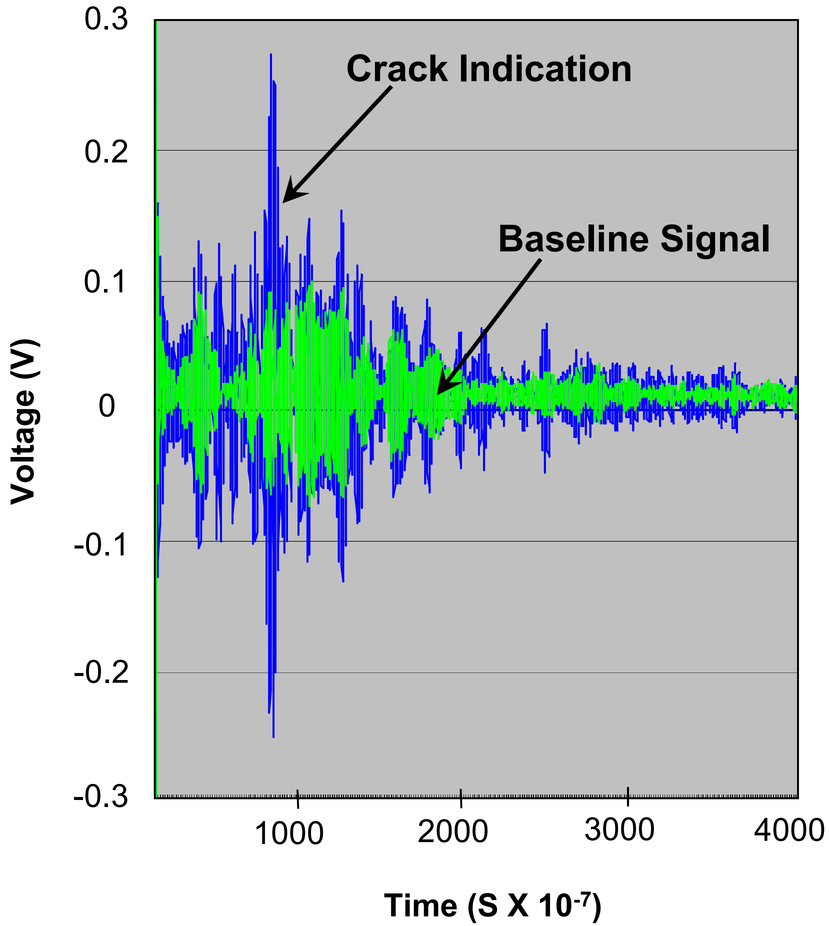
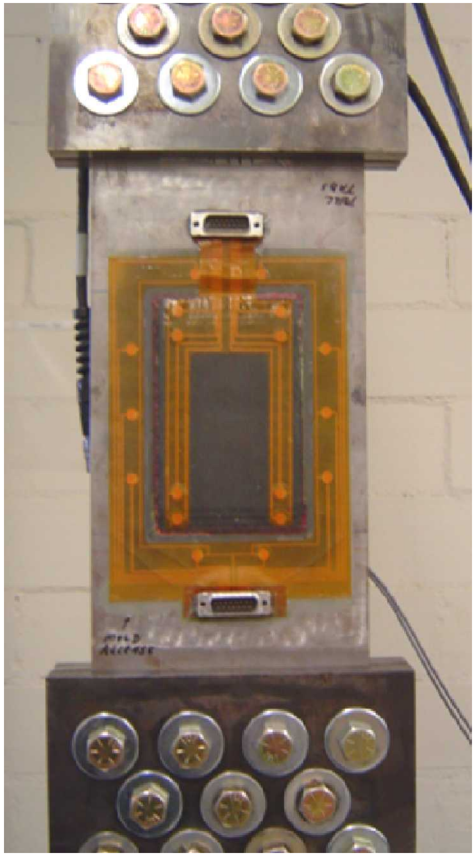
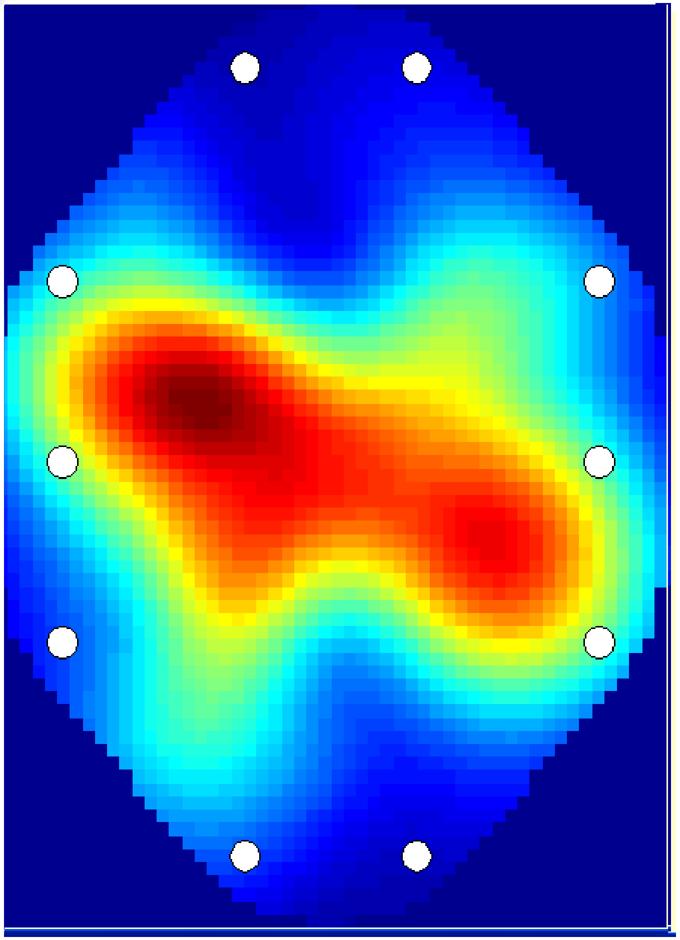
Crack Detection & Growth Monitoring with Piezoelectric Sensors



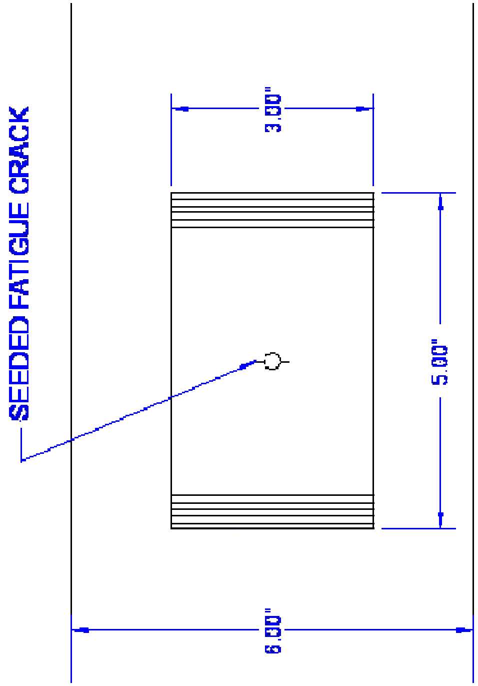
Inspection results from 500 KHz

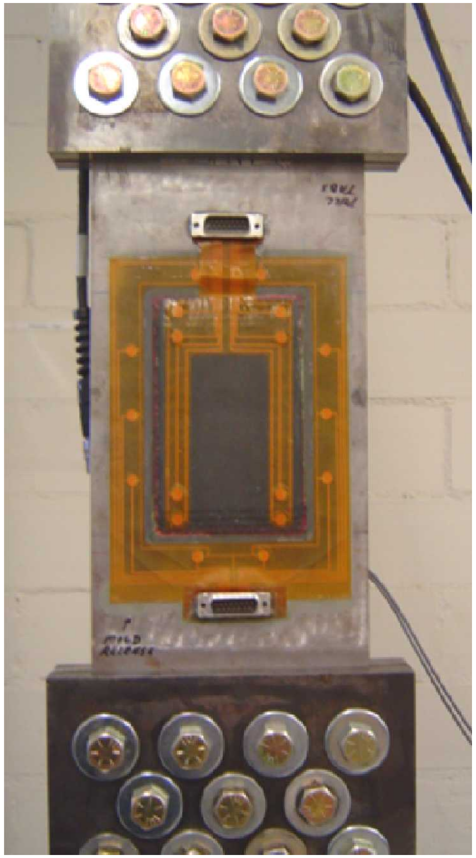


Crack Detection & Growth Monitoring with Piezoelectric Sensors



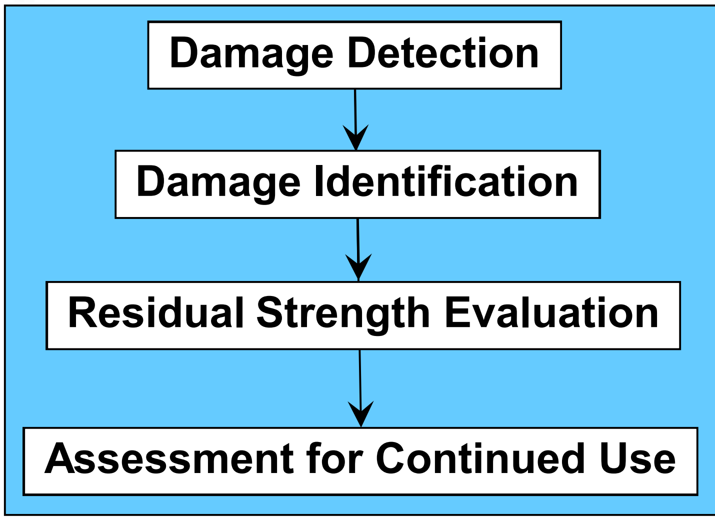
87K Cycles



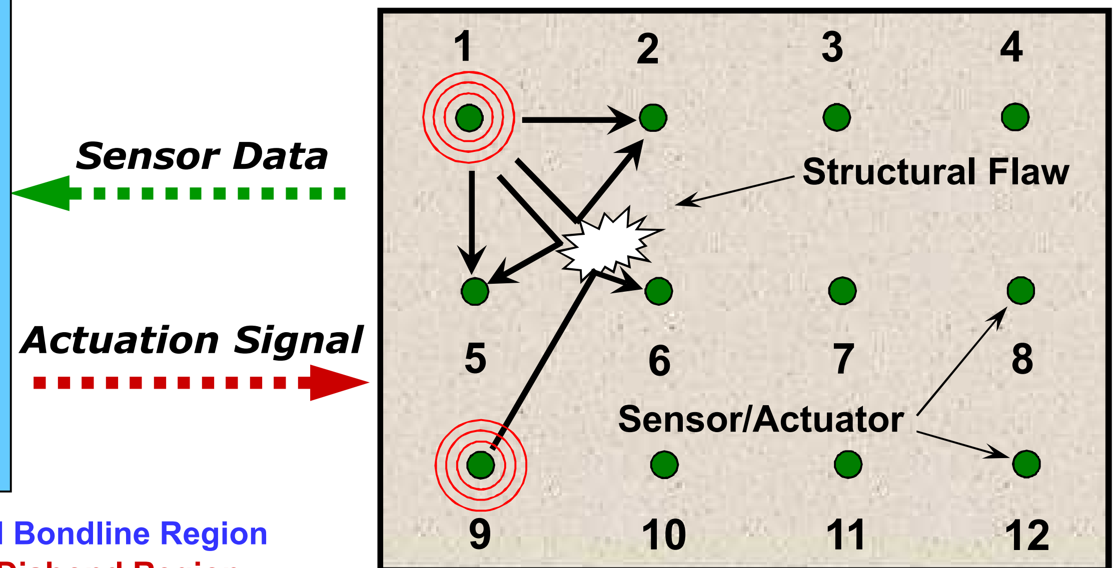


PZT crack length estimates within 5% of measured

Disbond Detection & Growth Monitoring with Piezoelectric Sensors

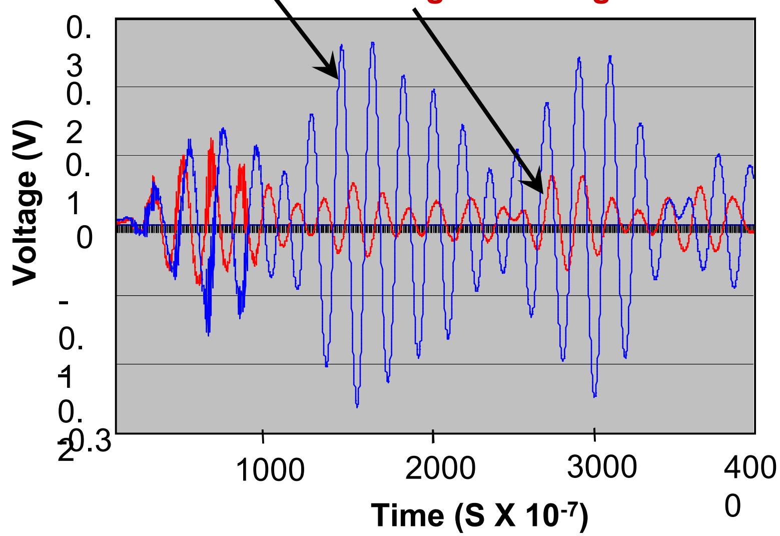


Piezoelectric Sensor Network



Blue = Signal Through Good Bondline Region

Red = Signal Through Disbond Region



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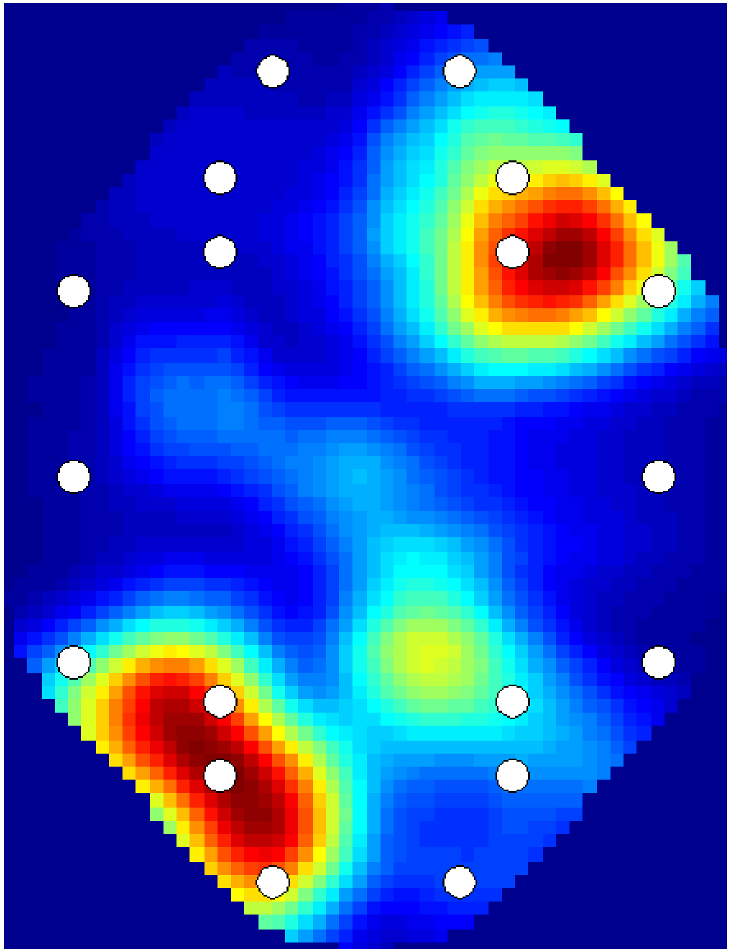
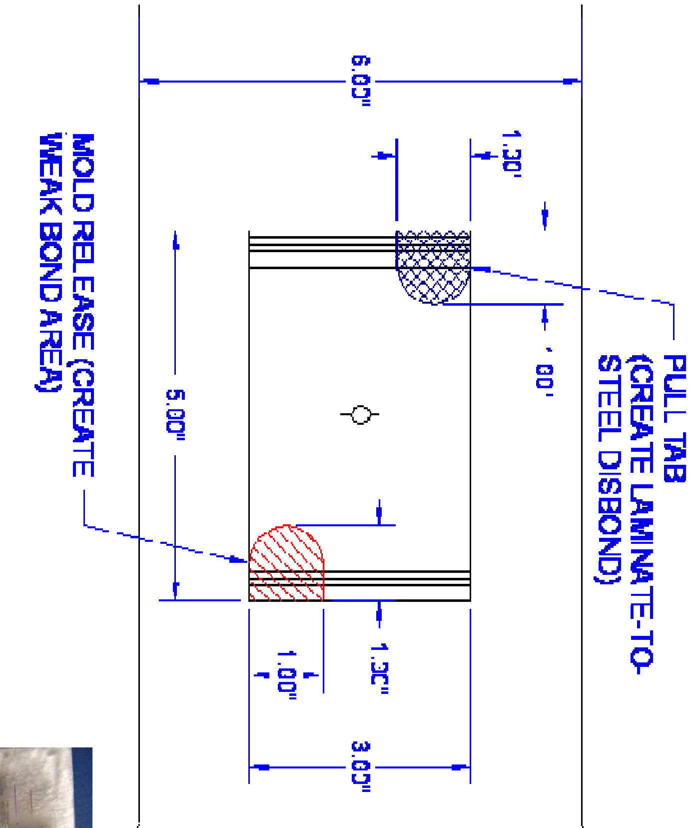
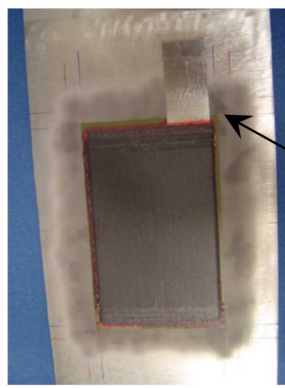
Disbond Detection & Growth Monitoring with Piezoelectric Sensors



After mold release flaw growth
(50 KHz inspection)





Pull tab flaw

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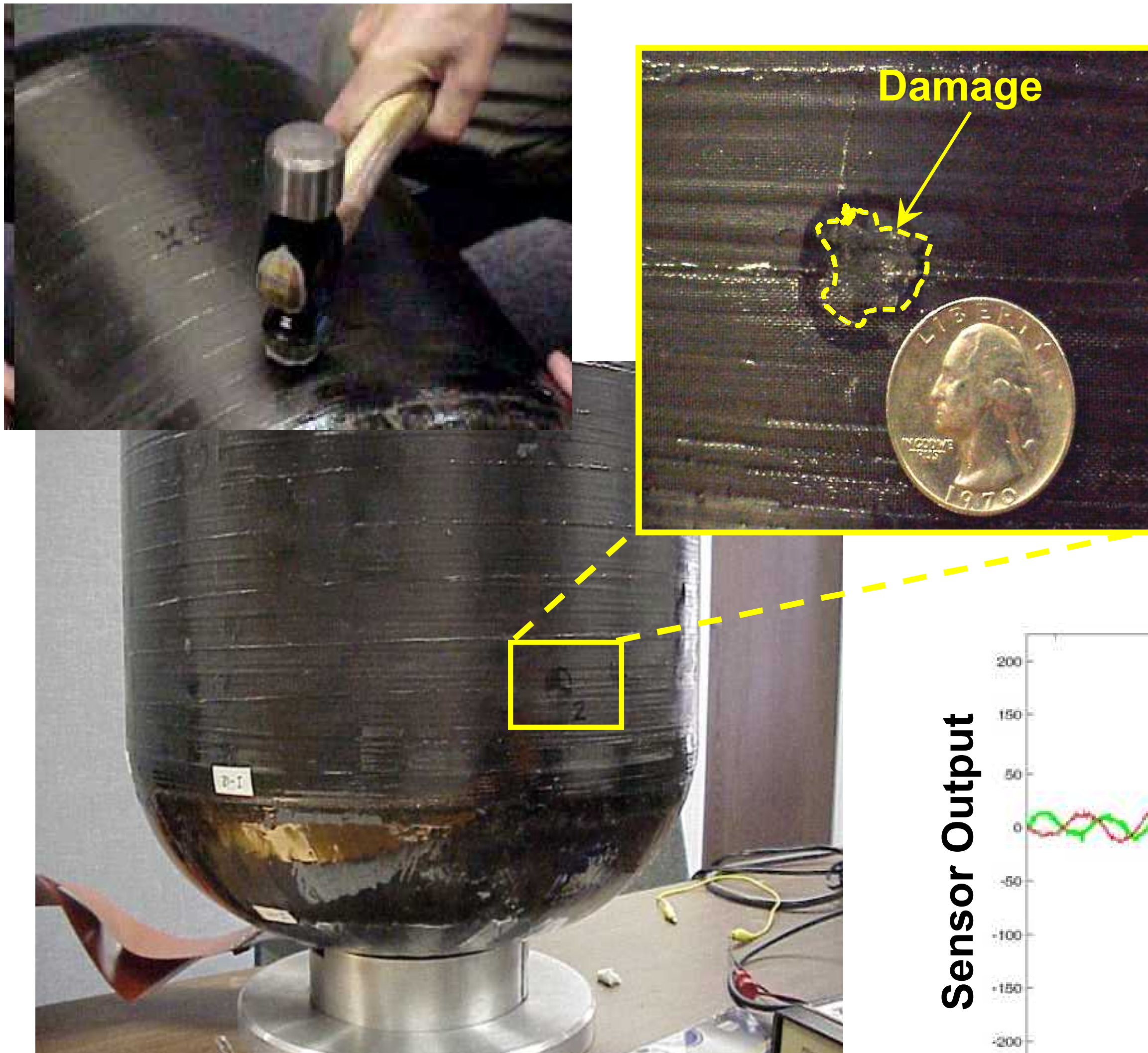
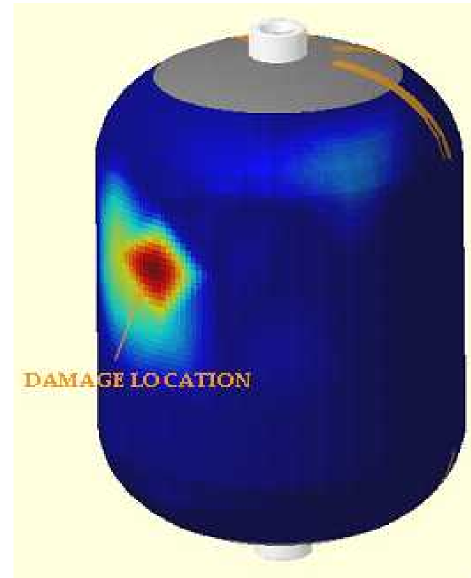
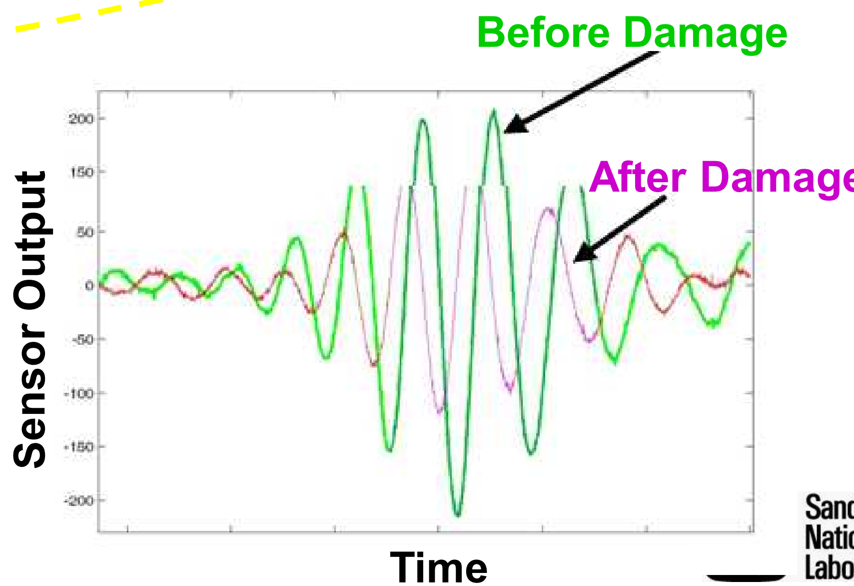
Embedded Piezoelectric Sensors on Filament Wound Vessels - Detection of Impact Damage

Visualization methods can locate and size flaws







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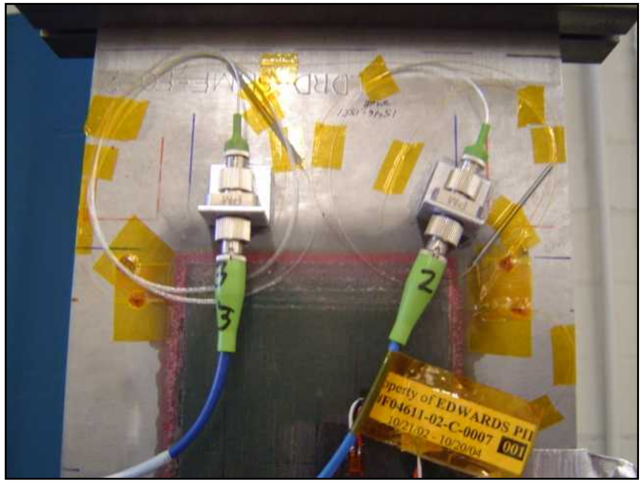
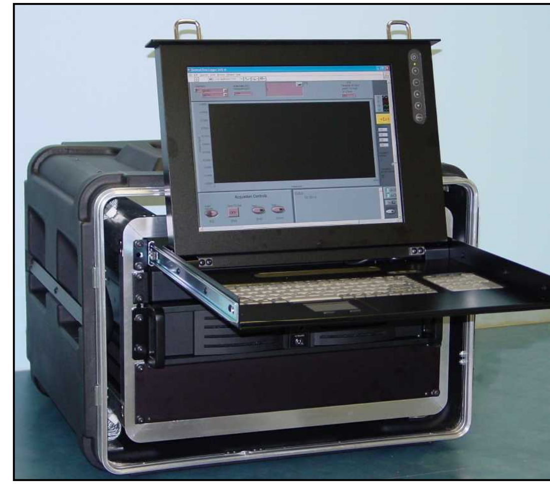
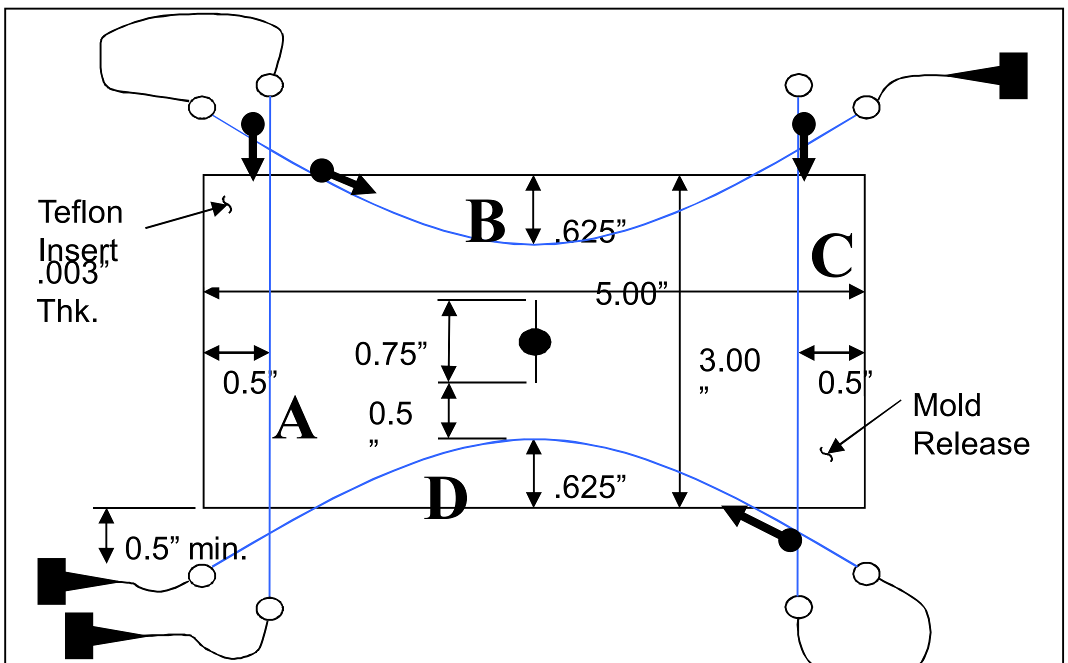
Fiber Optic Bragg Sensor Systems

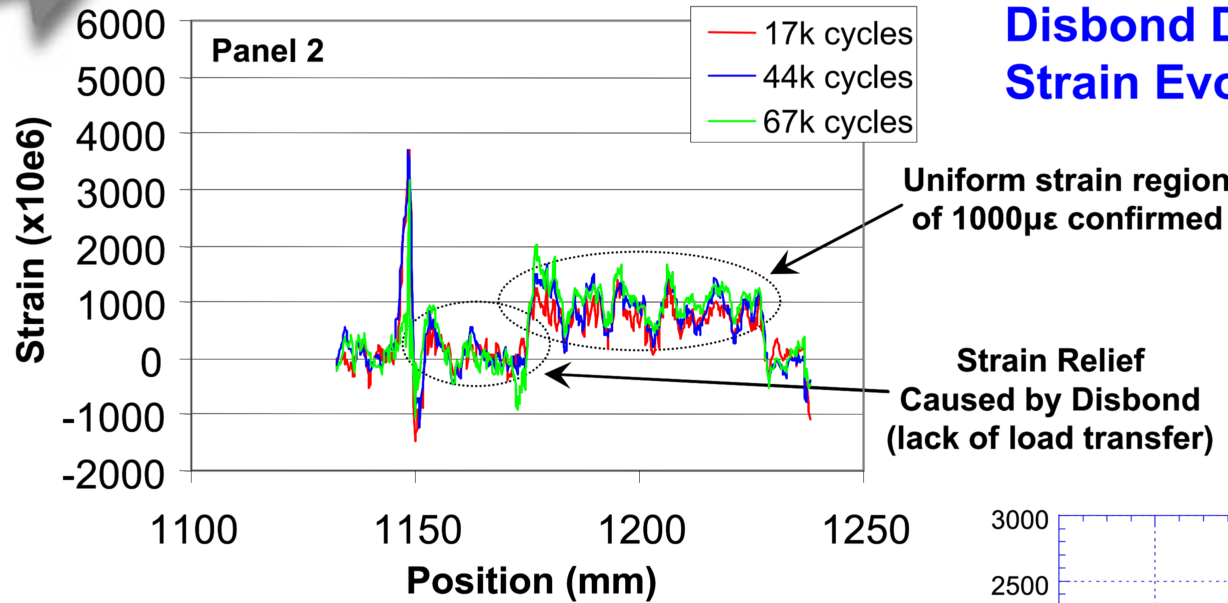






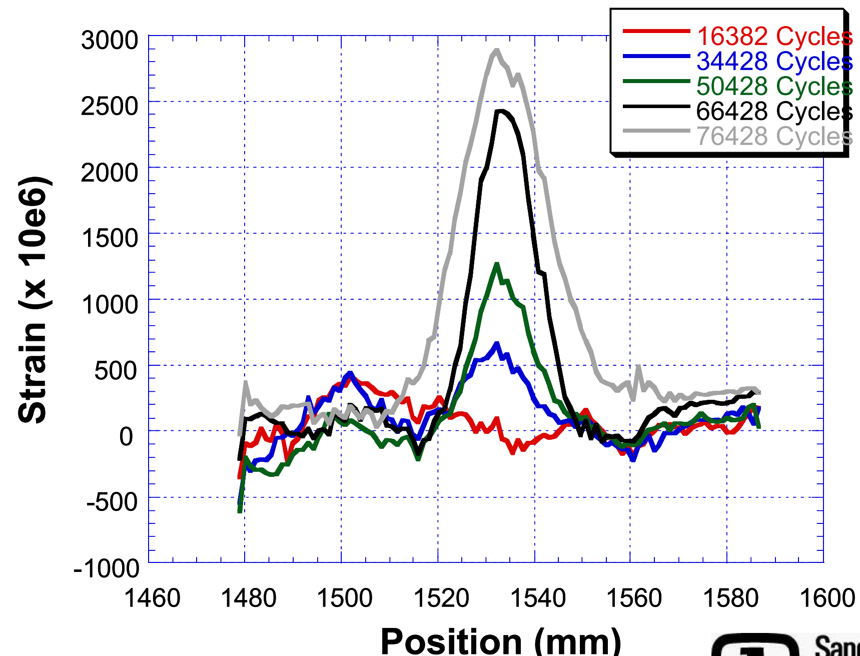
Multi-directional strain monitoring using a birefringement fiber (difference in index of refraction along orthogonal directions)

Health Monitoring with Fiber Optic Sensors



Disbond Detection - Grating A Shear Strain Evolution at 34 kips Load

Axial Strain Distribution Along Sensor D as a Crack Tip Approaches



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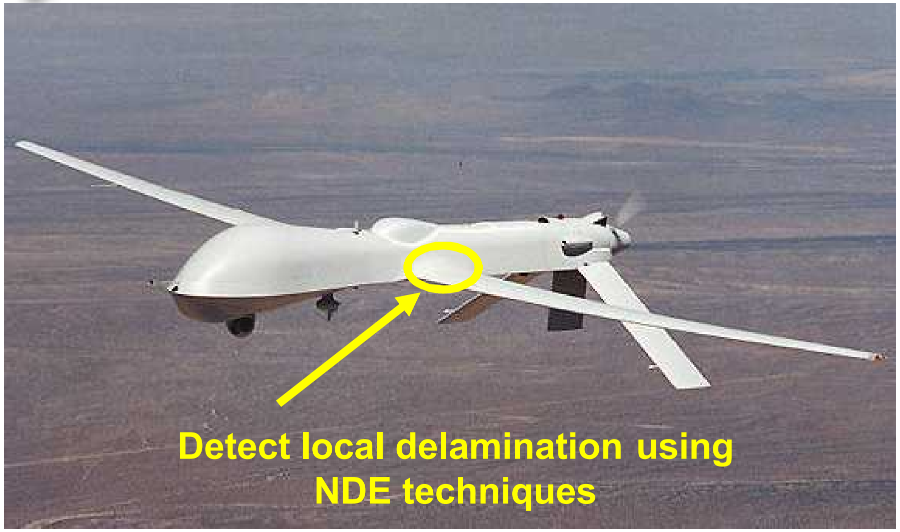
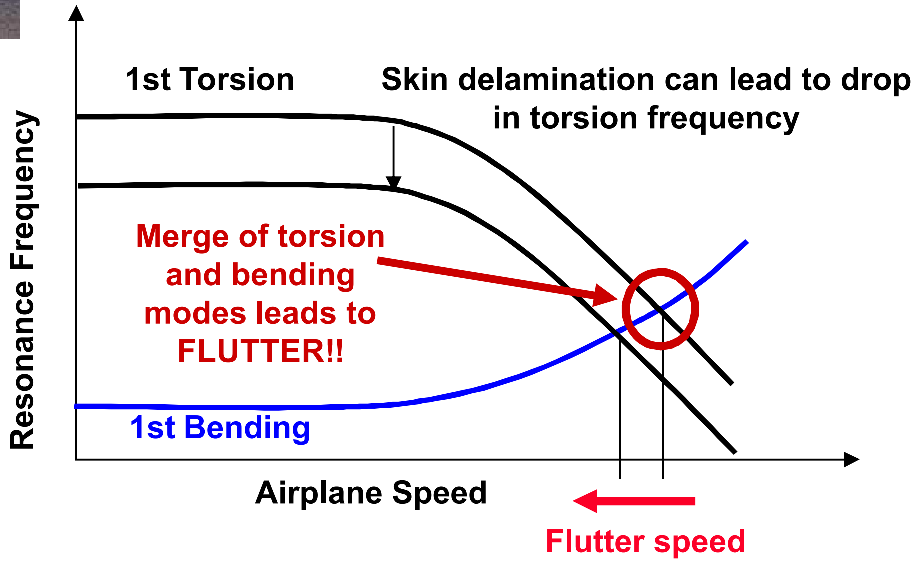
Application of SHM to UAV Operation





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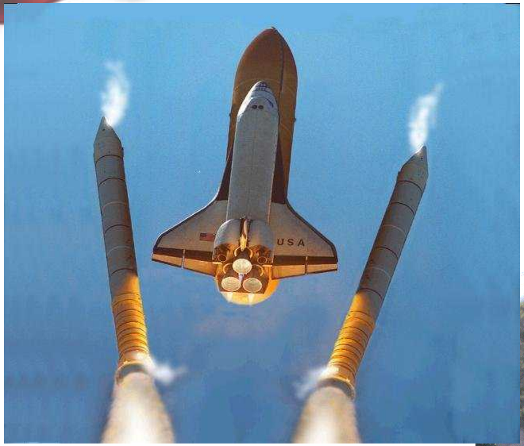

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