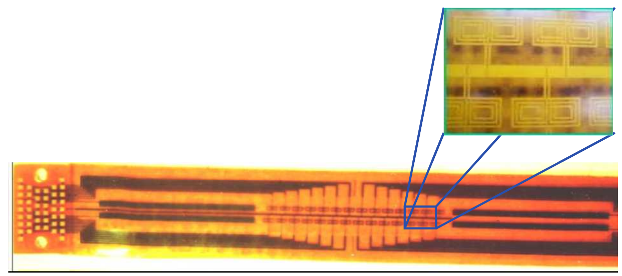
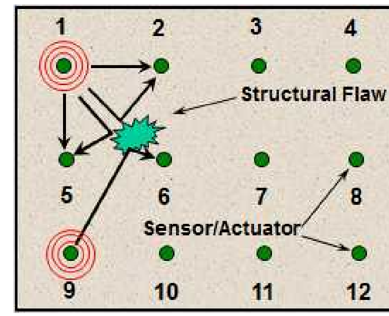
FAA Research Program Webinar Series on Structural Health Monitoring for Aircraft Maintenance

SAND2016-8003PE

MODULE 1: Introduction to SHM and Implementation





Presented by: Dennis Roach
Sandia National Labs
FAA Airworthiness Assurance Center

Sponsored by: Ian Won & Mark Freisthler, FAA-TAD
Paul Swindell & Jon Doyle – FAA WJ Hughes Tech Center

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FAA Webinar Series on Structural Health Monitoring

Module 1 – Introduction to SHM and Implementation

Part 1 – SHM Background and Motivation Driving Aviation Industry

Part 2 – SHM Implementation, Sensors and Systems

Part 3 – FAA SHM Roadmap, Industry Perspectives, SHM Guidance & Standards, and Future Prospects

Part 4 – Introduction to SHM Validation and Performance Assessment

FAA Research Program Webinar Series on Structural Health Monitoring for Aircraft Maintenance

MODULE 1: Introduction to SHM and Implementation

Background: The FAA (William J Hughes Technical Center (WJHTC) has been conducting a research program on Structural Health Monitoring (SHM) for transport category aircraft to support the research needs of the Transport Aircraft Directorate (TAD). These programs have moved SHM solutions into the arena of routine maintenance activities with accompanying certification efforts and flight test programs with airlines and airline requests for SHM usage in their maintenance programs. The Webinars will be a brief introduction of that research and include the topics listed below.

Goal: To bring ACO and other FAA people up to speed on SHM and the prospects of needing to approve SHM for routine use. The webinars will expose attendees to SHM technology, what's out there & how mature, what is the present & expected near-future state of the technology, provide example SHM deployment via summaries of some of the SHM validation/utilization programs conducted to date, and present airline perspectives on SHM utilization.

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MODULE 1: Introduction to SHM and Implementation

Target Audience: Members of the Aircraft Certification Offices (ACO) and TAD; particularly program managers and airframe specialists; engineers and managers. Members of PMI community that will oversee airline maintenance programs that include SHM deployment.

Webinar Topics:

1. Introduction to SHM – what it's about & why is it important to discuss; overview of what FAA folks should expect to see from an SHM applicant
2. FAA SHM Roadmap - status of SHM technologies (SHM survey, maturity & airline perspectives on use); issues to SHM implementation
3. SHM Performance Assessment – initial SHM program for general fuselage use (2005-2010 Boeing program)
4. SHM Certification/Approval for Use – validation; OEM approval, FAA approval (options); sample array of uses identified thus far
5. SHM Deployment – airline perspective (Delta)

Components of FAA SHM R&D Program

1. SHM General Validation – Initial laboratory and field evaluation (decals) to assess CVM as an inspection tool; program for modification of Boeing NDT Standard Practices Manual
2. SHM Roadmap – Identify maturity of SHM; plan for certification & continued airworthiness requirements for safe adoption of SHM practices
3. SHM for Regional Aircraft – Understand drivers for SHM usage; airline and non-USA regulatory agency
4. SHM Certification for an Application - Conduct first SHM certification & integration activity with an operator; establishes an OEM-airline-regulator process; addition of SHM chapter in NDT Manual; release of Service Bulletin allowing routine use of SHM for maintenance action
5. SHM Reliability – Determine optimum means of quantifying performance of SHM solutions.

Timeline

Synopsis of SHM Validation/Utilization Programs Supporting Safe Adoption of SHM Systems

2005

FAA — General SHM Validation

- Assess performance for fuselage applications
- Lab & field testing
- CVM adoption into Boeing NDT Standard Practices Manual

2008

FAA — SHM R&D Roadmap

- Industry survey
- SHM TRL assessment
- Industry perspectives
- Validation methodology
- Considerations for regulatory guidance

2010

FAA — SHM for Commuter Aircraft

- Trial on known damage prone area
- Successful detection on-aircraft
- Transport Canada participation
- Assess repair as-needed

2012

Embraer — Certification for Families of SHM

- CVM & PZT usage over range of A/C applications
- Quantify performance
- Use approval via SBs
- ANAC & FAA interface

2014

FAA — SHM Certification & Adoption by Airlines

- Specific CVM application
- Joint with FAA, Sandia Labs, Delta Air Lines & Boeing
- Formal validation & flight tests
- CVM added to NDT Manual
- SB released – first routine use of SHM

Boeing — SHM for Aft Pressure Bulkhead

2016

FAA — SHM for Rotorcraft

- Validation of local & global SHM approach
- Process for routine use
- Integration into rotor maint.
- Mock certification with FAA
- Integration into HUMS

Program Participants

Structural Health Monitoring – Integration into Routine Maintenance

Sandia National Laboratories — Dennis Roach, Tom Rice, Stephen Neidigk

Federal Aviation Administration — Paul Swindell, Dave Galella, Ian Won, Mark Freisthler

Delta TechOps — David Piotrowski, Alex Melton, John Bohler, Joe Reeves, Chris Coleman, John Hays

Bombardier — Jérôme Pinsonnault, Colin Vollrath, Yves Theriault

Boeing — John Linn, Jeff Kollgaard

Structural Monitoring Systems — Toby Chandler, Mike Reveley, Andy Chilcott

Anodyne Electronics Manufacturing Corp. — Trevor Lynch-Staunton, Henry Kroker, Brian Shiagec, Dave Veitch

Air Canada — Bernie Adamache, Joe Zee

Embraer — Ricardo Rulli, Fernando Dotta, Paulo Anchieta, Luis Santos

Transport Canada — John Mitchell, Hin Tsang, Maurizio Molinari, Marc Lord

Sikorsky — Mark Davis, Andrew Brookhart, Preston Bates, Ray Beale

Acellent — Amrita Kumar, Fu-Kuo Chang, Howard Chung, Franklin Li

Part 1 – SHM Background and Motivation Driving Aviation Industry

Motivation for FAA SHM Validation Activities

- Current aircraft maintenance operations require disassembly of structure, removal of sealant venting of fuel cells or other disassembly processes which could induce damage to the structure.

- Use of in-situ sensors for real-time health monitoring of aircraft structures - overcome inspection impediments stemming from accessibility limitations, complex geometries, and the location and depth of hidden damage.

- Reliable, structural health monitoring (SHM) systems can automatically process data, assess structural condition, and signal the need for human intervention.

- Structural health assessments can occur more often, with significant time savings.

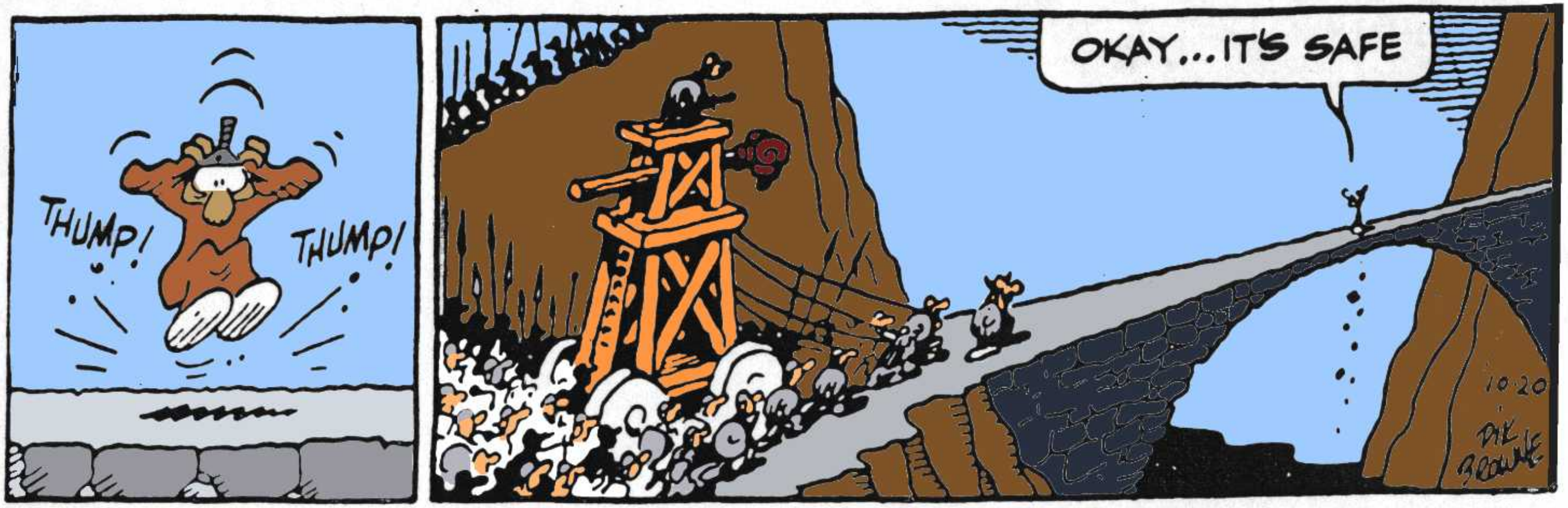
- Federal Aviation Administration is addressing these the safe adoption of SHM practices through a series of SHM validation programs.

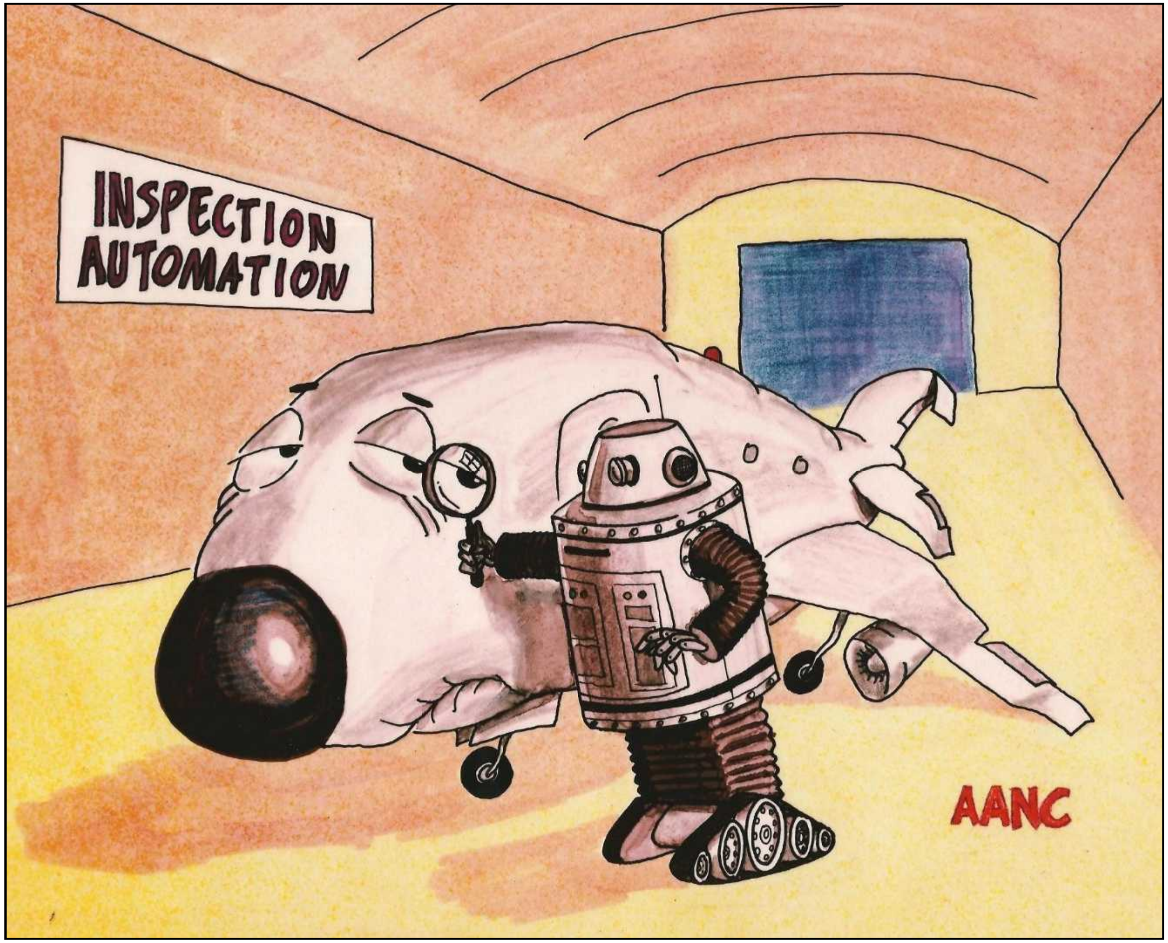
- Assess what regulatory guidance is needed to assure the safe incorporation of SHM through formal certification programs.

Motivation for FAA SHM Program

- Ad-hoc efforts to introduce SHM into routine aircraft maintenance practices are valuable. However, there is a significant need for an overarching plan that will guide activities to uniformly and comprehensively support the evolution and adoption of SHM practices.
- SHM evaluation and deployment plan - needs input from OEMs, regulators, operators, and research organizations so that the full range of issues is appropriately considered → roadmap document.
- Need guidelines for sensor and SHM system designers.
- Need guidelines, or agreed-upon procedures, for assessing the performance of SHM systems or certifying them for use on aircraft.
- Must identify SHM research needed to fill in critical information gaps.
- FAA SHM Program supports the safe adoption of SHM practices and allow OEMs, regulators, and carriers to make informed decisions about the proper utilization of SHM.

Structural Health Monitoring Dates Back Many Years





Definition is somewhat agreed upon. Usage and deployment covers a wide range of thoughts and options.

SHM – Wikipedia

<u>Structural</u> - offers an account of what a system is made of: a configuration of items, a collection of inter-related components; lattice featuring connections between components that are neighbors in space

<u>Health</u> - level of functional and/or metabolic efficiency of a living being

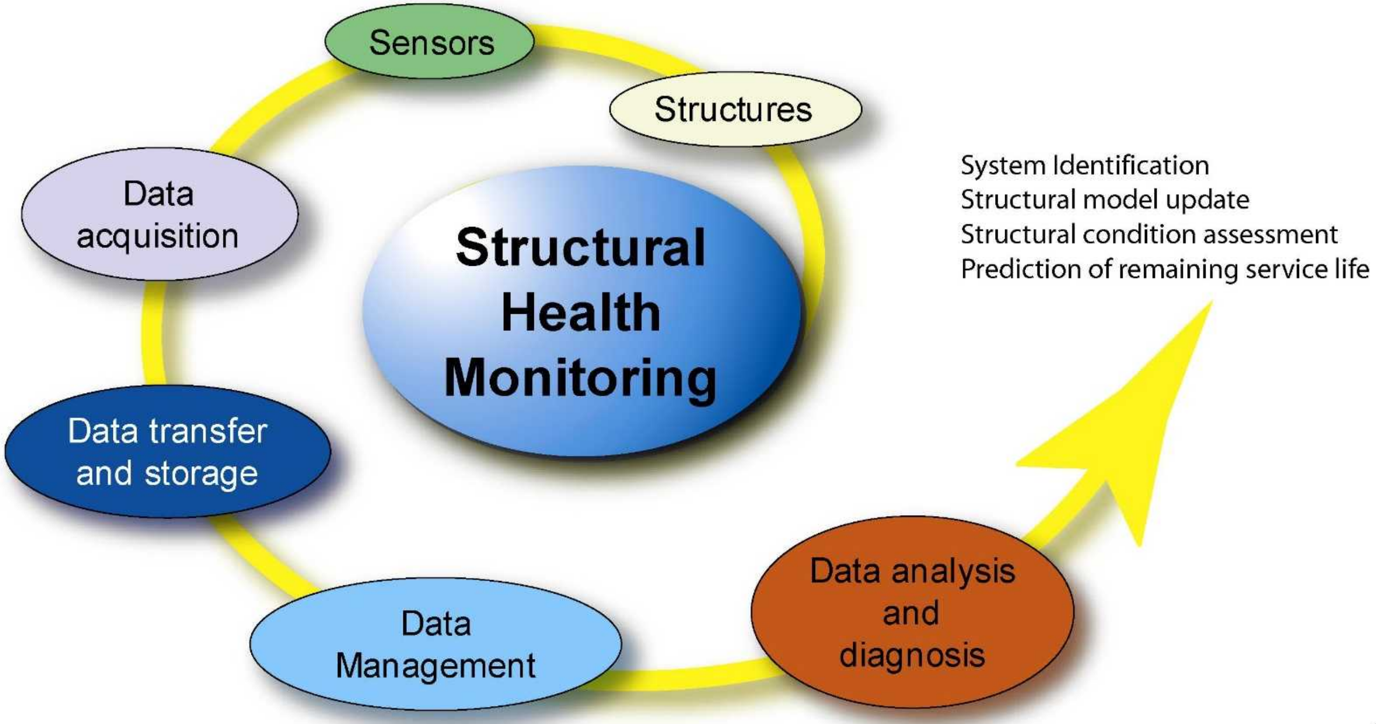
<u>Monitoring</u> - to be aware of the state of a system (performance, deformation, competence)

<u>Structural Health Monitoring</u> - process of implementing a damage detection and characterization strategy for engineering structures to detect changes that adversely affect the system's performance

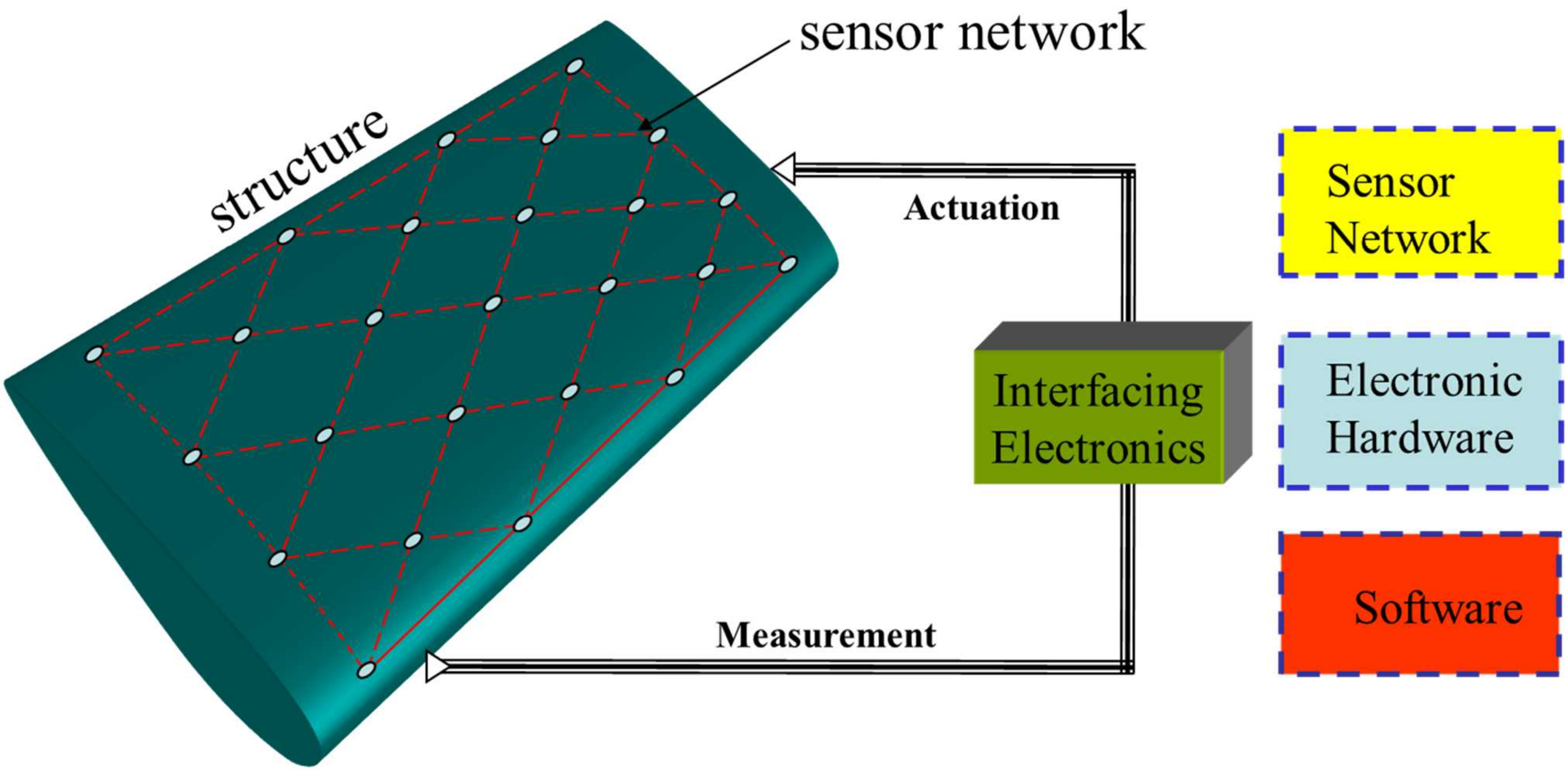
Definition is somewhat agreed upon. Usage and deployment covers a wide range of thoughts and options.

What is Structural Health Monitoring ?

- SHM refers to the broad concept of assessing ongoing, in-service performance of structures using a variety of inspection techniques.
- The core of the technology is the development of *self-sufficient* sensor systems for the continuous inspection of structures with minimal labor involved.
- The aim is not simply to detect structural failure, but also provide an early indication of physical damage to define remedial strategies before the structural damage leads to failure.



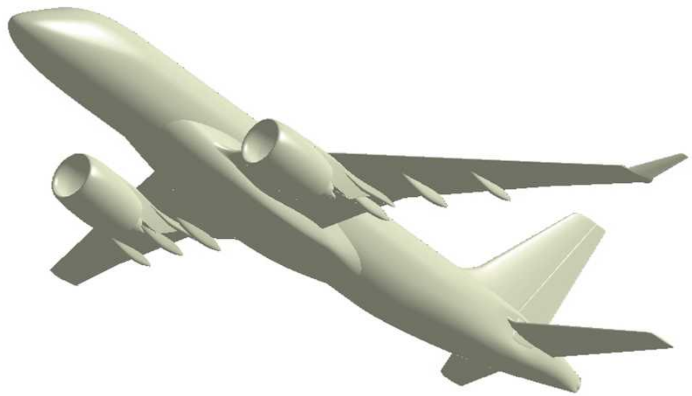
What is Structural Health Monitoring ?



STRUCTURAL HEALTH MONITORING (SHM) ARCHITECTURE

OPERATIONAL MONITORING

- Fatigue Monitoring
- Incident Monitoring
- Environmental Monitoring



DAMAGE MONITORING

- Fatigue damage sensing
- Environmental damage sensing
- Accidental damage sensing

OUTPUTS

- Usage Evaluation
- Advisory Indication
- Inspection Result

BENEFITS

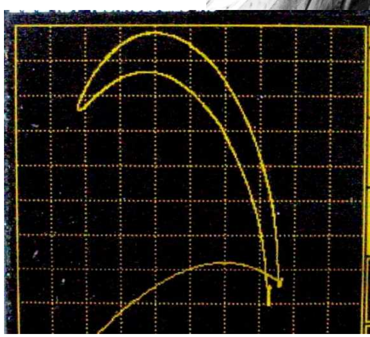
Direct Maintenance Cost
- Improve Repair Planning
- Increase Inspection Intervals
- Reduce Inspection Time and Cost

Direct Operating Cost
- Reduce Weight, Cost & Downtime

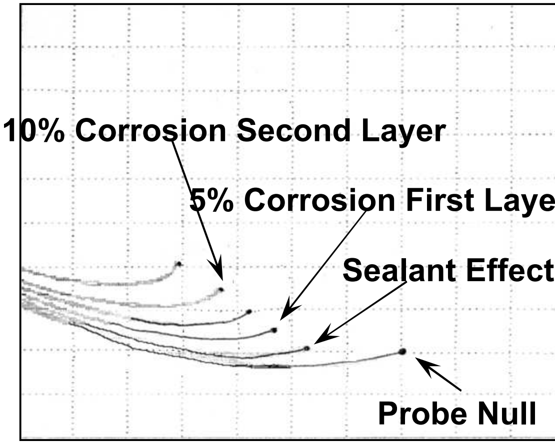
Ownership Cost
- Increase Residual Value
- Life Extension

Future design enhancements

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

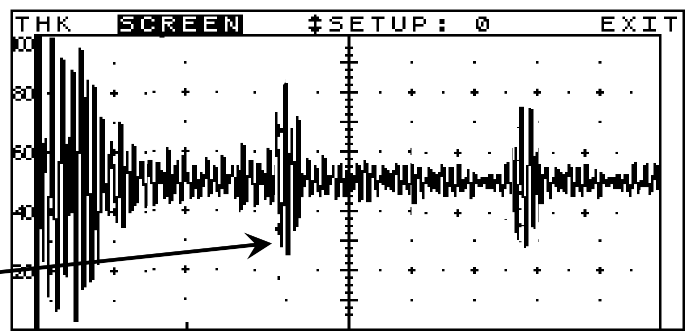


Eddy Current Signal at Crack Site



Corrosion Detection with Dual Frequency Eddy Current

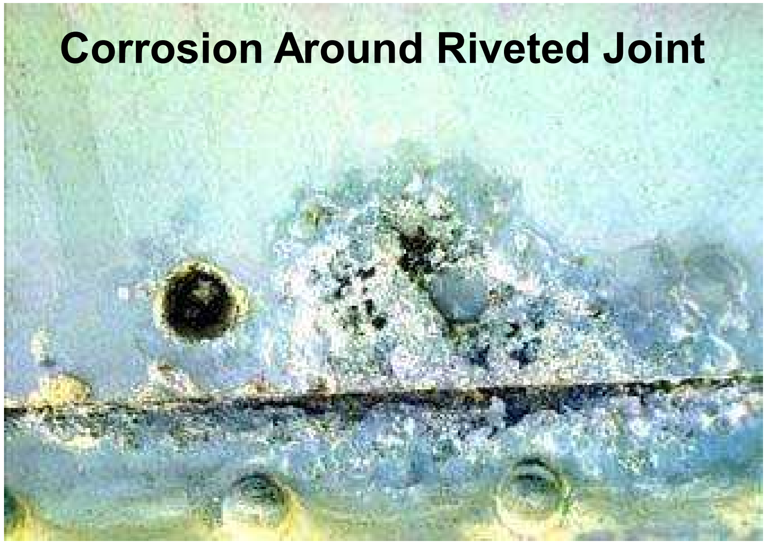
Intermediate Echo Caused by Delamination



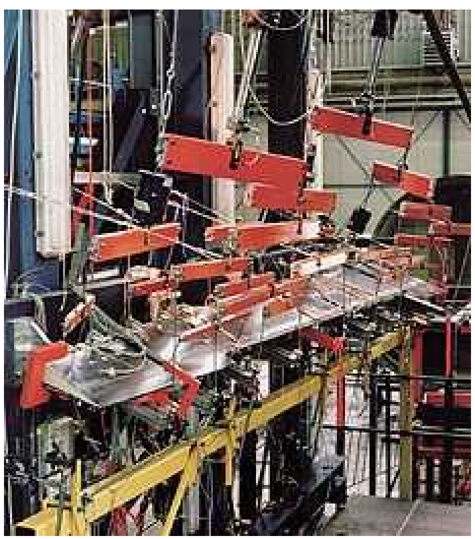
Ultrasonic Pitch-Catch UT Signals Comparing Flawed and Unflawed Signatures

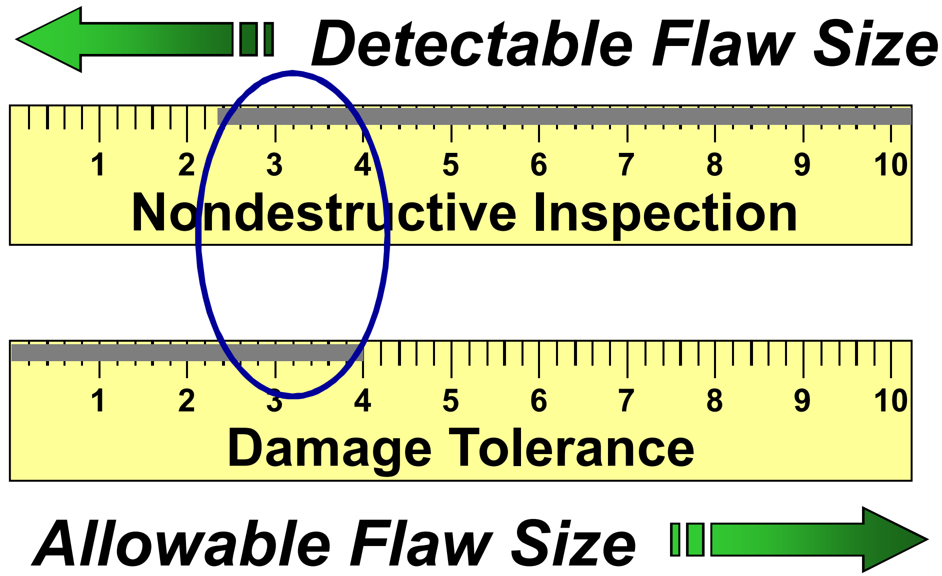
Typical Aircraft Flaw Scenarios

Potential Uses:
- **Aft Pressure Bulkhead**
- **Substructure**
- **Wiring**
- **Flight loads monitoring**
- **System response**



Required Relationship Between Structural Integrity and Inspection Sensitivity

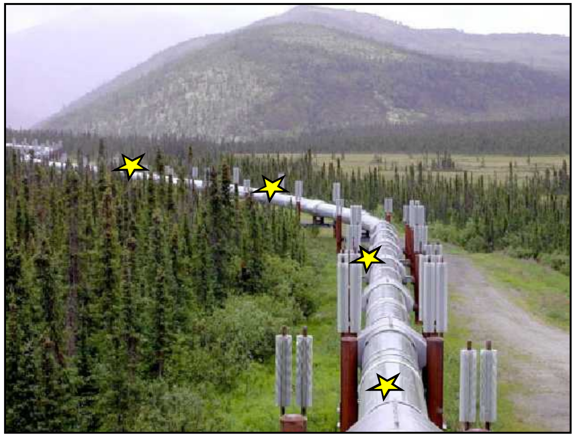


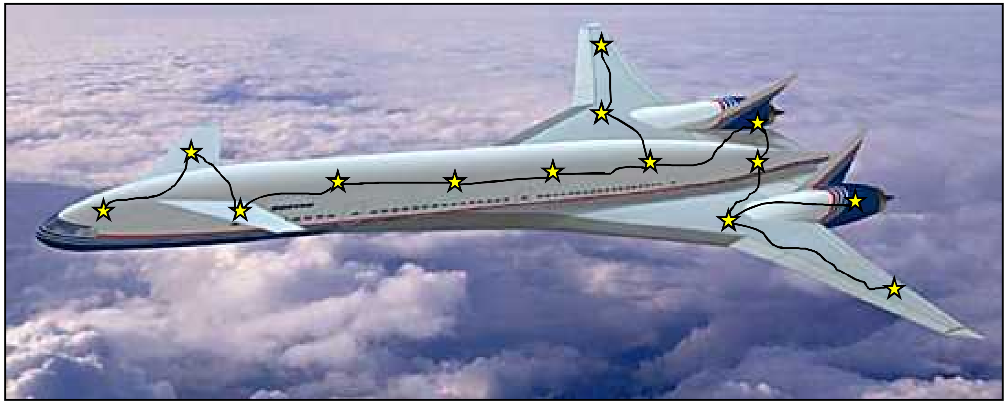


Distributed Sensor Networks for Structural Health Monitoring

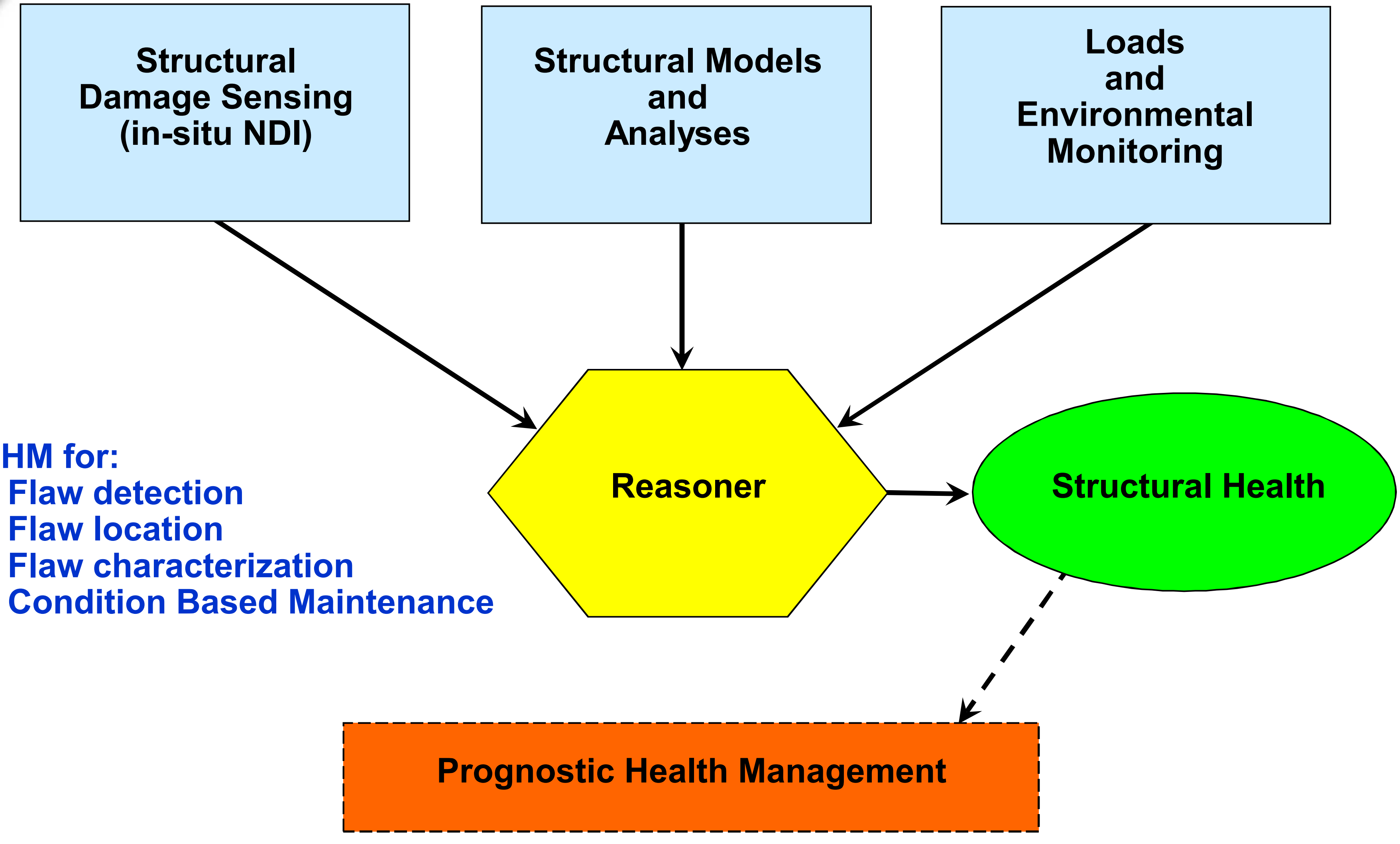
Smart Structures: include in-situ distributed sensors for real- time health monitoring; ensure integrity with minimal need for human intervention

- Remotely monitored sensors allow for condition-based maintenance
- Automatically process data, assess structural condition & signal need for maintenance actions
- SHM for:
  - Flaw detection
  - Flaw location
  - Flaw characterization
  - Condition Based Maintenance





Structural Health Monitoring



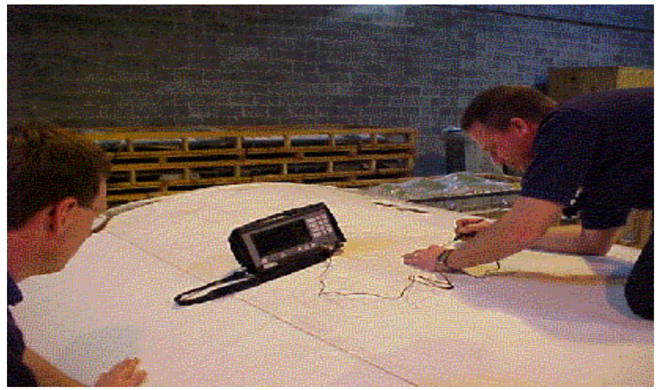
SHM for:
- Flaw detection
- Flaw location
- Flaw characterization
- Condition Based Maintenance

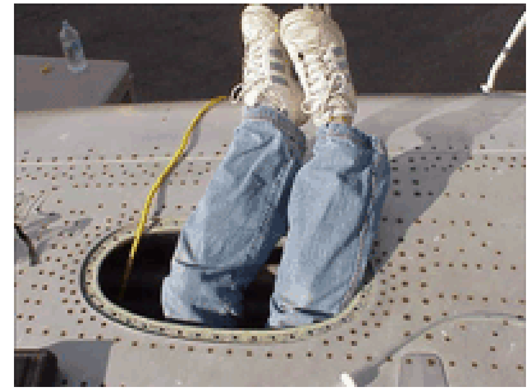
The Trouble with Math or…..
How do we calculate DT ??

Difficulty in loads assignment, stress and fatigue calculations produces demands on NDI -

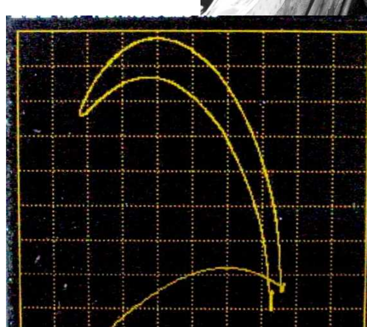
"You want me to find a flaw where, and how small??"

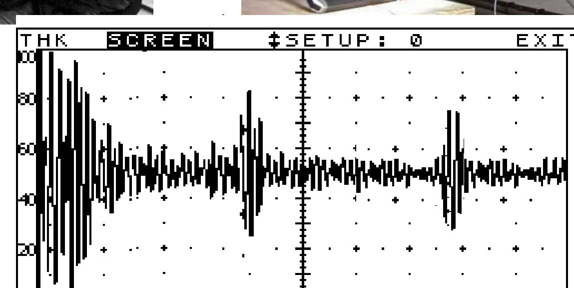
Difficult Conditions





Lots of Rapid Data Interpretation





NDI vs. SHM – Definition

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)

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 (flaw detection); goal is to reduce operational costs and increase lifetime of structures & mechanisms

- 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

The use of in-situ mounted sensors and analysis to assess structural or mechanical condition.

Potential Benefits of SHM

Near-Term

- Elimination of costly & potentially damaging structural disassembly
- Reduced operating and maintenance costs
- Detection of blunt impact events occurring during operation
- Reduction of inspection time
- Overcome accessibility & depth of flaw impediments
- Early flaw detection to enhance safety and allow for less drastic and less costly repairs
- Minimized human factors concerns due to automated, uniform deployment of SHM sensors (improved sensitivity)
- Increased vigilance with respect to flaw onset

Long Term

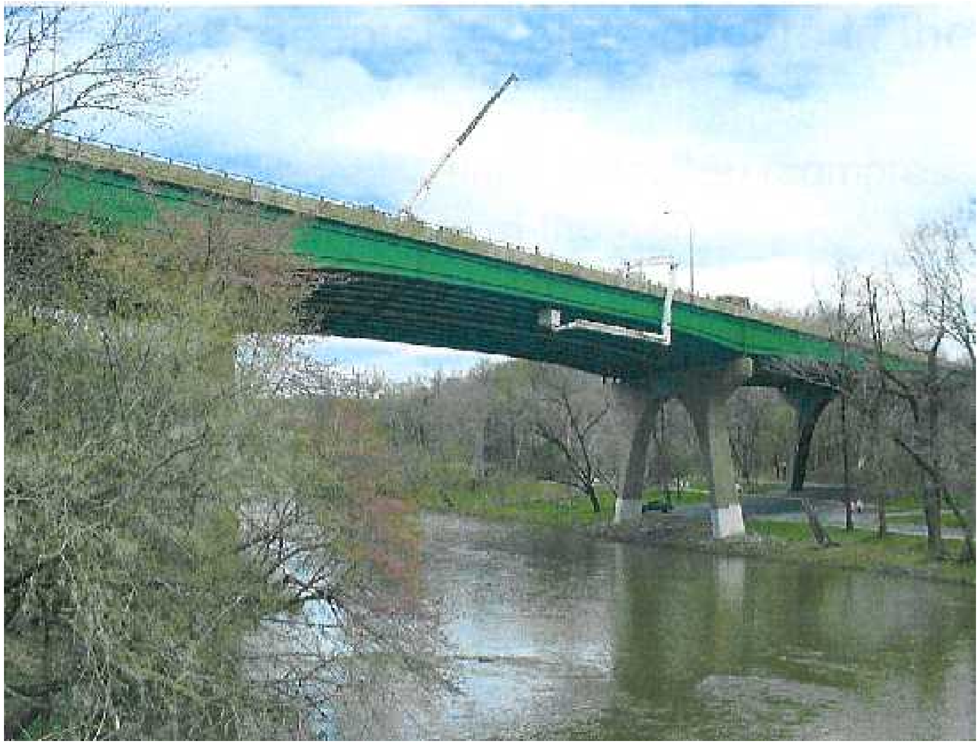
- Optimized structural efficiency (weight savings)
- New design philosophies (SHM designed into the structure)
- Substitution of condition-based maintenance for current time-based maintenance practices

Part 2 – SHM Implementation, Sensors and Systems

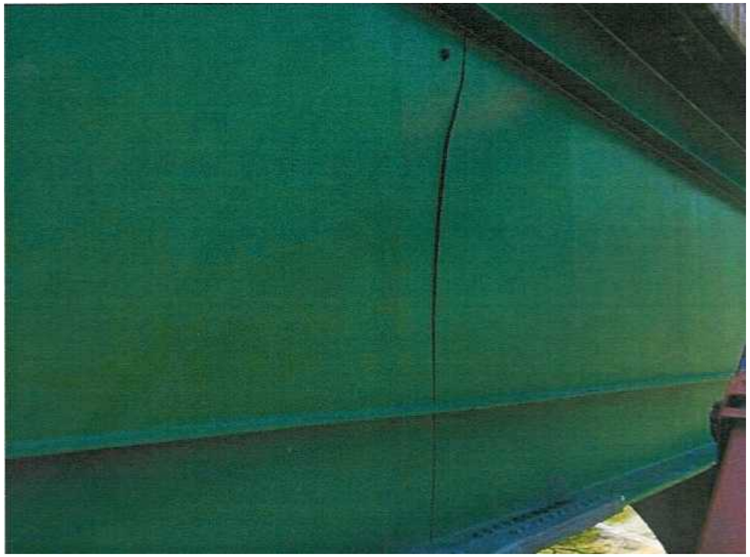
Wide Range of Uses for SHM Systems

Wide Range of Uses for SHM Systems

Sample Bridge Repair Needs



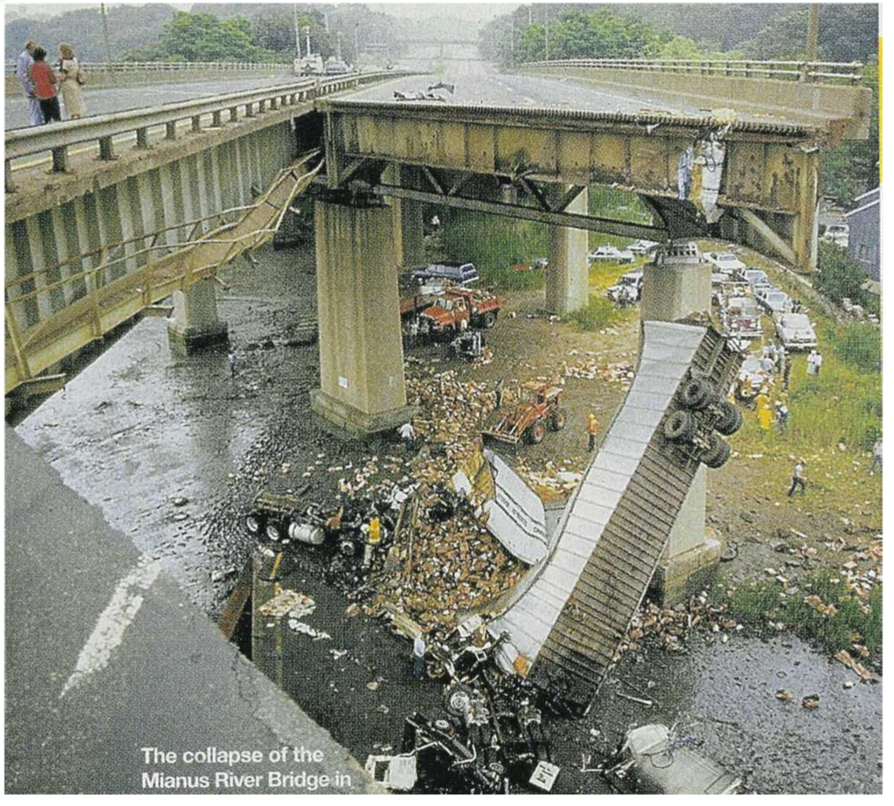
Brandywine River Bridge
Interstate Highway 95
Delaware



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

Majority of RR bridges in U.S. are operating beyond their initial design life

Sample Infrastructure Repair and Health Monitoring Needs



ASCE 2006 Report on U.S. Infrastructure (ranges from roads to hazardous-waste systems):

- Gives the country a grade of "D"
- Warns that "rotting" infrastructure poses risks to safety & economic growth
- Urges wholesale changes including increased R&D

"Even modest gains in the efficiency of construction and repair could yield huge overall savings."

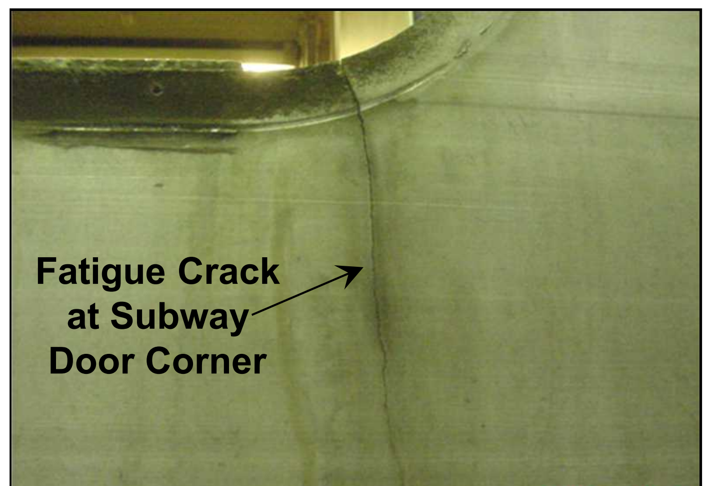
-Tom Warne, Chairman
Transportation Research Board

Sample Infrastructure Repair and Health Monitoring Needs

Monitor and Reinforce Bridges

Pre-emptive Reinforcement of Buildings

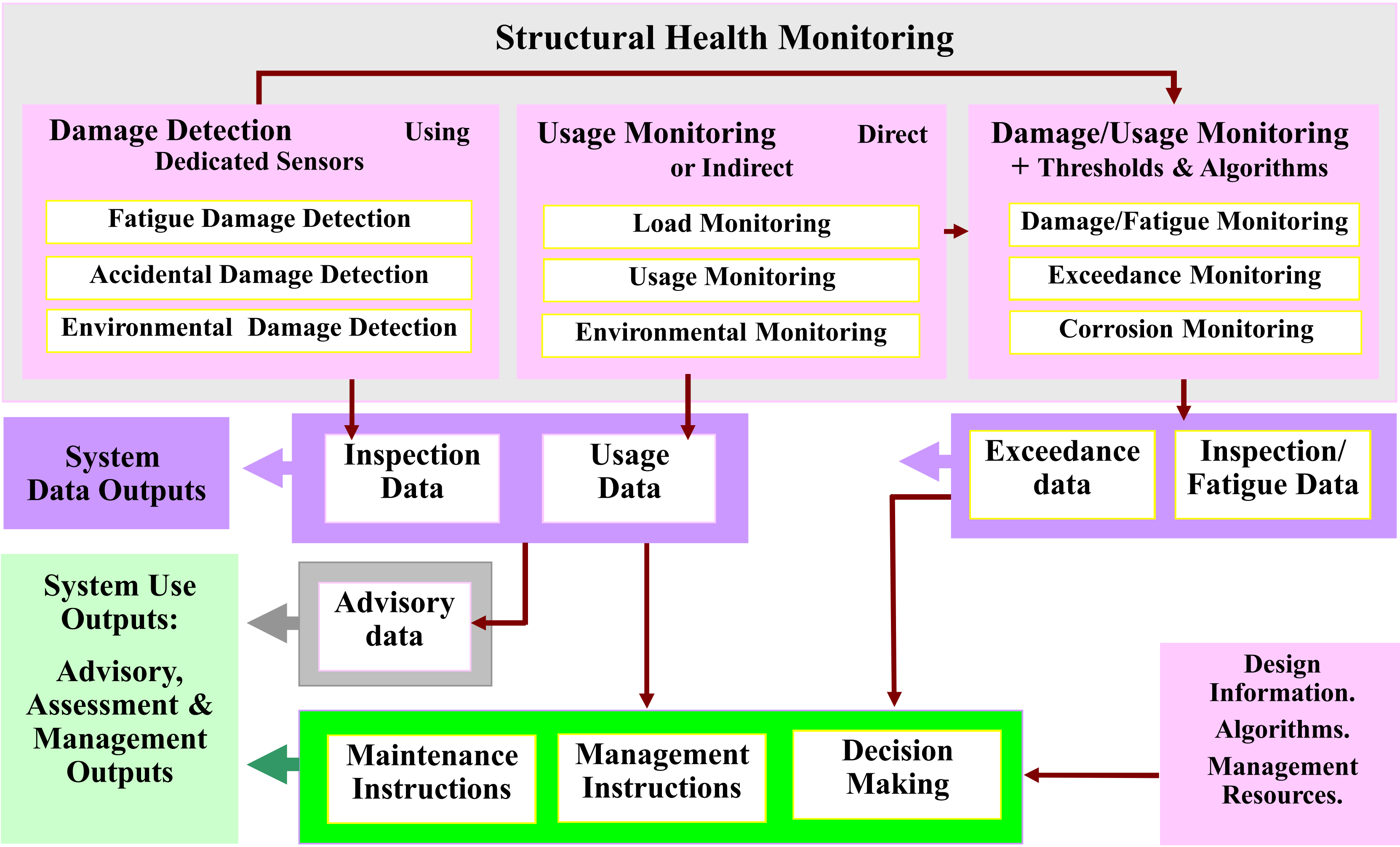
Interest from Washington DC Transit Authority



Is Structural Health Monitoring a Viable Alternative Today?

- Evolution of miniaturized sensors & supporting technology
- Design of turnkey systems with reasonable costs
- Ability to monitor new & unexpected phenomena (new inspection needs; DTA and rapid flaw growth)
- Promise for technical & economic gains more clearly defined
- OEM willingness to explore SHM merits
- Long-term prognosis -
  - Complete health assessment with network of SHM "nerves"
  - Automated data transmission (real-time monitoring; alarms)
  - Embedded sensors (MEMS)
  - Improved diagnostics using neural networks (historical data)
  - Direct ties to maintenance planning and actions
  - Reduction in life-cycle costs

Potential Functions of SHM Systems



Deterministic vs. Derivative Sensors

Deterministic sensors produce direct flaw detection & flaw growth

Examples: CVM, EC, cMUT, Corrosion, Fiber Optics, PZT

Derivative sensors require calibration & produce indicators (follow-up NDI needed)

Examples: Force, Accelerometer, Temperature, Pressure, Strain

Load Cells - Load monitoring could be used for design credits (structural optimization) and/or operation credits (modify maintenance program)

Strain Sensors – Can determine excess strain levels but subsequent NDI visit is required to determine if strain readings correlate to damage

Pressure Transducer

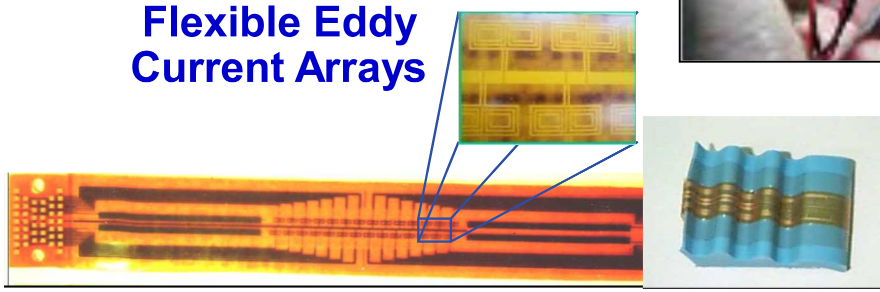
Thermocouple

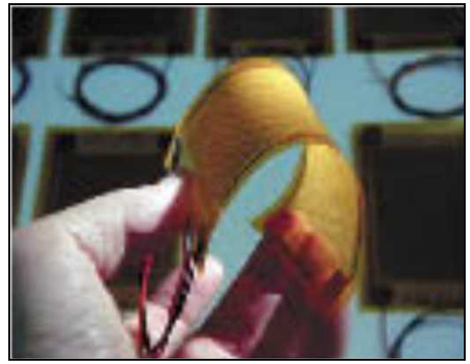
Strain Gages

Accelerometer

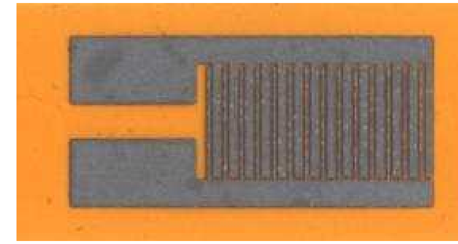
SHM Deterministic Sensors

Flexible Eddy Current Arrays

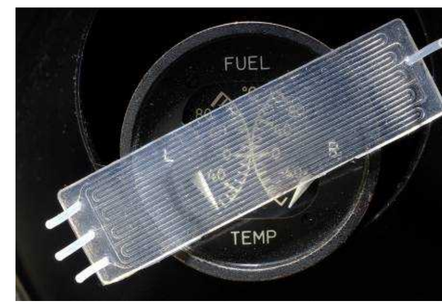




Macro Fiber Composite (PZT)

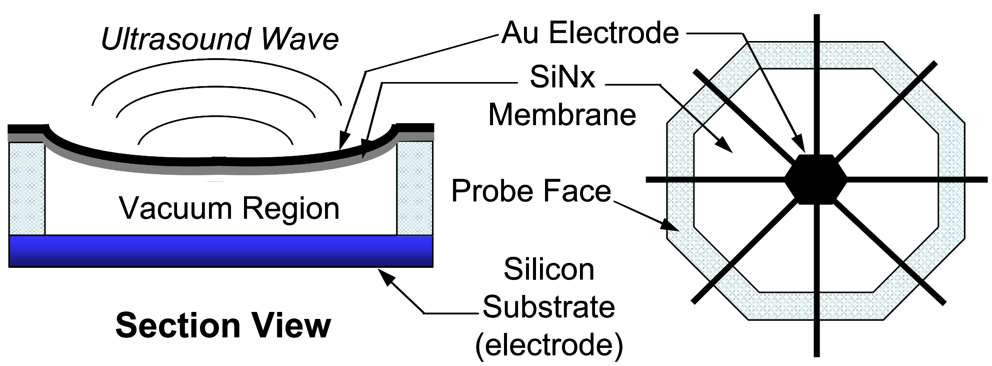


Corrosion Sensor

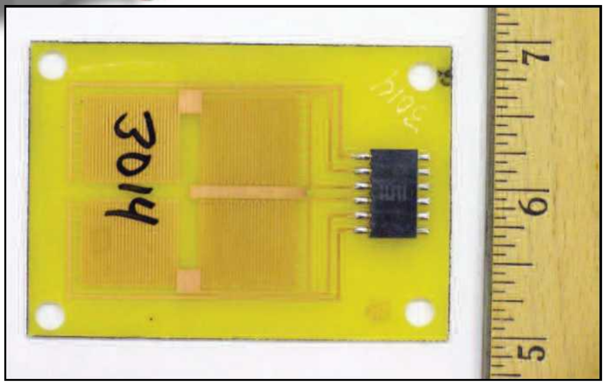


Comparative Vacuum Monitoring Sensor

Capacitive Micromachined Ultrasonic Transducer (cMUT)



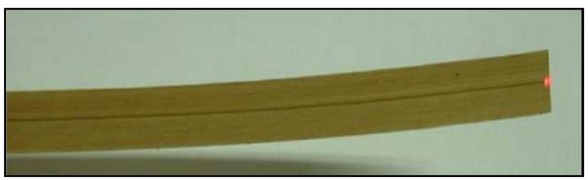
Sample SHM Sensors



Cumulative Environmental Corrosion Sensor

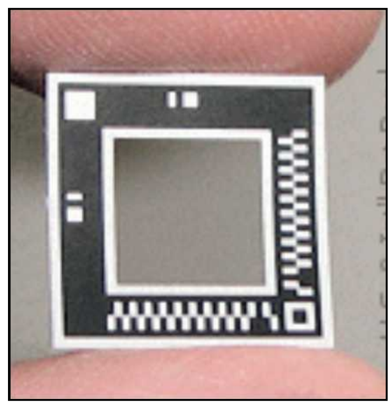
Magneto Elastic Active Sensor

Remote Field Eddy Current Sensor

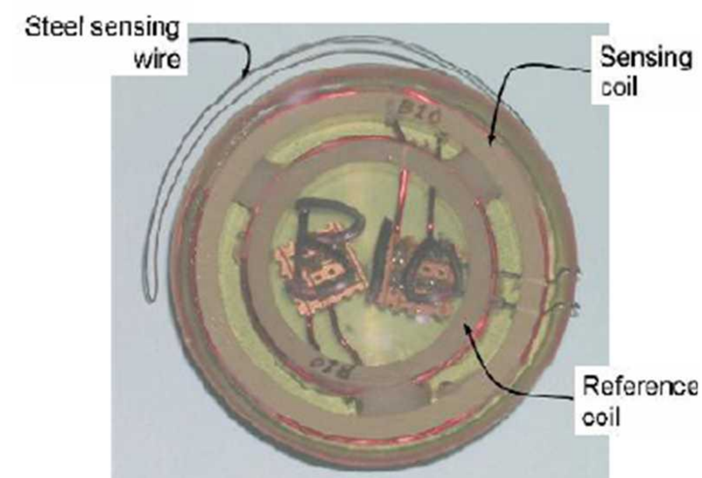


SMARTape Membrane Deformation Sensor

Spot-Weldable Strain Gauge



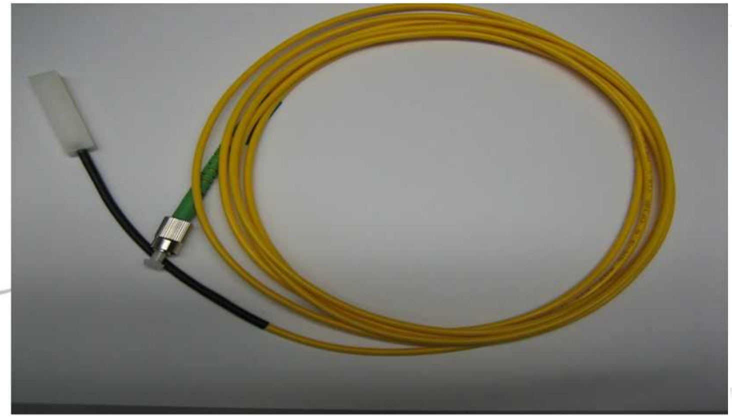
Direct Measurements Strain Sensor

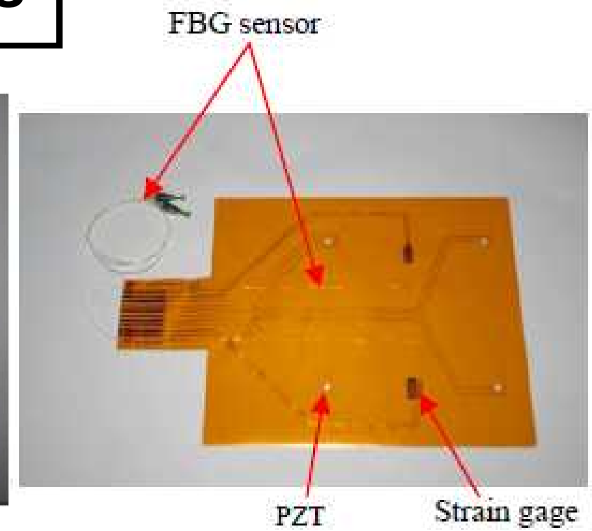


Wireless Corrosion Sensor

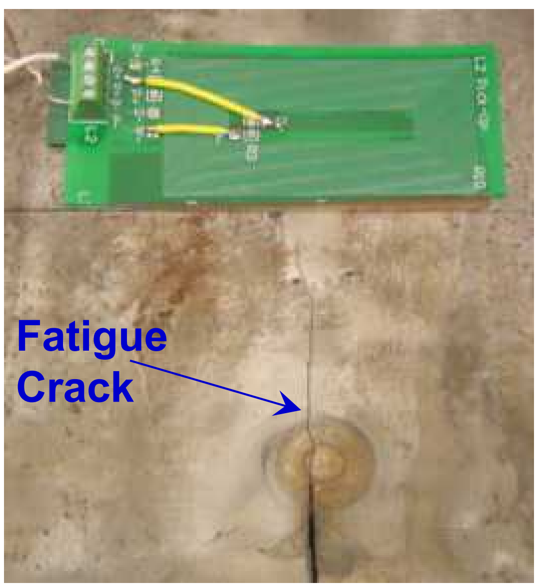
Sample SHM Sensors

Smart FO Patch



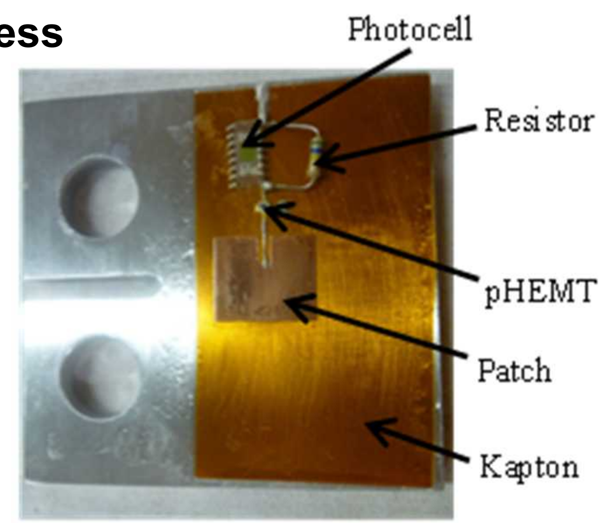


Fiber Optic Sensors

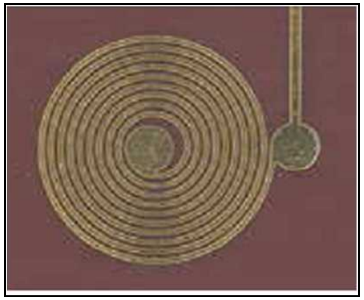


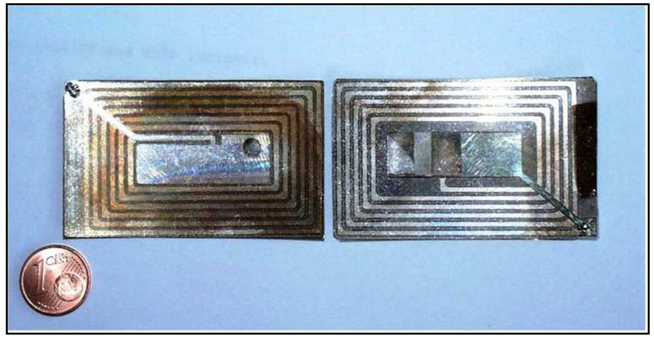
Mountable Eddy Current Sensor for Crack Detection

Unpowered Wireless Strain Sensor

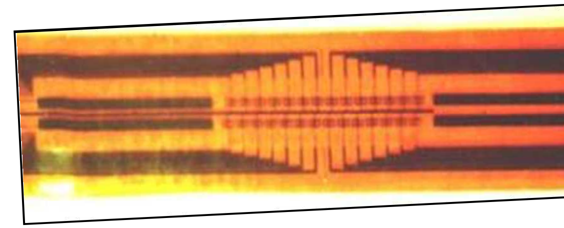


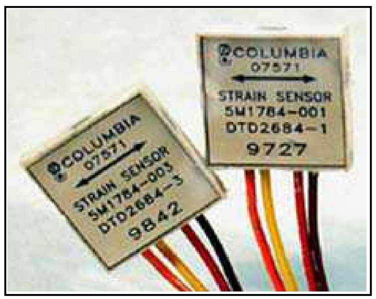
Sample SHM Sensors

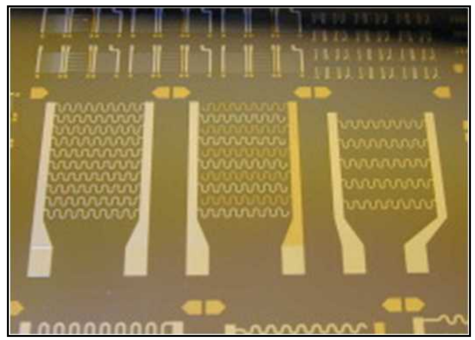




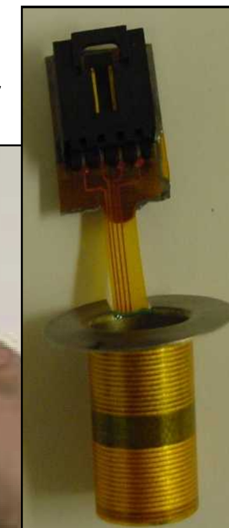
Passive Sensory Resonant Sensor

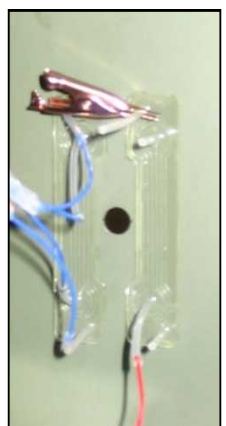






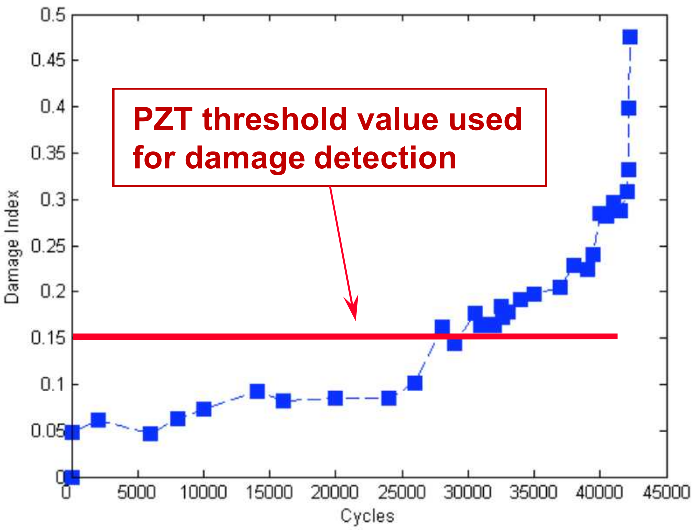
Smart Fastener

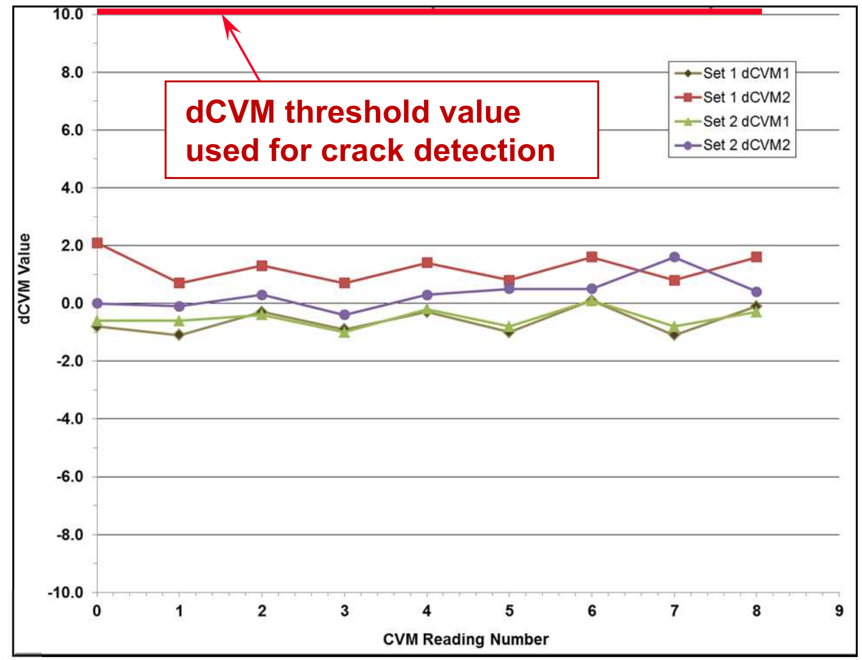


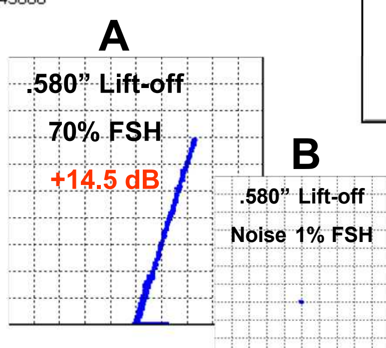


SHM Information – Minimize Intrepretation or Data Analysis

- Automated data analysis is the objective – produce a "Green Light – Red Light" approach to damage detection
- Final assessment and interpretation by trained NDI personnel







A = Sensor Response to Crack (flaw signal)
B = Sensor Response at Uncracked Region (signal noise)

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SHM Impediments & Challenges

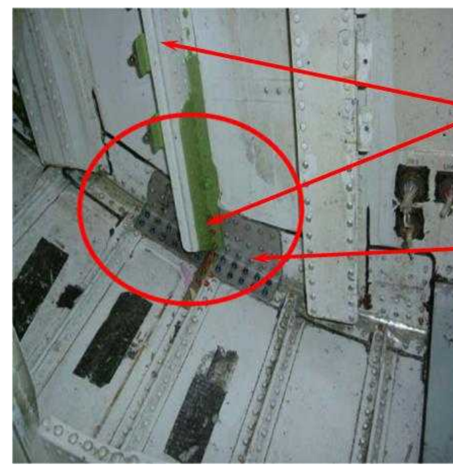
- Cost of sensors and sensor systems
- Ease of use and coverage area
- Need for rapid customization of sensors
- Need for substantial business case (cost-benefit analysis) – operators must realize benefits of multi-use
- OEMs may need to own technology
- Small-scale damage must be detected in large-scale structures
- Validation activities – general performance assessments needed; reliability of SHM systems must be demonstrated
- Validation activities – field trials on operating aircraft is necessary but time consuming
- Certification – need to streamline specific applications; technical, educational and procedural initiative (OEMs, operators, regulators)
- Standardization needed for validation and certification activities
- Technology transfer and implementation requires changes in maintenance programs

SHM Implementation

Issues to Consider
- Identifying "hot spots"
- Local vs. Global
- Sensor performance (sensitivity, reliability, durability)
- Fail-safe operation
- Ease of installation & operation (human factors +/-)
- Economic drivers

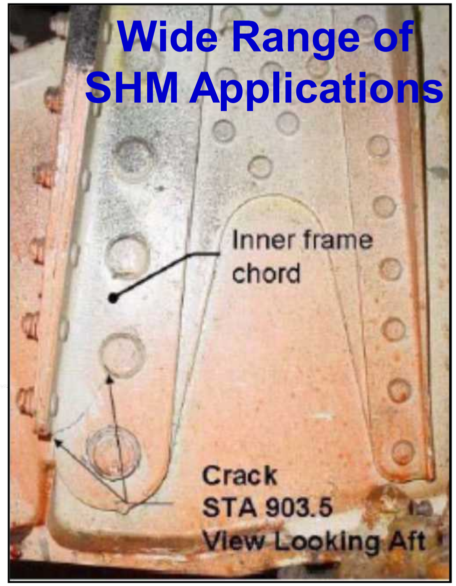
Potential Uses:
- *Aft Pressure Bulkhead*
- *Substructure*
- *Wiring*
- *Flight loads monitoring*
- *System response*

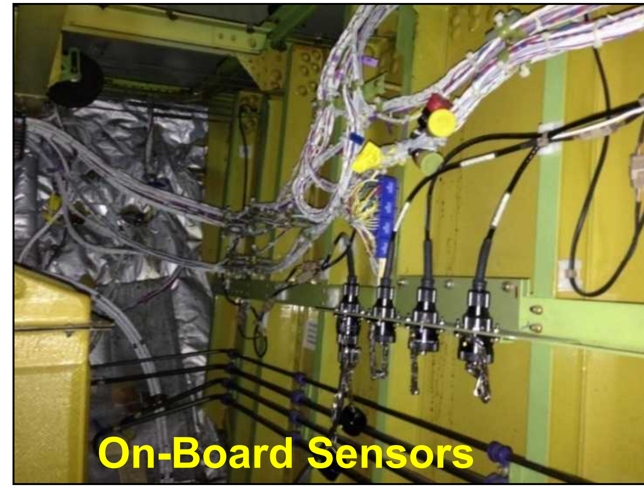
Applications – recent study found 24 applications, with economic drivers, on one aircraft type

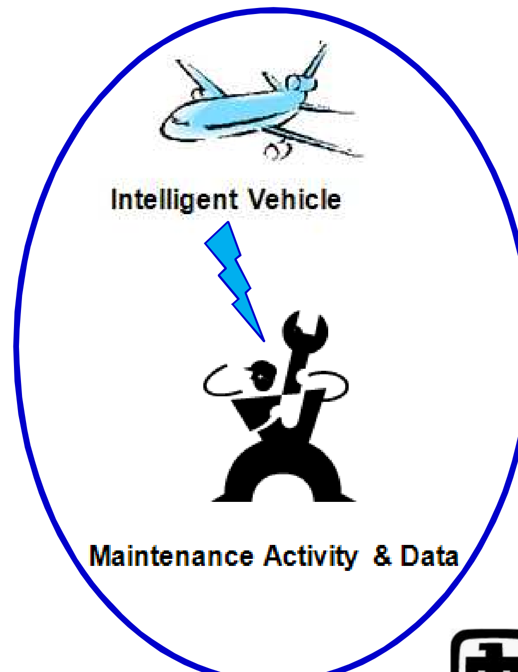


SHM utilization is still being formulated but successful performance assessments & flight history are rapidly increasing →

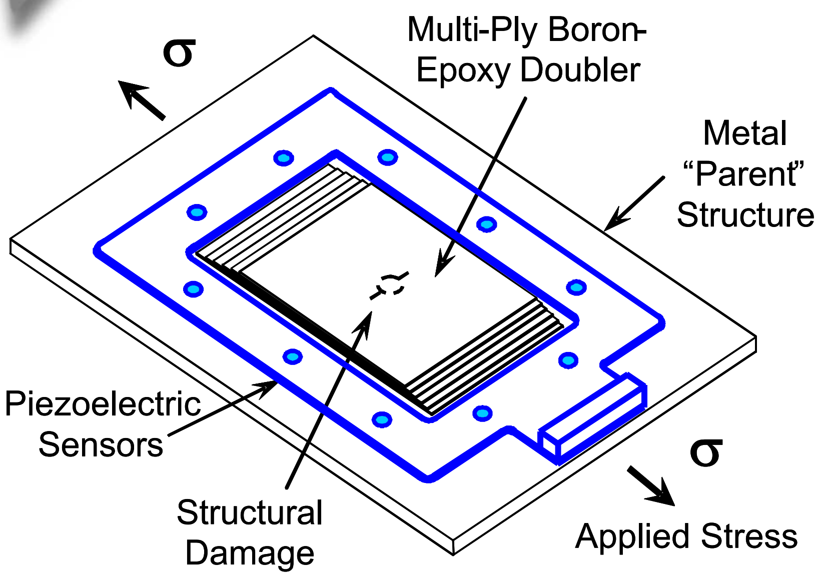
SHM Systems in Action





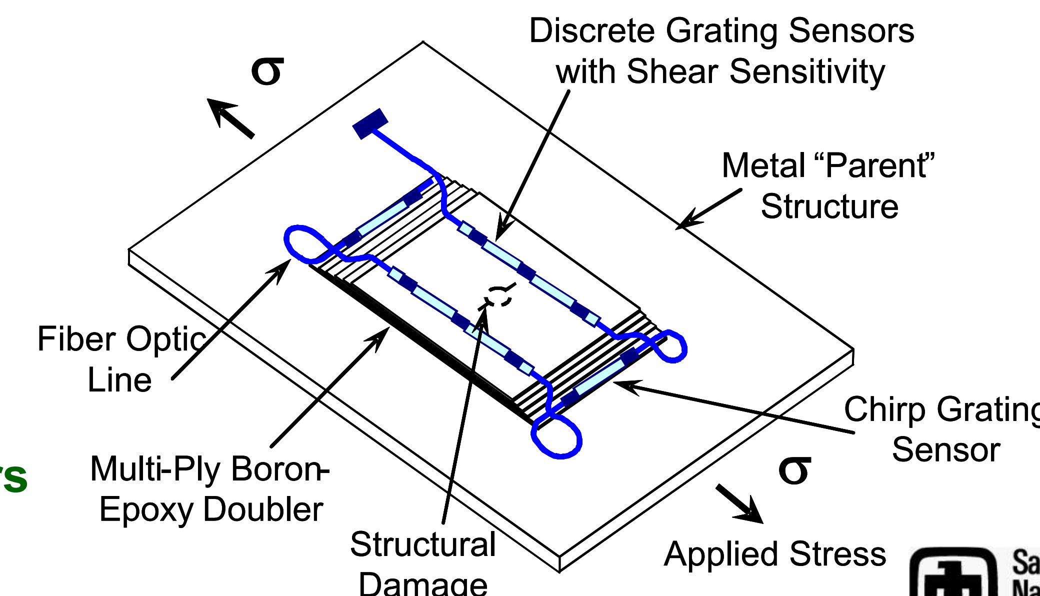


Fiber Optic and Piezoelectric Sensor Systems



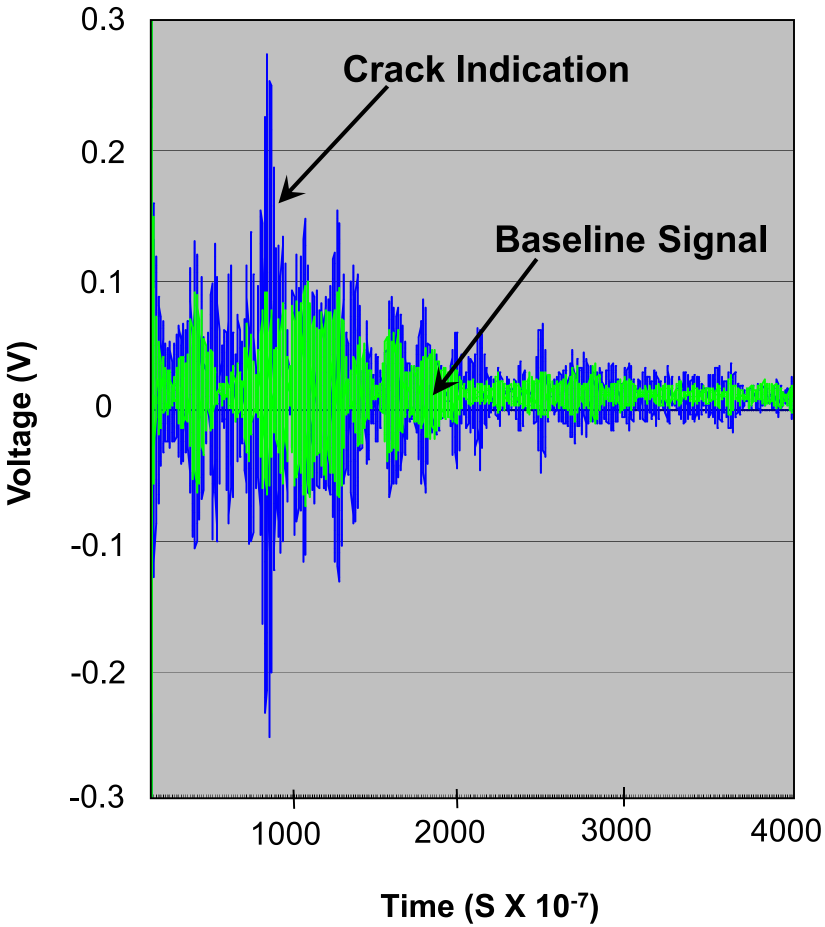
Embedded and peripheral monitoring for cracks, corrosion, and disbonds

Piezoelectric Sensors



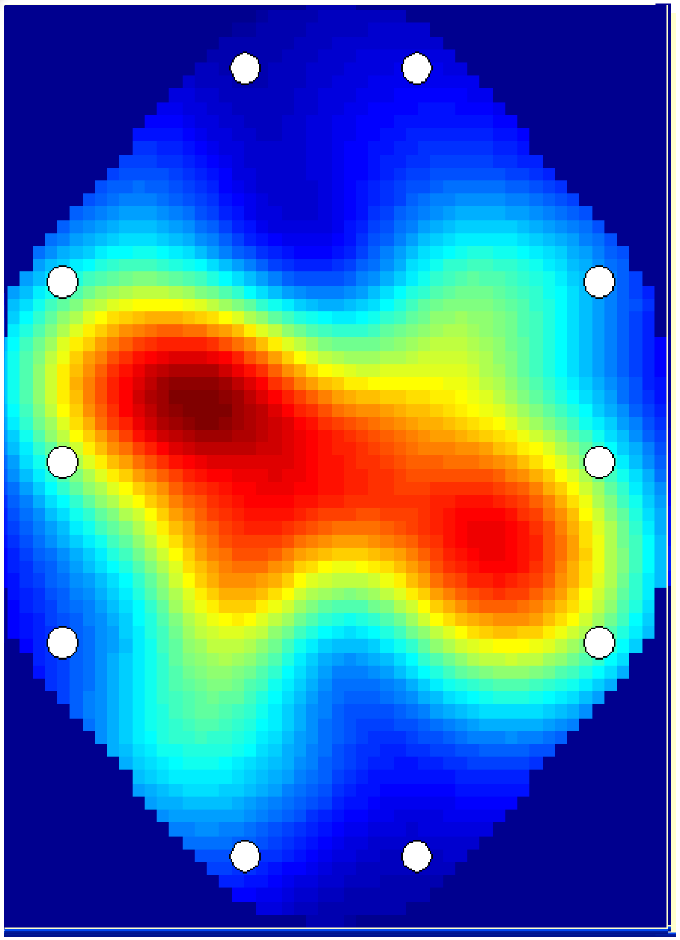
Fiber Optic Bragg Sensors

Crack Detection & Growth Monitoring with Piezoelectric Sensors

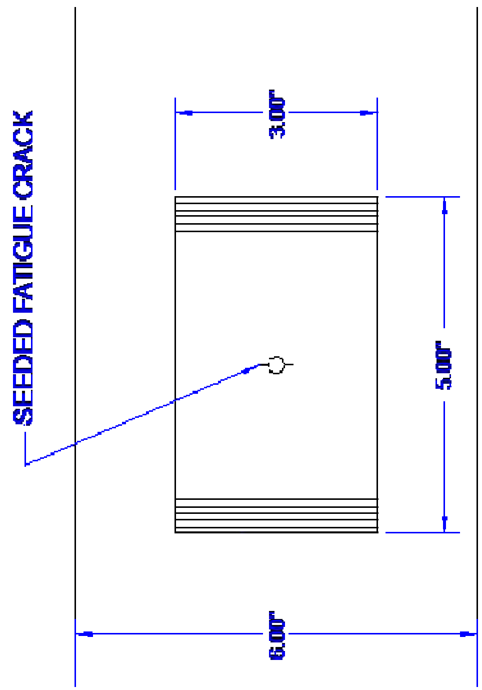


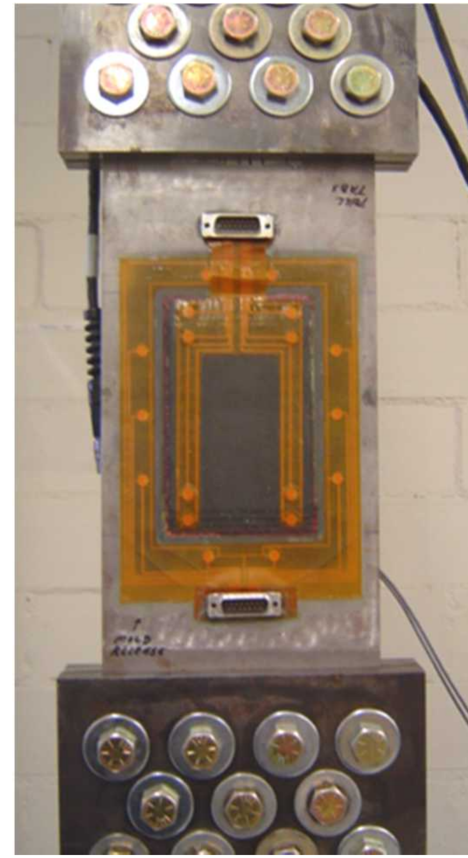
Inspection results from 500 KHz

Crack Detection & Growth Monitoring with Piezoelectric Sensors



87K Cycles





PZT crack length estimates within 5% of measured

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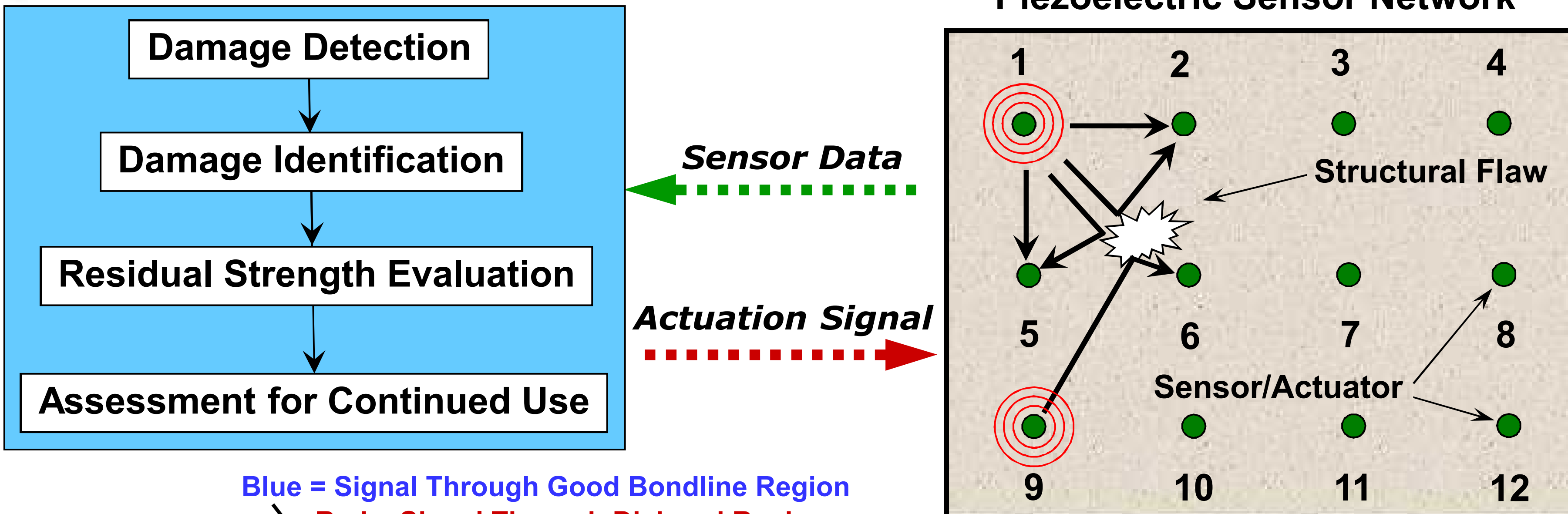
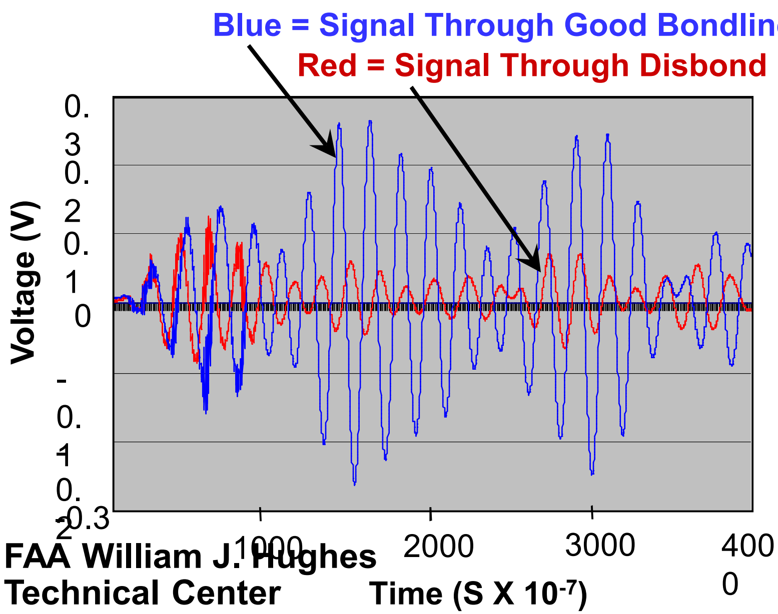
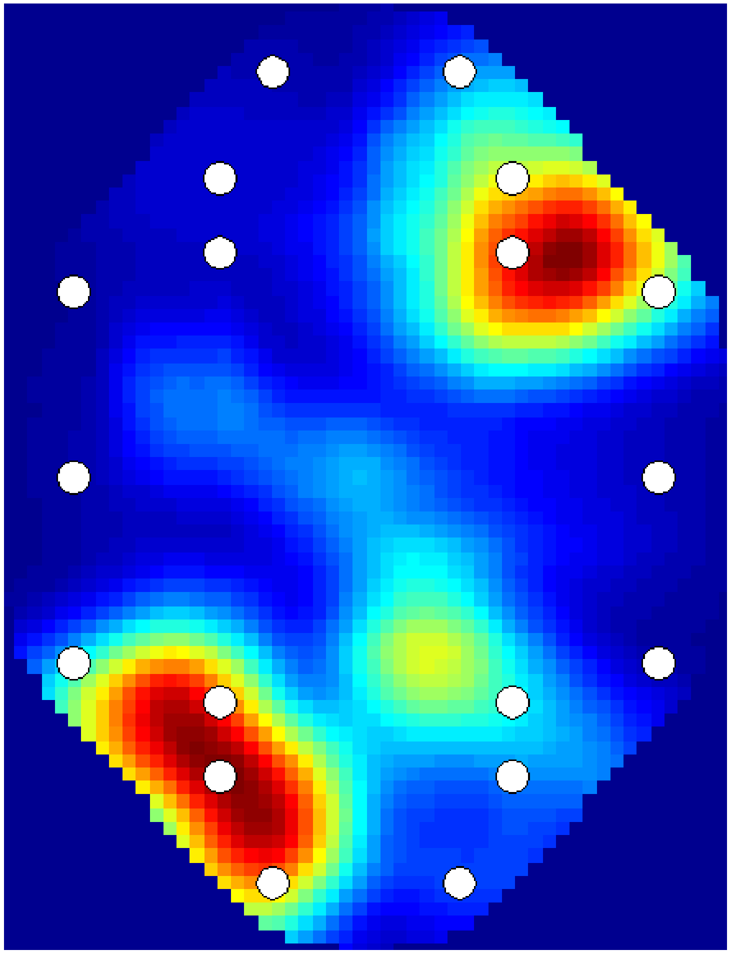
Disbond Detection & Growth Monitoring with Piezoelectric Sensors

Piezoelectric Sensor Network

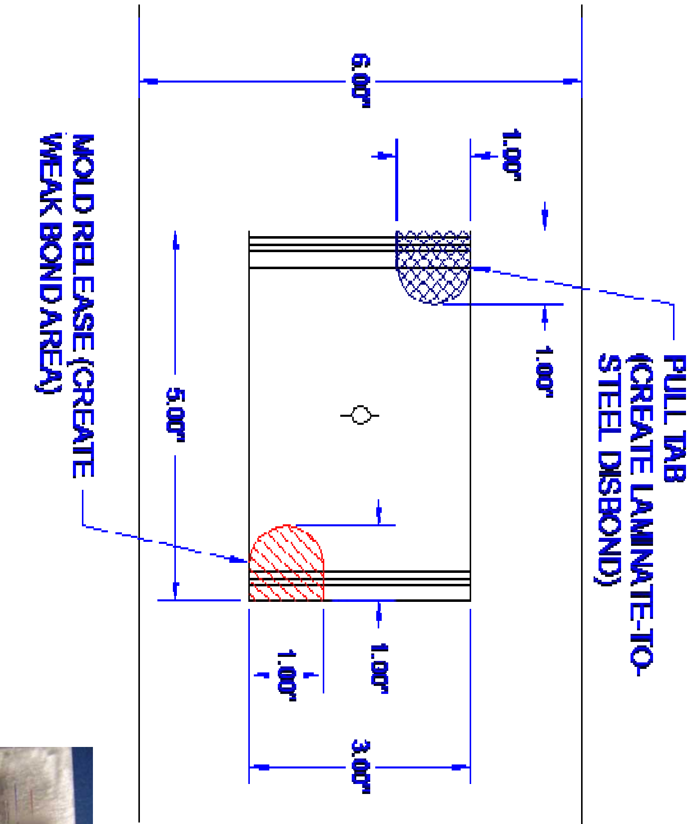


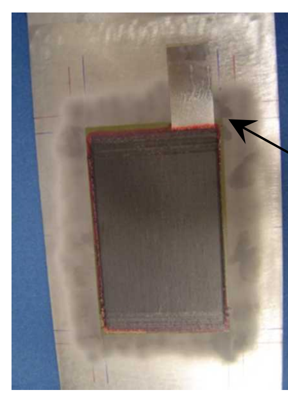


Disbond Detection & Growth Monitoring with Piezoelectric Sensors



After mold release flaw growth (50 KHz inspection)

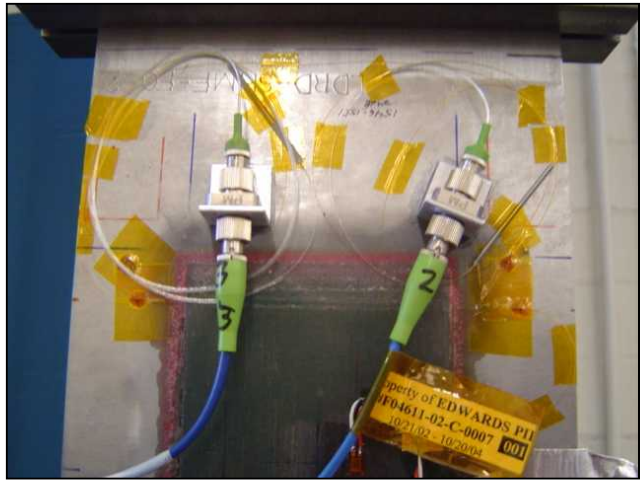




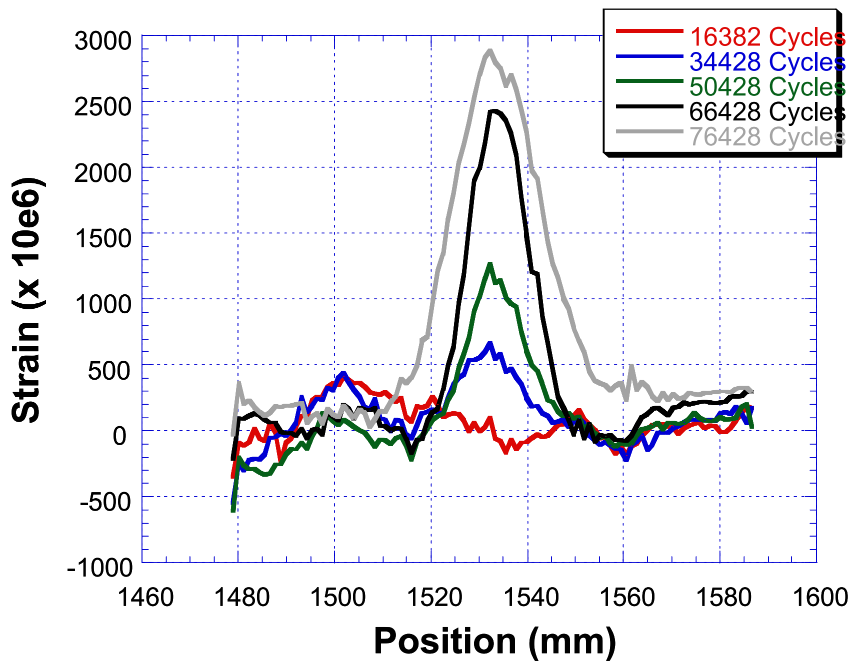
Pull tab flaw

Fiber Optic Bragg Sensor Systems

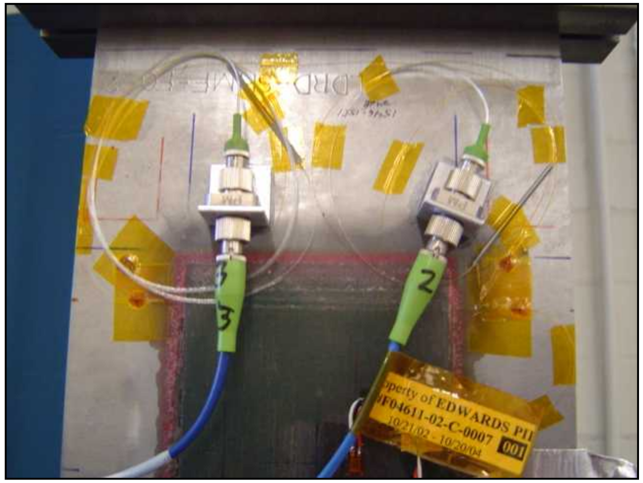
Multi-directional strain monitoring using a birefringement fiber (difference in index of refraction along orthogonal directions)

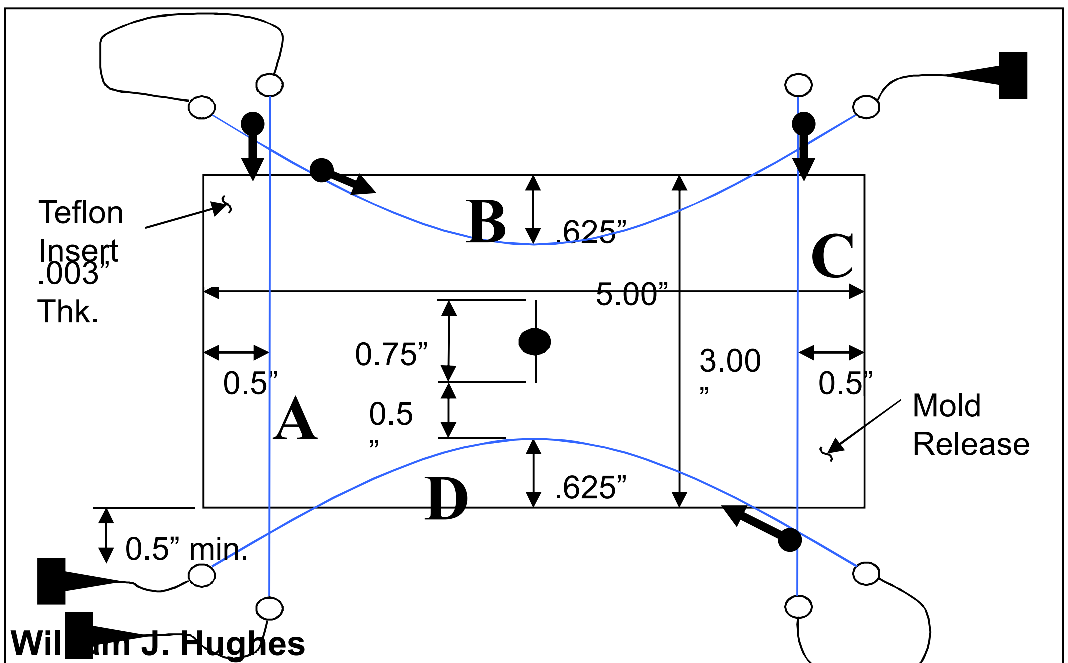


Axial Strain Distribution Along Sensor D as a Crack Tip Approaches



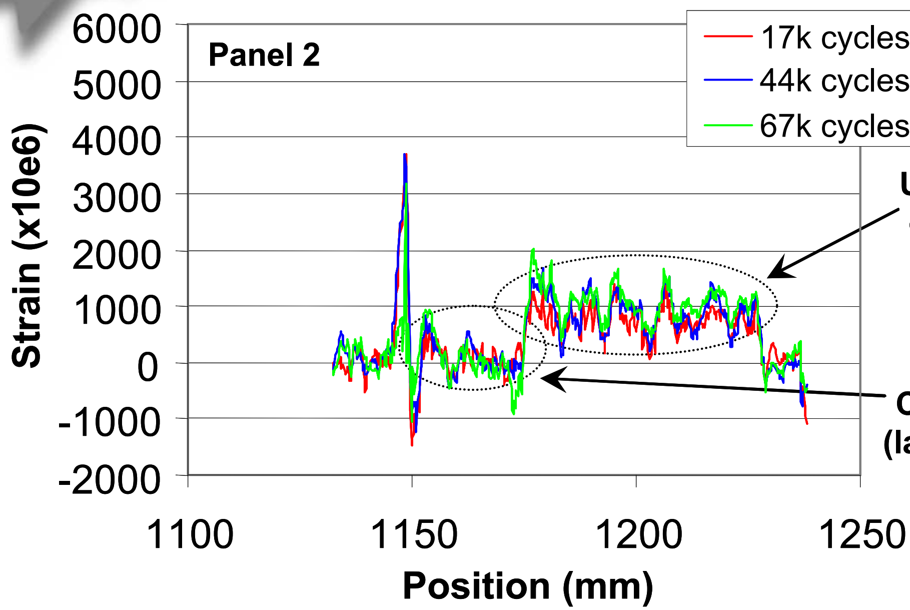
Fiber Optic Bragg Sensor Systems





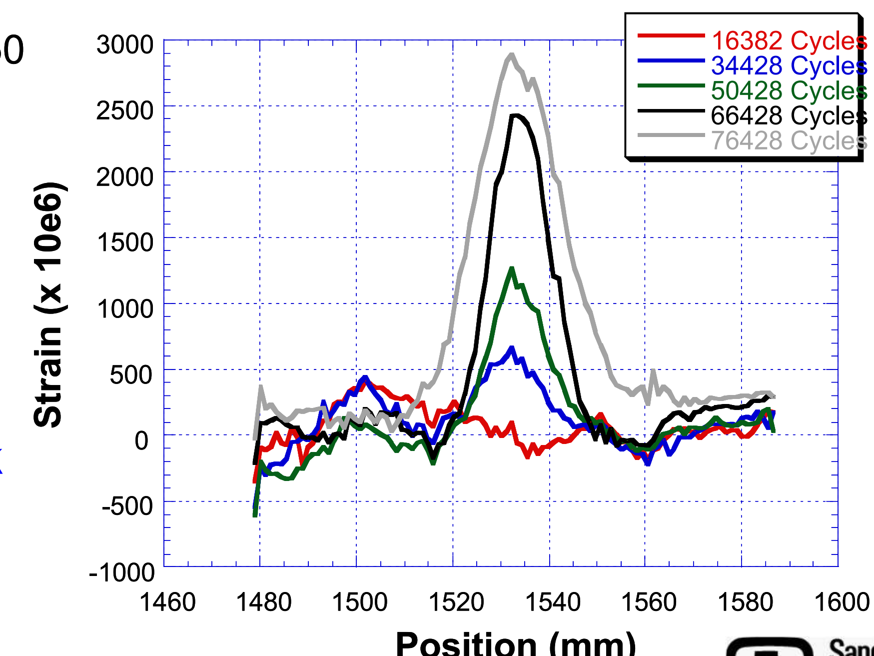
Multi-directional strain monitoring using a birefringement fiber (difference in index of refraction along orthogonal directions)

Health Monitoring with Fiber Optic Sensors

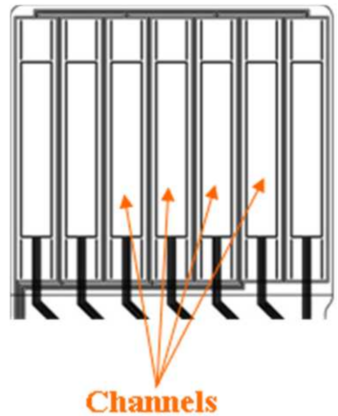


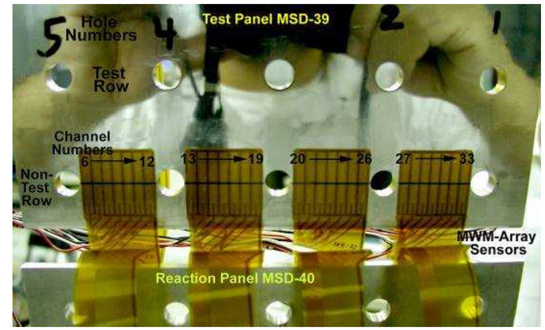
Disbond Detection - Grating A Shear Strain Evolution at 34 kips Load

Axial Strain Distribution Along Sensor D as a Crack Tip Approaches

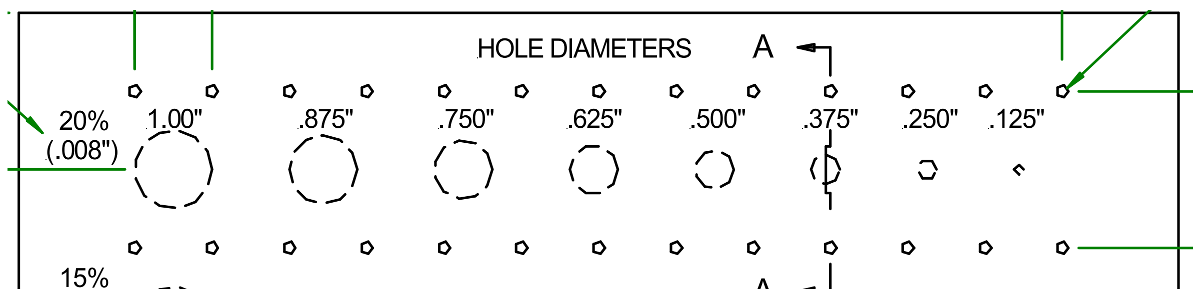


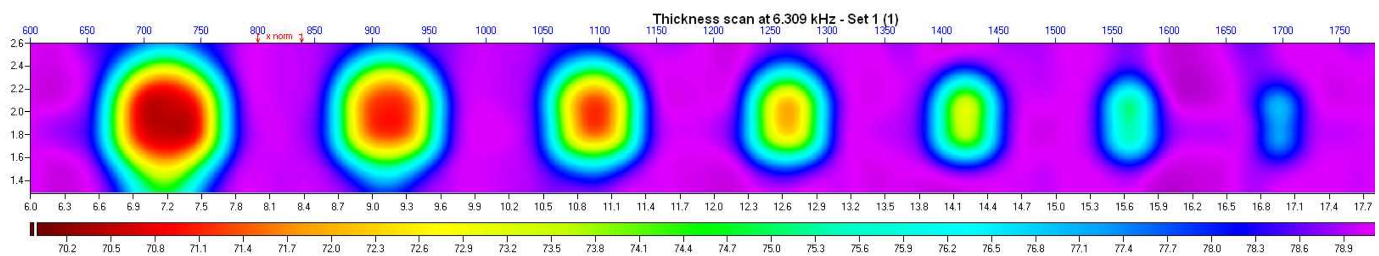
Corrosion Imaging with MWM Mountable Sensors





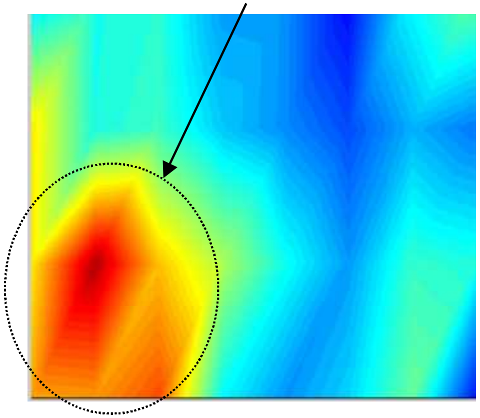
Multi-Channel MWM Arrays



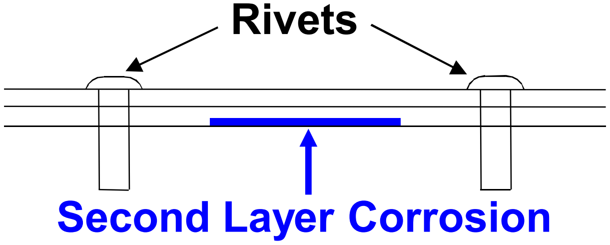


Corrosion Imaging with RFEC Carpet Probe Sensor

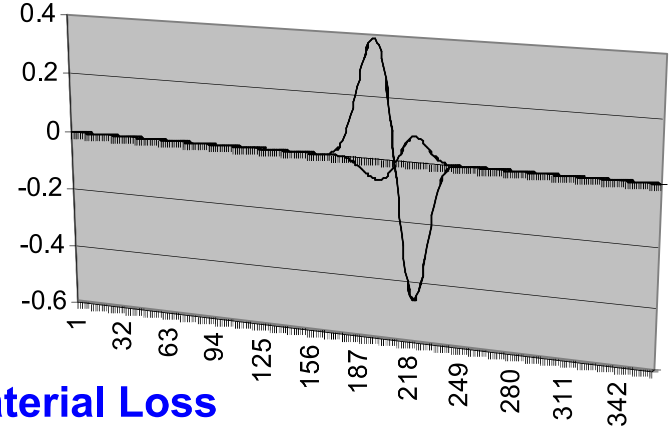
Image Produced by Sensor - 20% Material Loss



Magnetic Carpet Probe



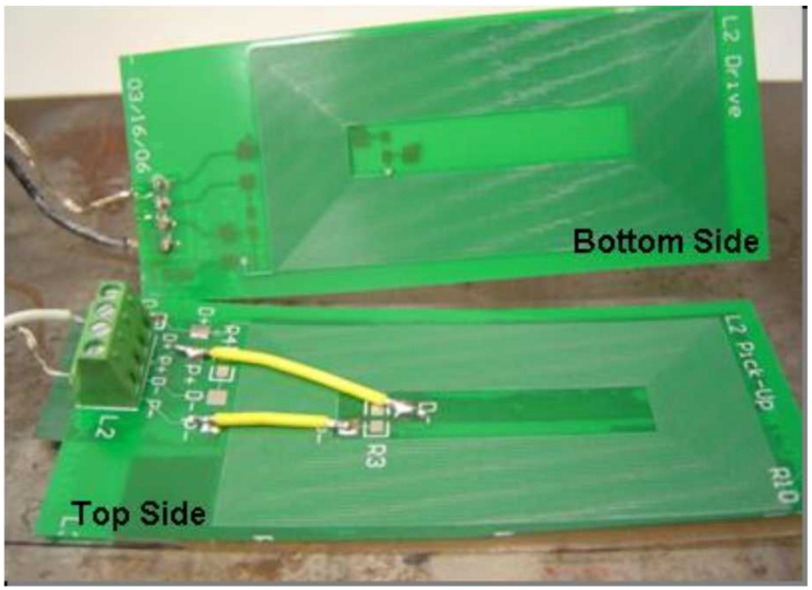
0.040” thick skins

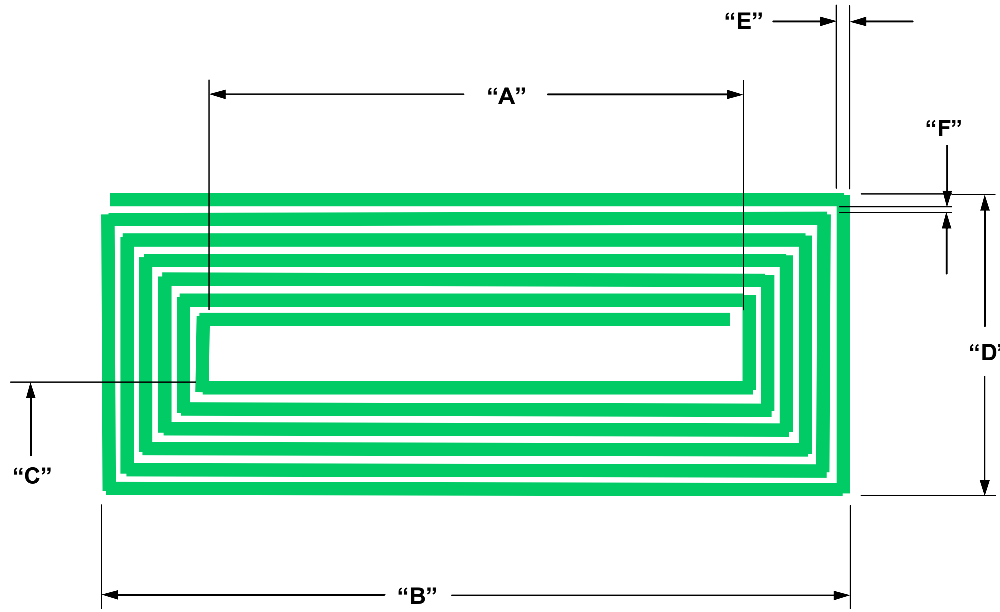


2% Material Loss

Smart Mountable Eddy Current Sensor (SMECS)

Coil properties affect performance – coil dimensions (area, turn radius), material used in coil, tracing pitch, number of layers





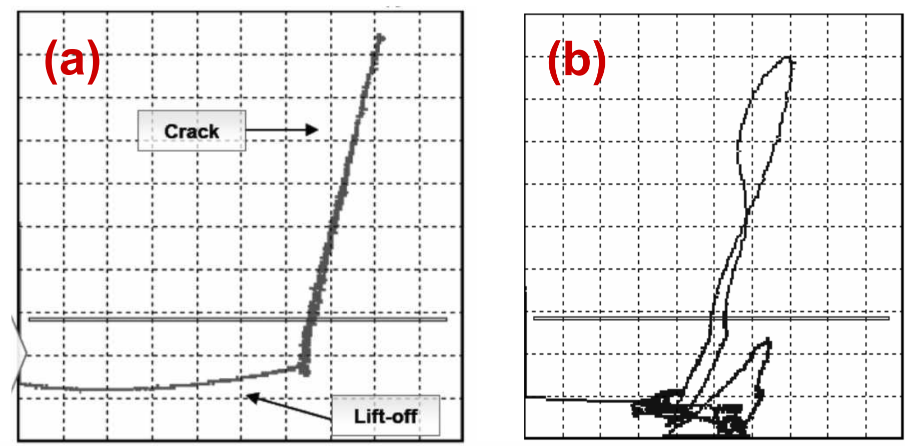
EC Sensor Design Parameters

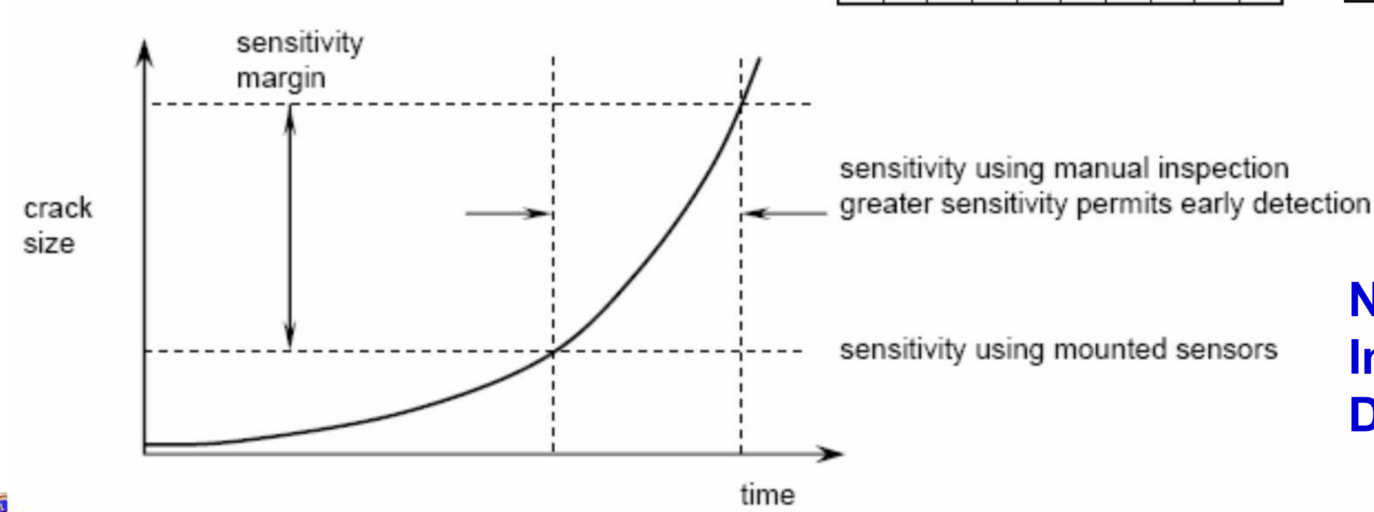
Design of the coil is determined by the inspection requirements – spatial resolution, sensitivity, desired coverage area, depth of penetration (lift off), material being inspected (conductivity)

Fixed Deployment - Noise Reduction for More Reliable Crack Detection

Sensor planar coil produces large coverage area - eliminates the need for manual scanning of the structure. Scanning techniques can introduce noise into the measurement (probe wobble)

Examples of Crack Detection Signals From (a) Fixed Sensor, (b) Scanning Probe

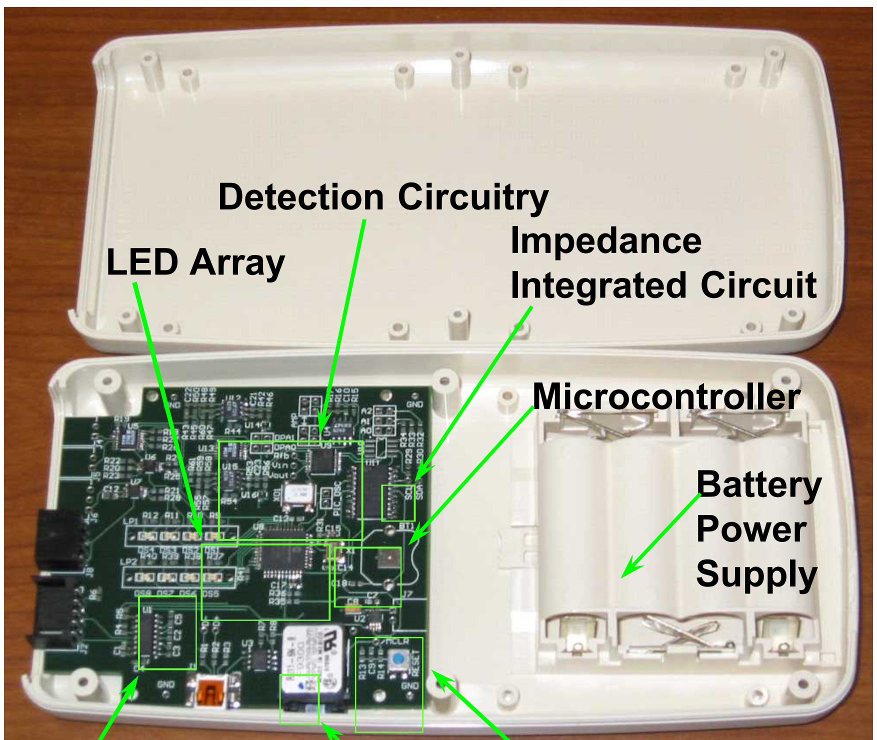


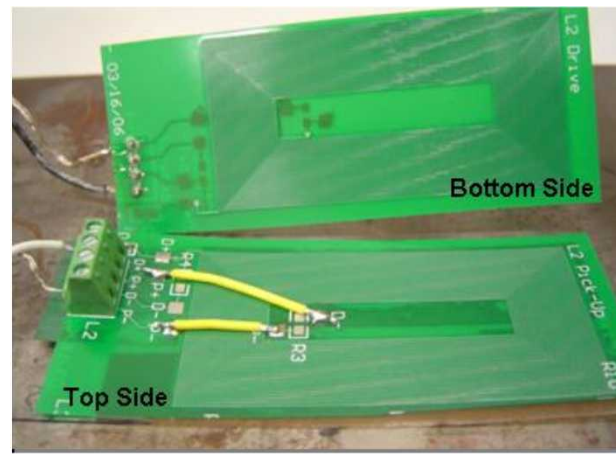


Noise Reduction Improves Flaw Detection Sensitivity

SMECS Microcontroller

- EC coil is driven by an impedance integrated circuit with A-to-D converter
- LC resonant circuit used to detect changes in the coil’s impedance
- Two detection circuits and two calibration circuits to facilitate analysis
- External real-time-clock (RTC) is used to wake up the system at pre-selected interrogation intervals to make measurements

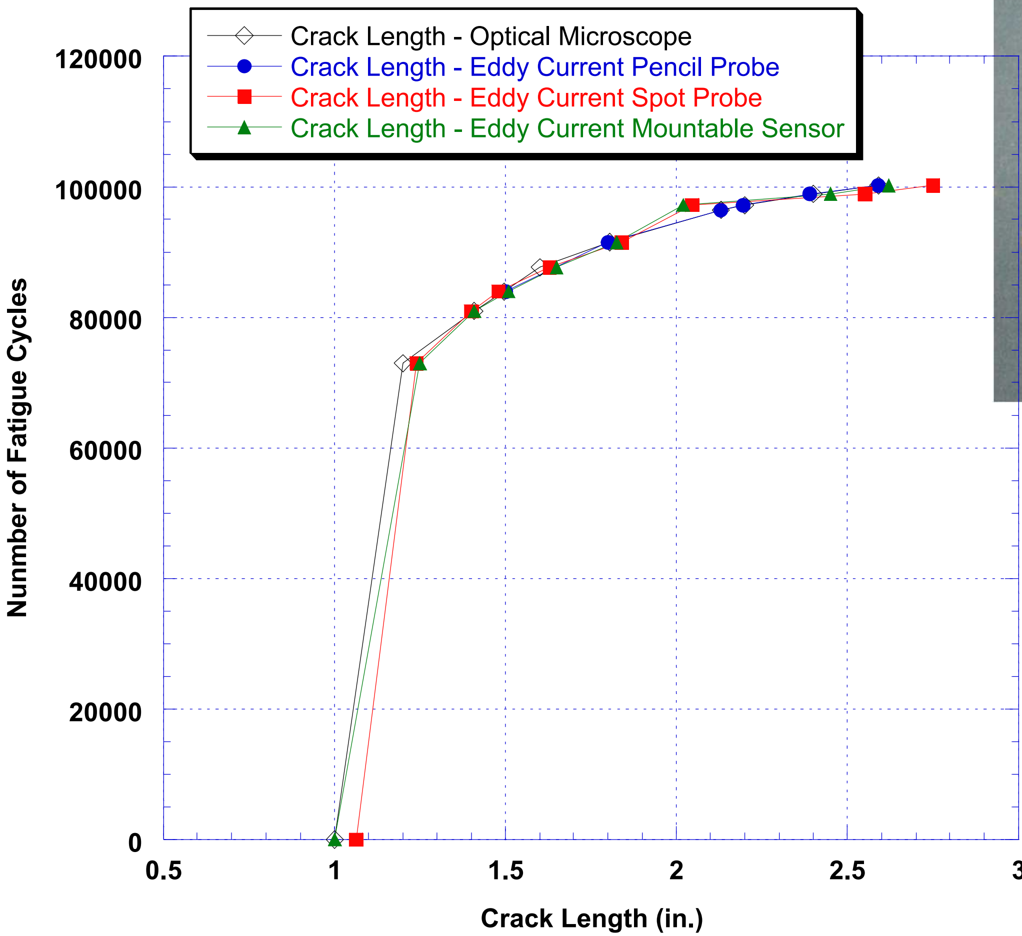


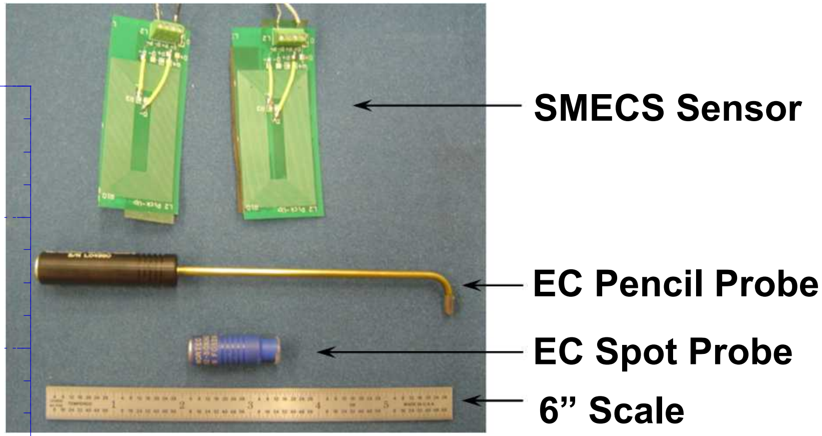


Patent Pending

SMECS System Performance Testing

Tracking crack growth – less than 4% deviation from referee measurements





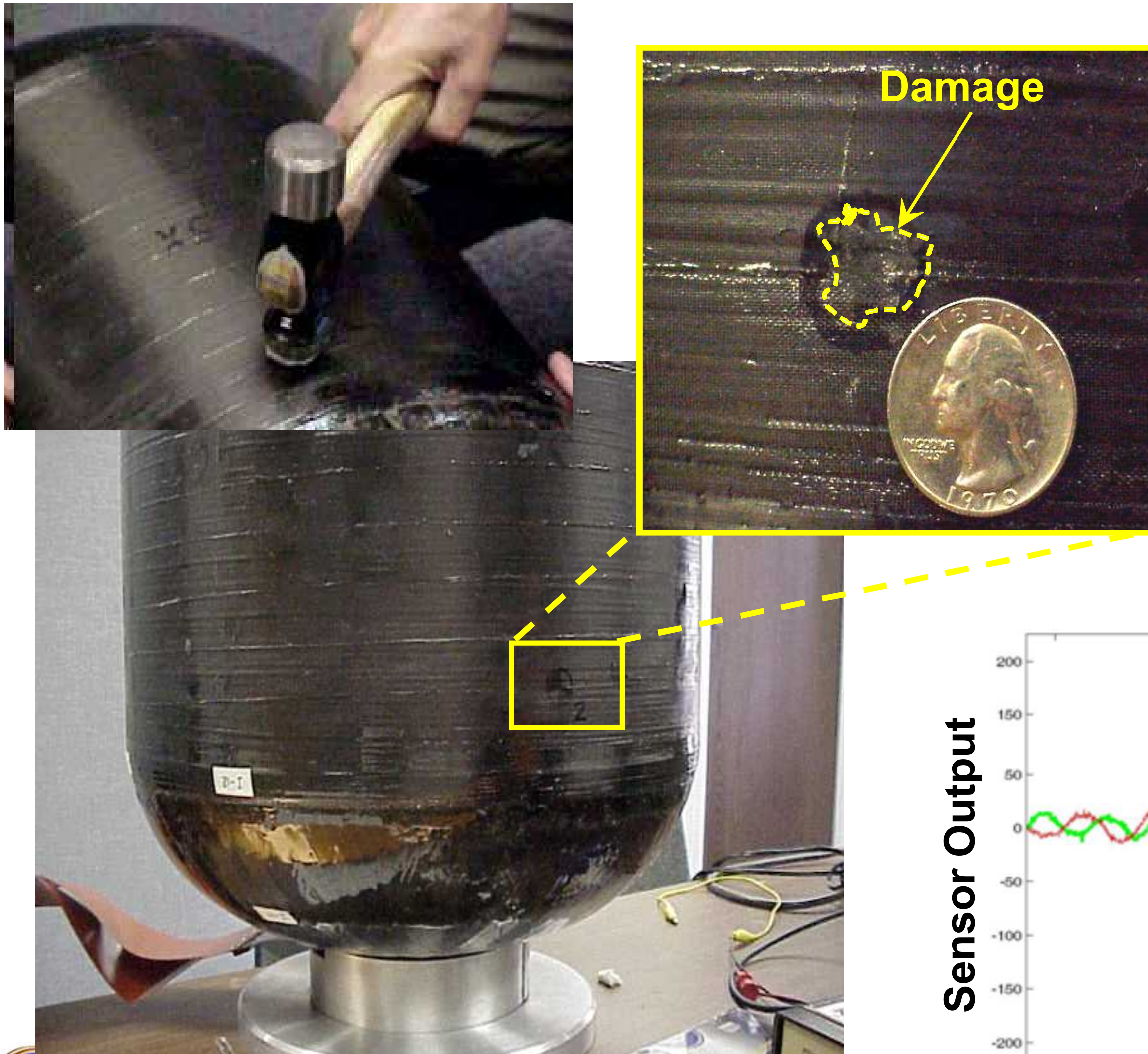
Comparison of Crack Lengths Measured by Four Different NDI Methods

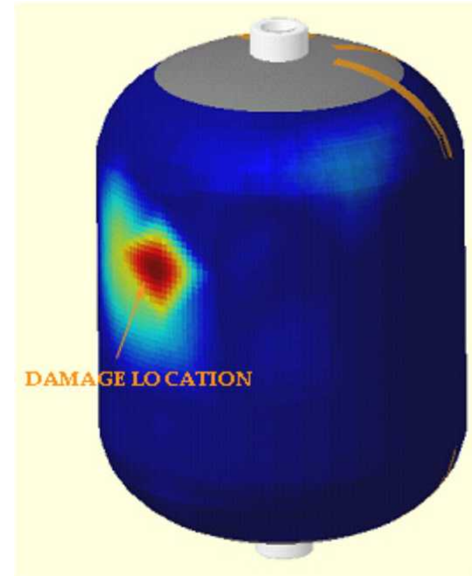
Conclusions on SMECS and SHM Approach

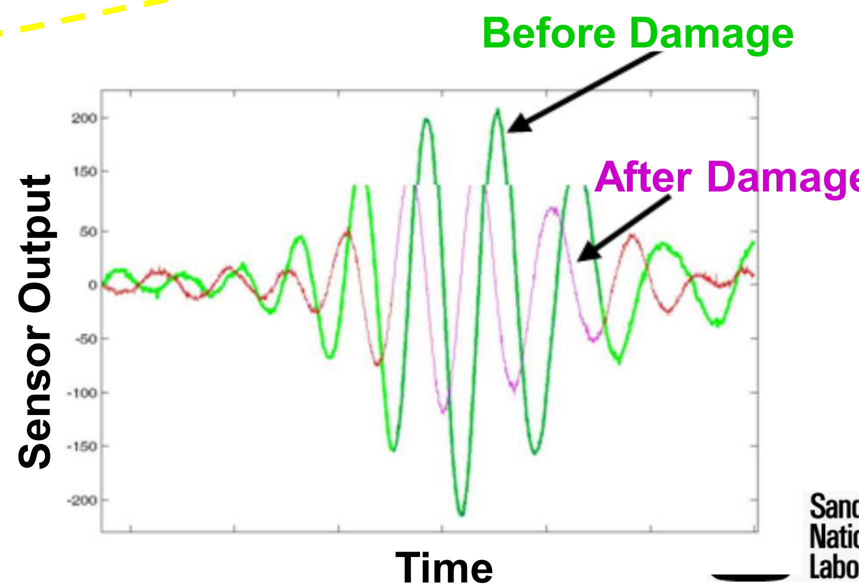
- Health monitoring of structures is a major concern especially in the case of aging aerospace and civil structures (operate beyond design life)
- Smart Mountable Eddy Current Sensor (SMECS) - provides a wireless, battery-operated, non-contact, in-situ sensor network for real-time detection of surface and subsurface cracks
- Sensors must be low-profile, easily mountable, durable & reliable
- Calibration for flaw identification (damage signatures) is key
- Ease of use allows for more frequent inspections – minimize repair costs through early detection of structural damage
- SHM can decrease maintenance costs (NDI man-hours; disassembly) & allow for condition-based maintenance
- SHM may be a desirable alternative to meet new inspection requirements or to address unexpected phenomena
- Extension to automated SHM networks shows promise for increased technical & economic gains
- Overall performance, integration, and long-term operation needs to be proven

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

Visualization methods can locate and size flaws

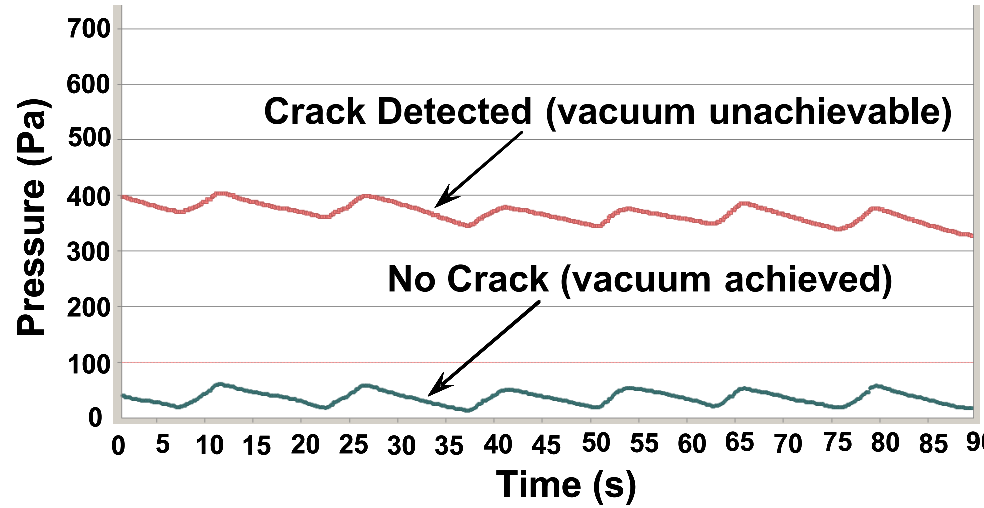




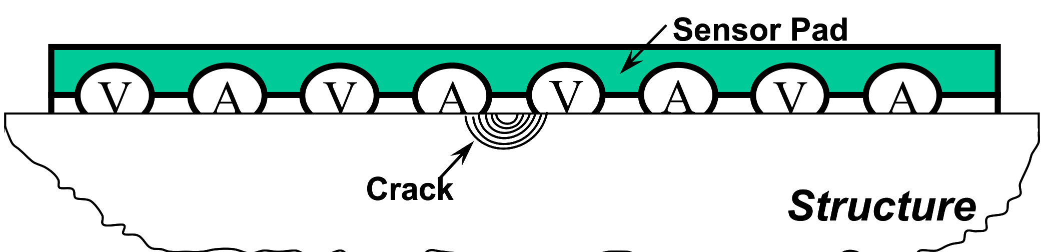


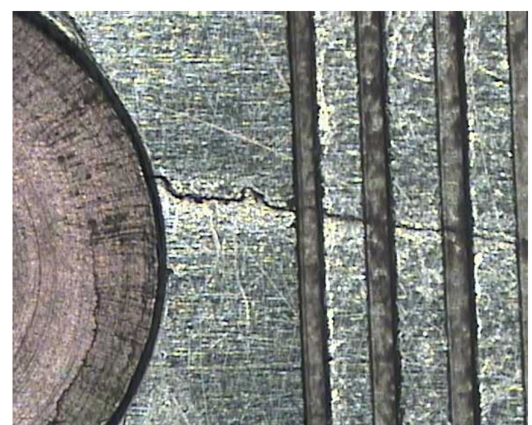
Comparative Vacuum Monitoring System

- Sensors contain fine channels - vacuum is applied to embedded galleries
- Leakage path produces a measurable change in the vacuum level
- Doesn't require electrical excitation or couplant/contact



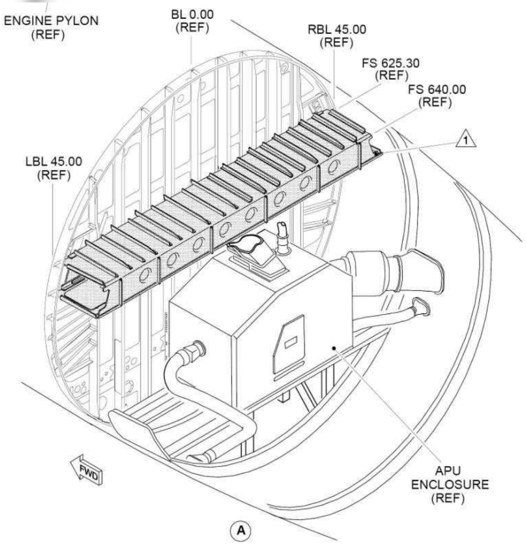
CVM Sensor Adjacent to Crack Initiation Site



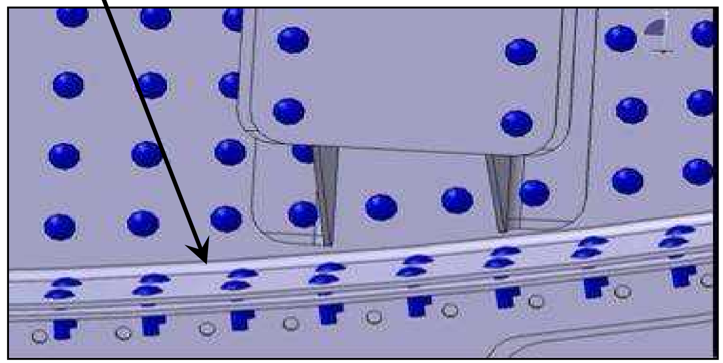


CVM Success on CRJ Aircraft

Pilot program with Bombardier and Air Canada



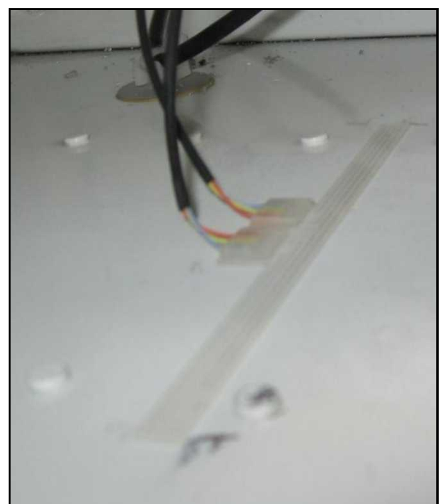
Inspect in the radius

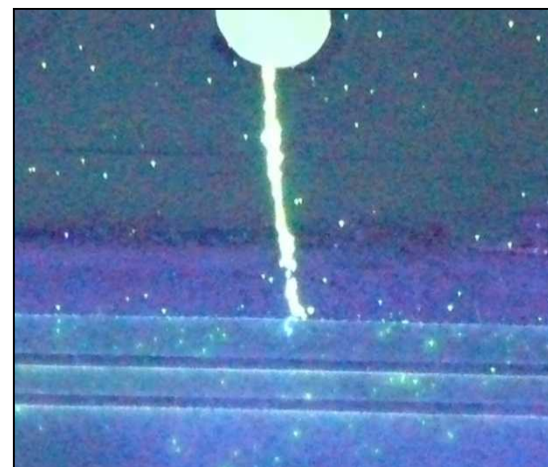


Sensor Issues:

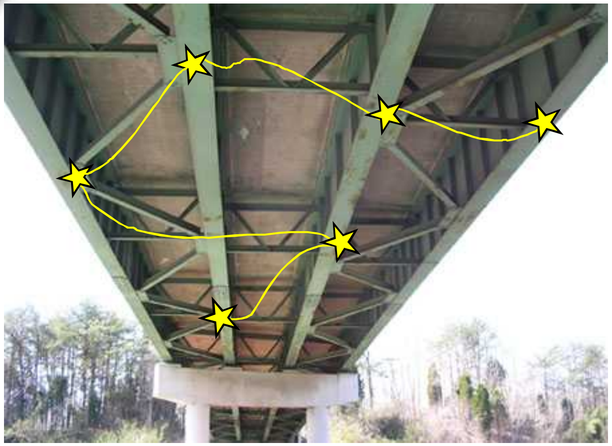
- Design
- Surface preparation
- Access
- Connection
- Quality control

Aft Equipment Bay





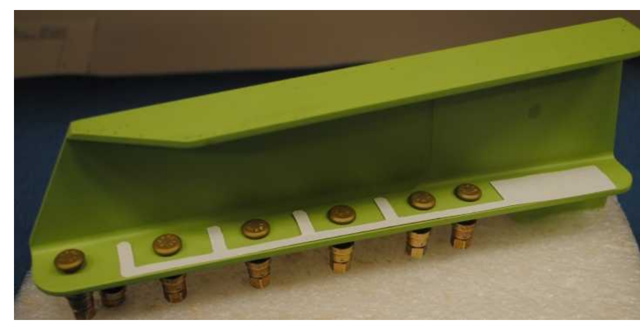
Real-Time Structural Health Monitoring Using Distributed CVM Sensor Networks



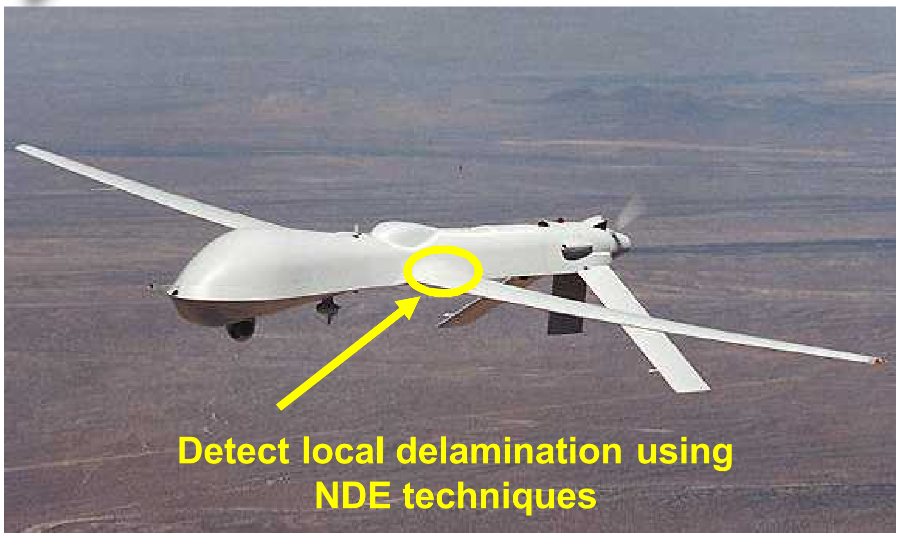
Real-Time, Remote Monitoring System for a Network of CVM Sensors

CVM Sensor Network Applied to 737 Wing Box Fittings

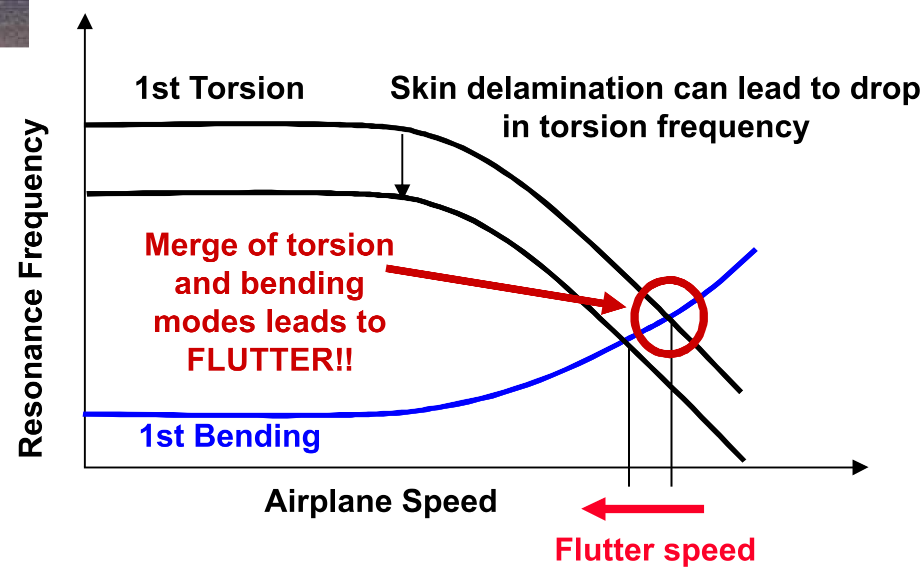
Alternate Means of Compliance with Current Visual Inspection Practice



Application of SHM to UAV Operation



Avoid unstable aerodynamic condition - convergence of torsion and bending modes



Part 3 – FAA SHM Roadmap, Industry Perspectives, SHM Guidance & Standards, and Future Prospects

FAA SHM R&D Roadmap: Introduction and Background

- SHM sensors have been demonstrated to reliably detect damage in laboratory environment and in a few commercial applications
- Commercial implementation of SHM needs to be proven (produce the same reliability as current maintenance practices)
- Identified need for standardized procedures and implementation of SHM technologies prompted the establishment of the AISC SHM (primary goal: Standardization)
- Data requirements need to be established for determining the applicability of SHM (boundaries) and for meeting certification requirements.
- Effects on regulatory measures are important – Where are we now? Where are we heading? How do we get there?

Need for an overarching plan that will guide activities and comprehensively support the safe adoption of SHM practices

Goals of SHM Research and Development (R&D) Roadmap

- Produce overarching plan that will guide activities to uniformly and comprehensively support the evolution and adoption of SHM practices.
- To define what the FAA needs to enable the insertion of SHM in commercial transport airplanes including fatigue monitoring, corrosion and wear assessments, and condition based maintenance.
- Assessing what regulatory guidance is needed to ensure their safe incorporation in future certification programs.
- Will be used by the FAA to assess the state of SHM and define a program to assist them in developing SHM certification and continued airworthiness requirements.
- Set guidelines for assessing the reliability and maintainability of SHM
- SHM Roadmap will support the safe adoption of SHM practices and allow OEMs, regulators, and carriers to make informed decisions about the proper utilization of SHM.

Work Plan to Develop SHM Roadmap

- **Subtask 1: Assessment of SHM:** Determine the current state of SHM for commercial aircraft; applications, utilization & safe adoption
- **Subtask 2: Identify Technologies and Implementation Schedule:** Identify candidate SHM technologies that may be implemented
- **Subtask 3: Review Certification and Airworthiness Requirements:** Determine certification processes that are technically and administratively agreeable to the regulatory agencies.
- **Subtask 4: Identify Gaps and Technology Requirements:** Identify gaps that may prevent the implementation of SHM [design, manufacturing, durability, POD, ease of use, spatial resolution]
- **Subtask 5: Develop SHM R&D Roadmap:** Identify R&D tasks that are needed to enable the FAA to evaluate and assess SHM technologies for certification and continued airworthiness requirements.

Work Plan to Develop SHM Roadmap (cont.)

- SHM Technology Readiness Database
- Industry survey (web-based)
- Solicit position papers from leaders in SHM community worldwide
- Site visits and interviews with OEMs, operators/MROs, regulatory agencies, research labs, SHM developers –
  - assess ability to adopt SHM including business case
  - determine requirements for certif. and continued airworthiness
  - determine SHM capabilities and costs
- Interfacing with the AISC SHM (especially SHM Guidebook effort)

Need input from OEMs, regulators, operators, and research organizations so that the full range of issues is appropriately considered

End Use of FAA SHM R&D Roadmap

- Recent advances in health monitoring methods have produced viable systems for on-board aircraft inspections
- Sensors must be low-profile, easily mountable, durable & reliable
- Roadmap can provide uniform approach for industry – OEMs, airlines, regulators, SHM developers
- SHM R&D Roadmap will assist the FAA in developing SHM certification and continued airworthiness requirements
  - Develop guidelines for regulatory needs
  - Advisory materials for the implementation of SHM systems
  - Set guidelines for assessing the reliability and maintainability of SHM systems
  - Provide guidelines to allow the FAA to evaluate changes to maintenance practices stemming from SHM usage
  - Provide guidelines to allow the FAA to evaluate any changes to design practices stemming from SHM usage
  - Standardize terminology for SHM

FAA SHM R&D Roadmap

- SHM sensors have been demonstrated to reliably detect damage in laboratory environment and in a few commercial applications

- Need for an overarching plan that will guide FAA activities (regulatory needs) and comprehensively support the safe adoption of SHM practices (initial use and continued airworthiness)

SHM Survey of Aviation Industry

Goal: To solicit input from aircraft manufacturers, regulators, operators, and research organizations to identify the current status of SHM technology and the issues facing the aviation industry to safely adopt SHM practices.

- Used responses to 50 questions to obtain industry information on SHM deployment & utilization, validation & certification, SHM standardization, sensor evolution & operation, cost-benefit analysis, & SHM system description

- 455 responses obtained including relevant numbers from OEMs, operators, and regulators

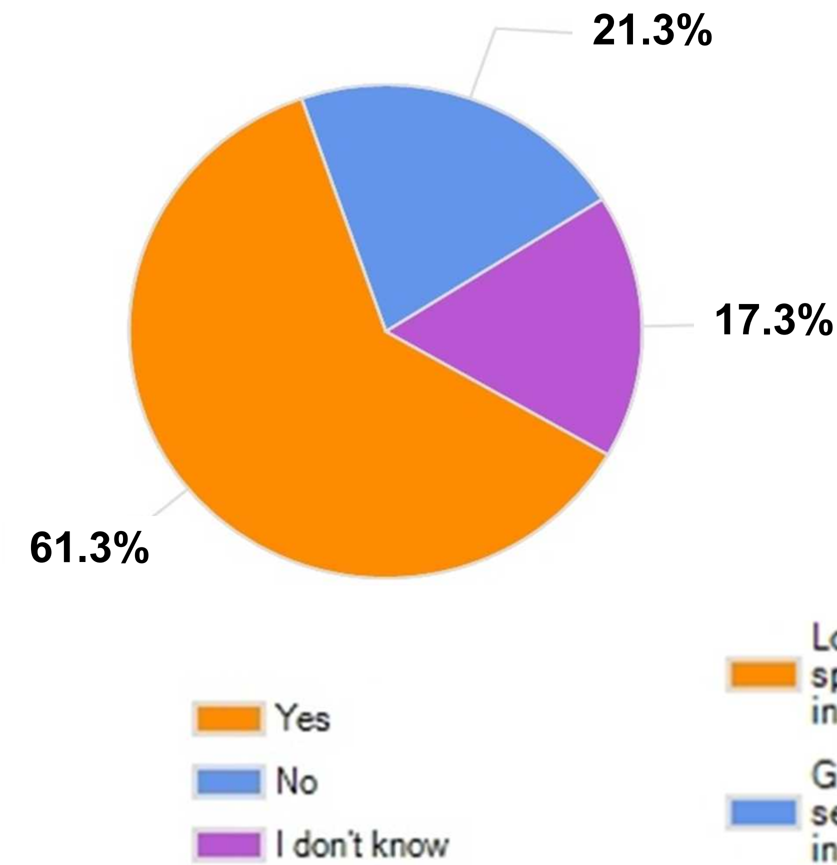
SHM Survey of Aviation Industry - Respondents

Owners/Operators	OEMs	Regulators	Maintainers
All Nippon Airways	Airbus	Air Transport Association	Aerotechnics Inc
American Airlines	Astronics-Adv. Electronic Systems	CAA - NL	Air New Zealand
Austrian Air Force	Avensys Inc.	CAA - Bra	China Airlines
China Airlines	BAE systems	EASA	Christchurch Engine Centre
Continental Airlines	Bell Helicopter Textron	FAA	Fokker Aircraft Services B.V.
Delta Air Lines	Boeing	NAVAIR	Fuji Heavy Industries, Ltd.
Federal Express	Bombardier Aerospace	NAWCAD	Jazz Air LTD
Finnair	Cessna Aircraft Company	Transport Canada (TCCA)	Lufthansa Technik AG
Hawaiian Airlines	Dassault Aviation	USAF	NASA
Japan Airlines	EADS Military Air Systems	US Army	Olympic Airways Services S.A.
Jazz Airlines	Embraer	USCG	SAA Technologies
Jet Blue Airways	Goodrich	US Navy	SR Technics Switzerland LTD
Kalitta Air LLC	Honeywell		Texas Aero Engine Services
NASA	Lockheed Martin Aeronautics		Timco / GSO
Qantas Airways	Messier-Dowty		United Airlines
Singapore Airlines	Mistras Group, Inc		USAF
Swiss Air	Polskie Zaklady Lotnicze Sp.		US Army
United Airlines	PZL Swidnik		USCG
US Airways	Rolls-Royce Corp		US Navy
USAF	Systems & Electronics, Inc.		
US Army	TecScan		
USCG			
US Navy			

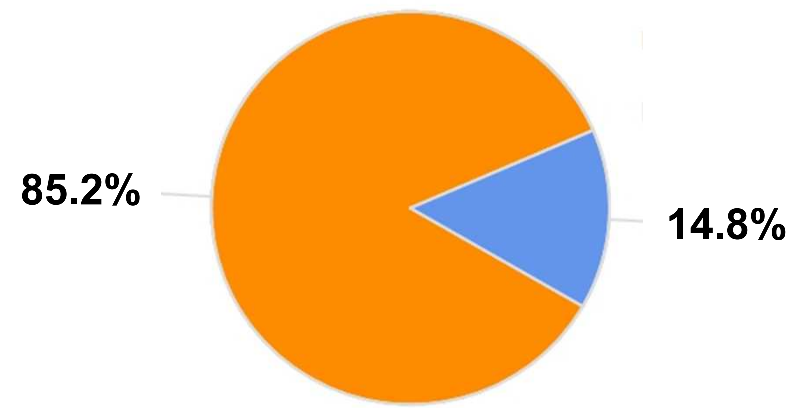
+ Over 100 SHM developers and research organizations

SHM Survey Results – Viability & Airline/OEM Usage

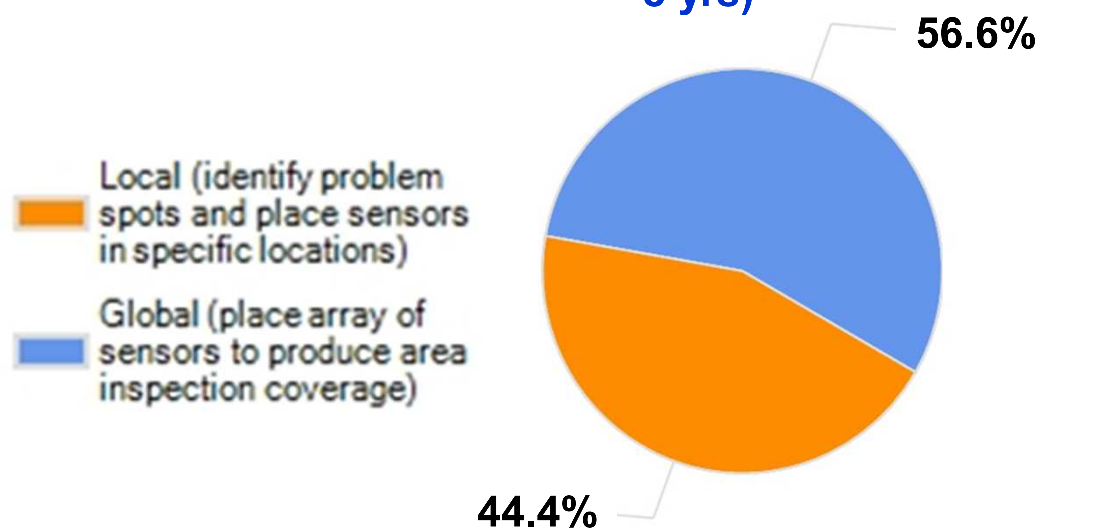
Viability of Using SHM as an Alternative Solution to NDT



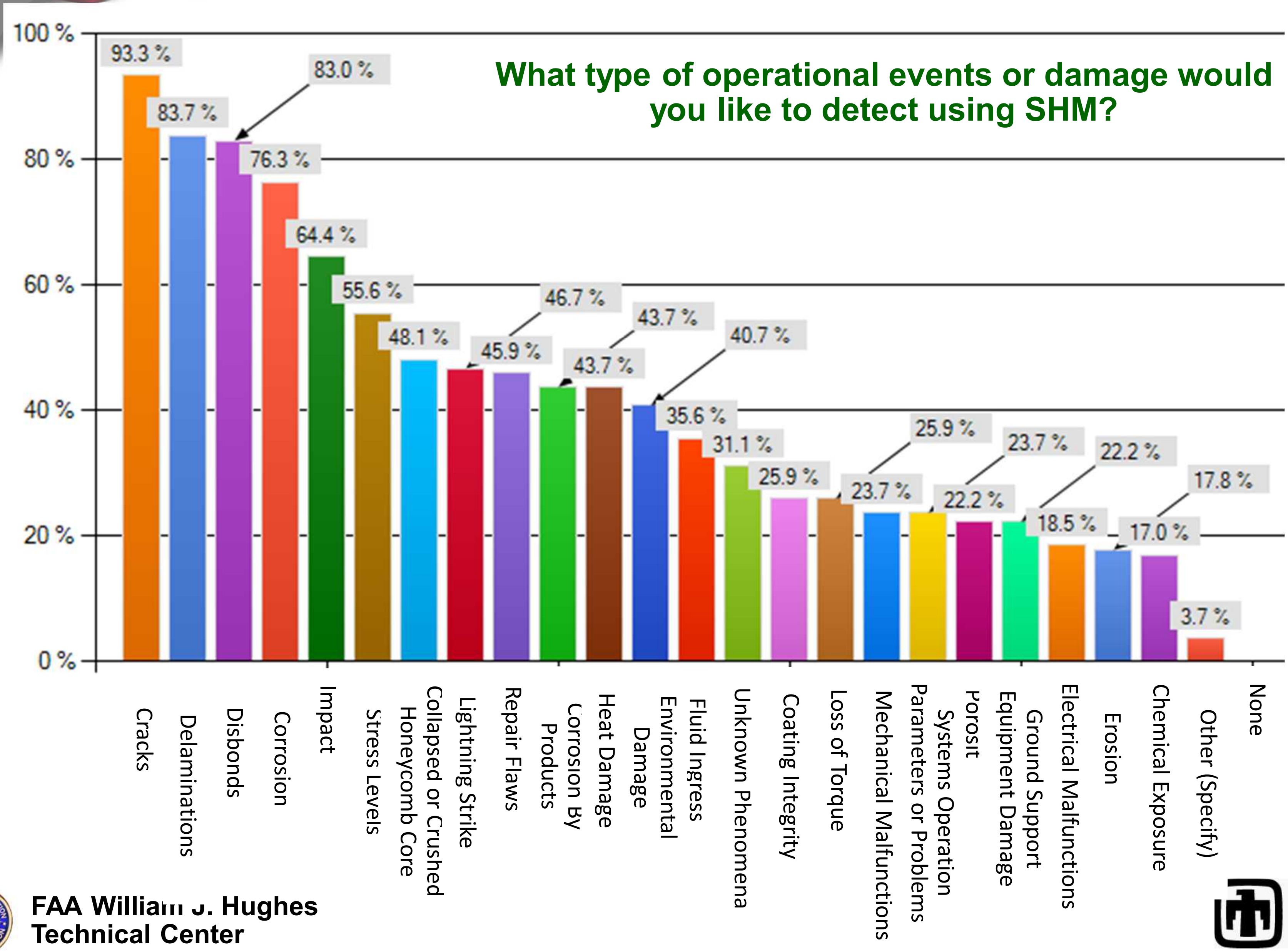
SHM Anticipated in the Near-Term (Now - 5 yrs)



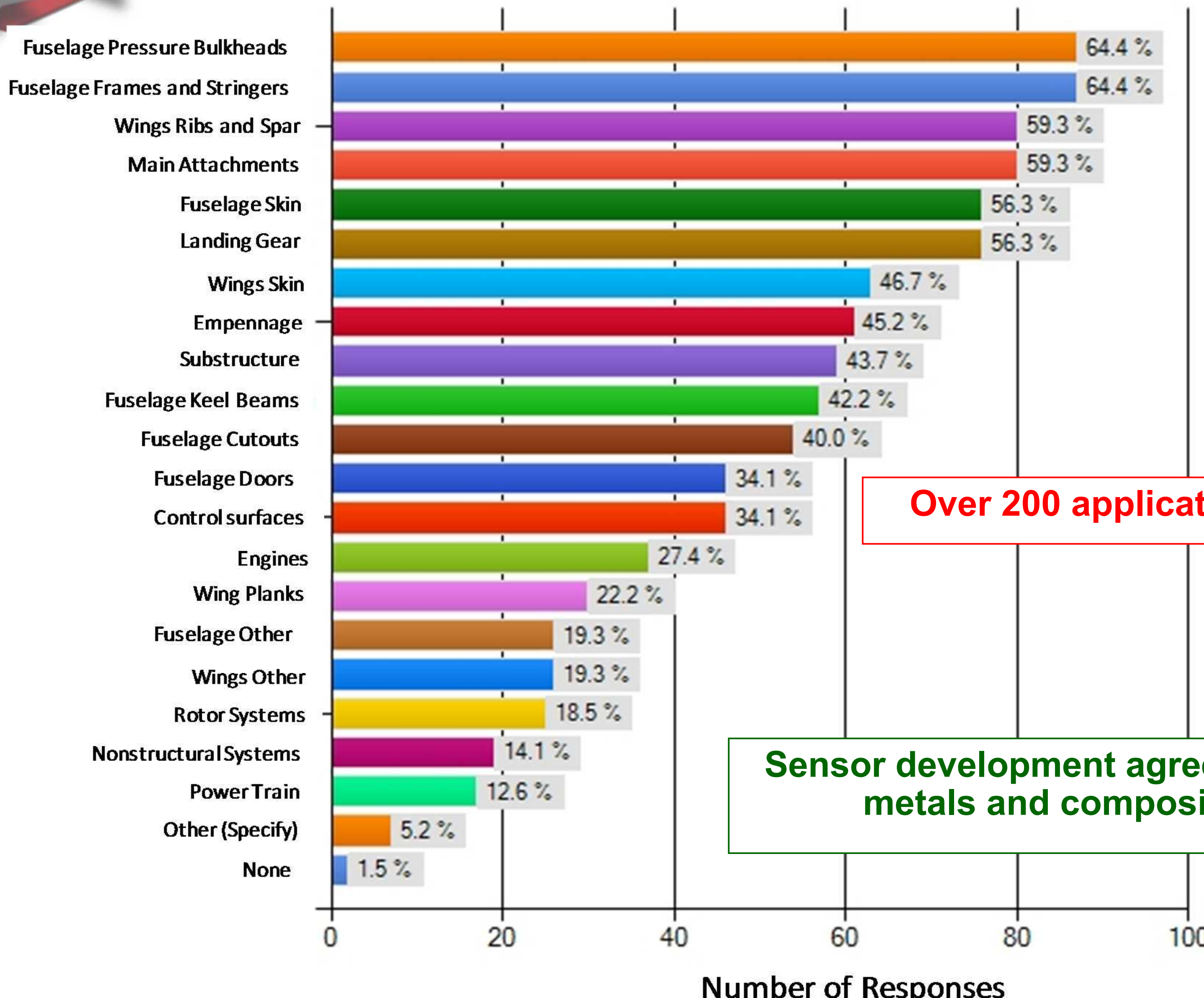
SHM Anticipated in the Long-Term (5 - 8 yrs)



SHM Survey Results – Damage to Be Detected



Areas Respondents Feel SHM Solutions are Viable



Over 200 applications listed

Sensor development agrees – both metals and composites

Top four perceived impediments to deployment of SHM on aircraft (OEMs, Operators, MROs)

1) Cost-benefit

2) Coverage area is small compared to size of structure

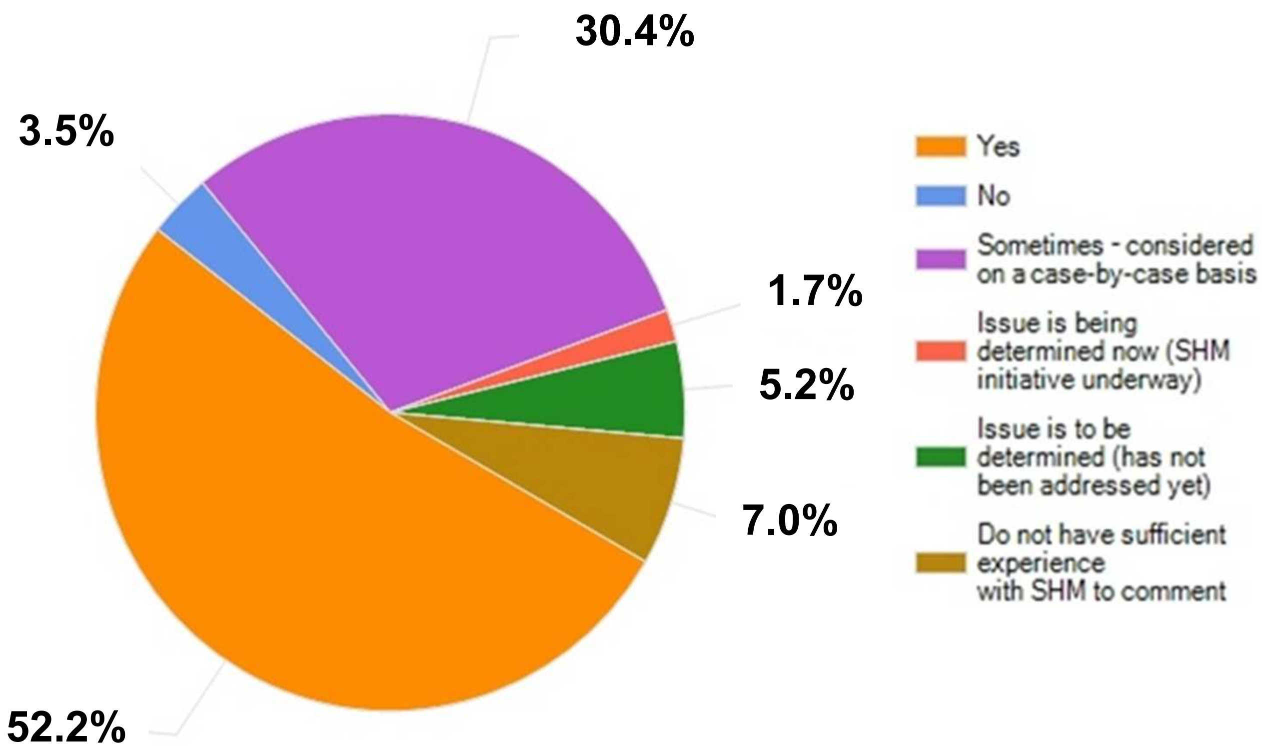
3) Overall performance assessment and validation of technology is needed

4) Certification for use

(installation, durability, adaptability, adoption, training)

Transitioning to SHM

Initially, would regulators and aircraft manufactures require SHM to run in parallel with existing NDI inspections?



SHM Industry Survey – Cost-Benefit & TRL

Top five cost-benefit considerations of an SHM solution:

1. Elimination of structural teardown to access regions to be monitored
2. Recurring cost of SHM sensors
3. Initial cost of SHM equipment
4. Time required for validation/qualification
5. Compliance requirements - existing or future needs

- **55% of aircraft operators, maintainers, and military personnel say that 5 years is a reasonable payback period for recouping the cost associated with using an SHM system**
- **31% say 2 years is reasonable**

Technology Readiness

- 43% have been through initial laboratory tests
- 37% had laboratory performance evaluation
- 9% have had field evaluation
- 7% have complete validation of SHM system
- 7% proven and ready for aircraft

Respondent's SHM System Costs

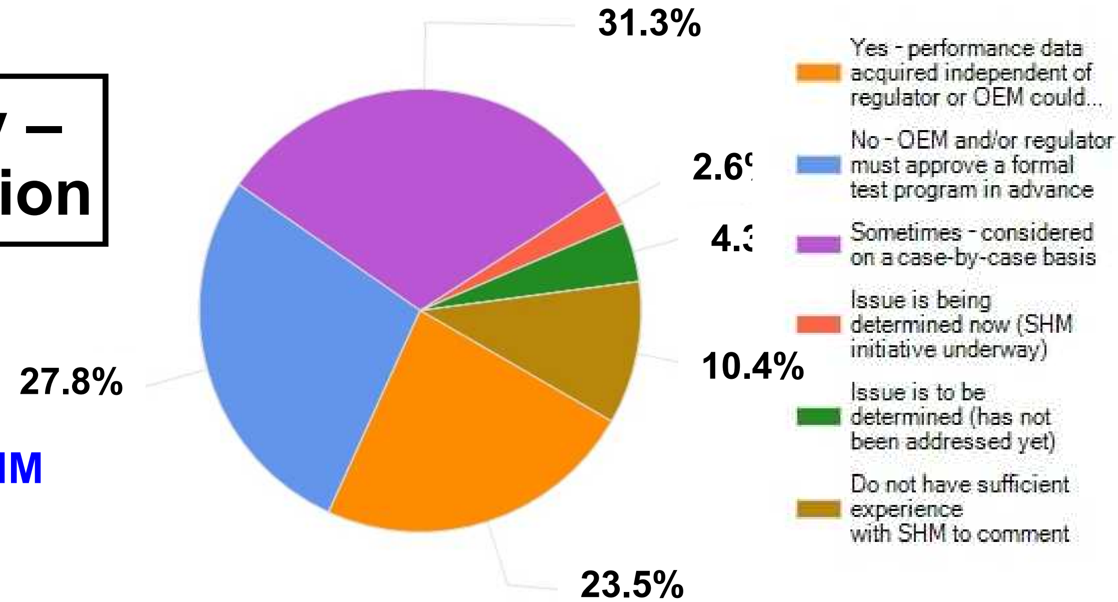
8% less than $1,000

28% between $1,000 and $8,000

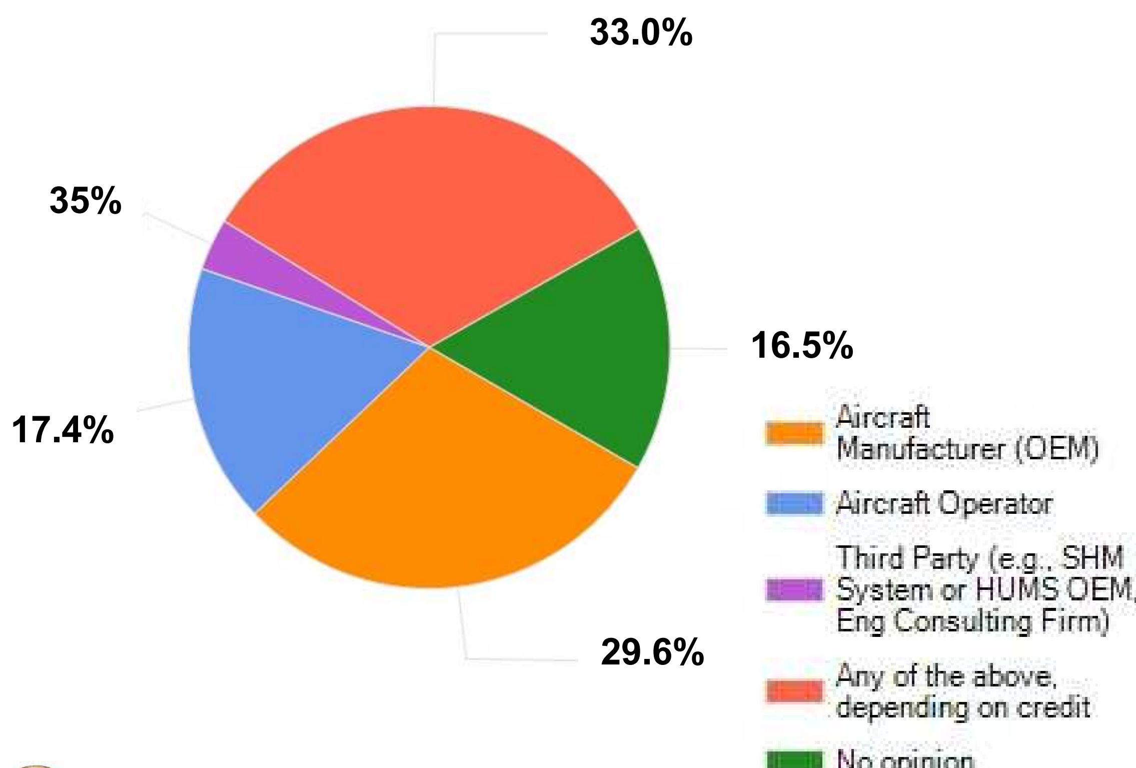
21% between $8,000 and $16,000

31% greater than $16,000

SHM Industry Survey – Operation & Certification

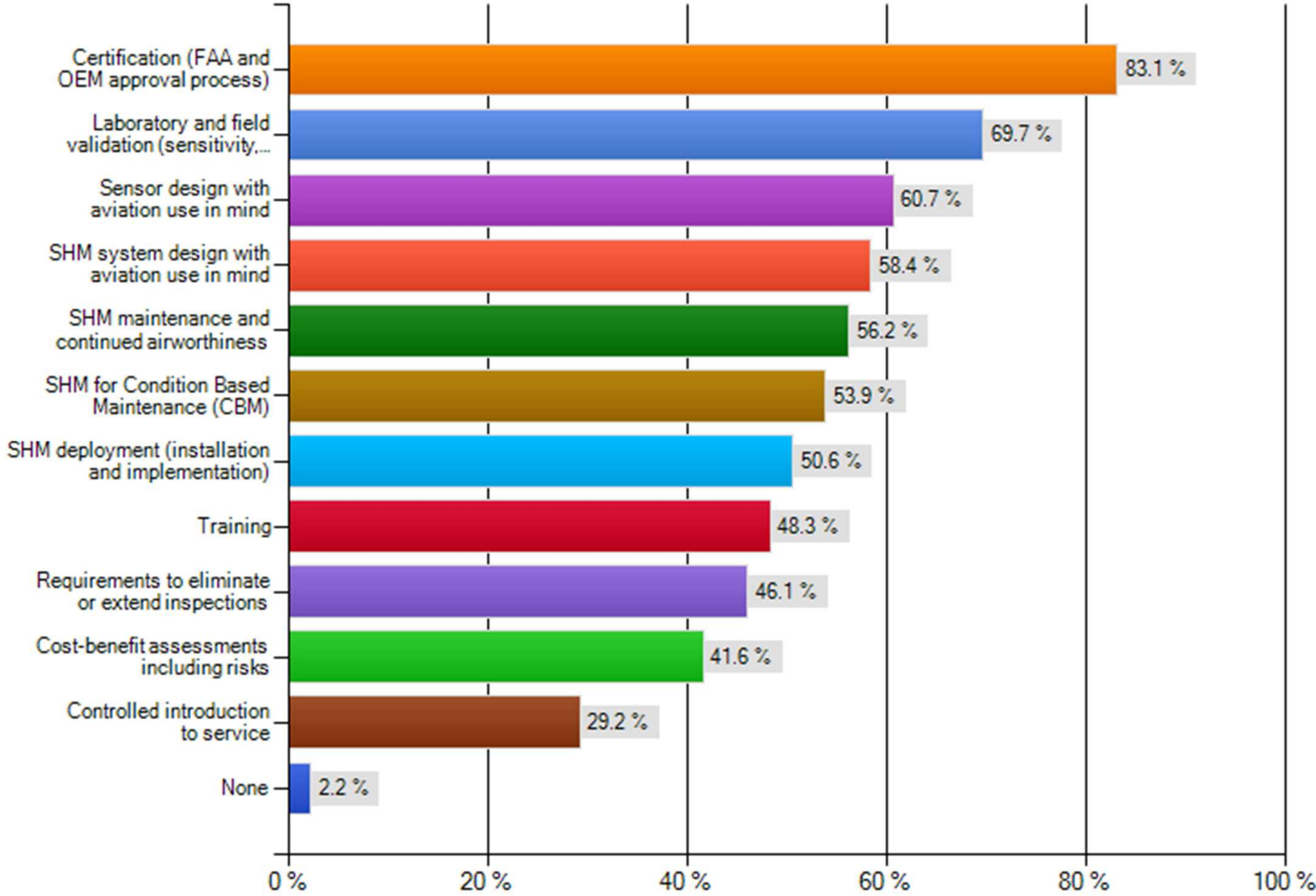


Who should apply for or own SHM based maintenance credits?

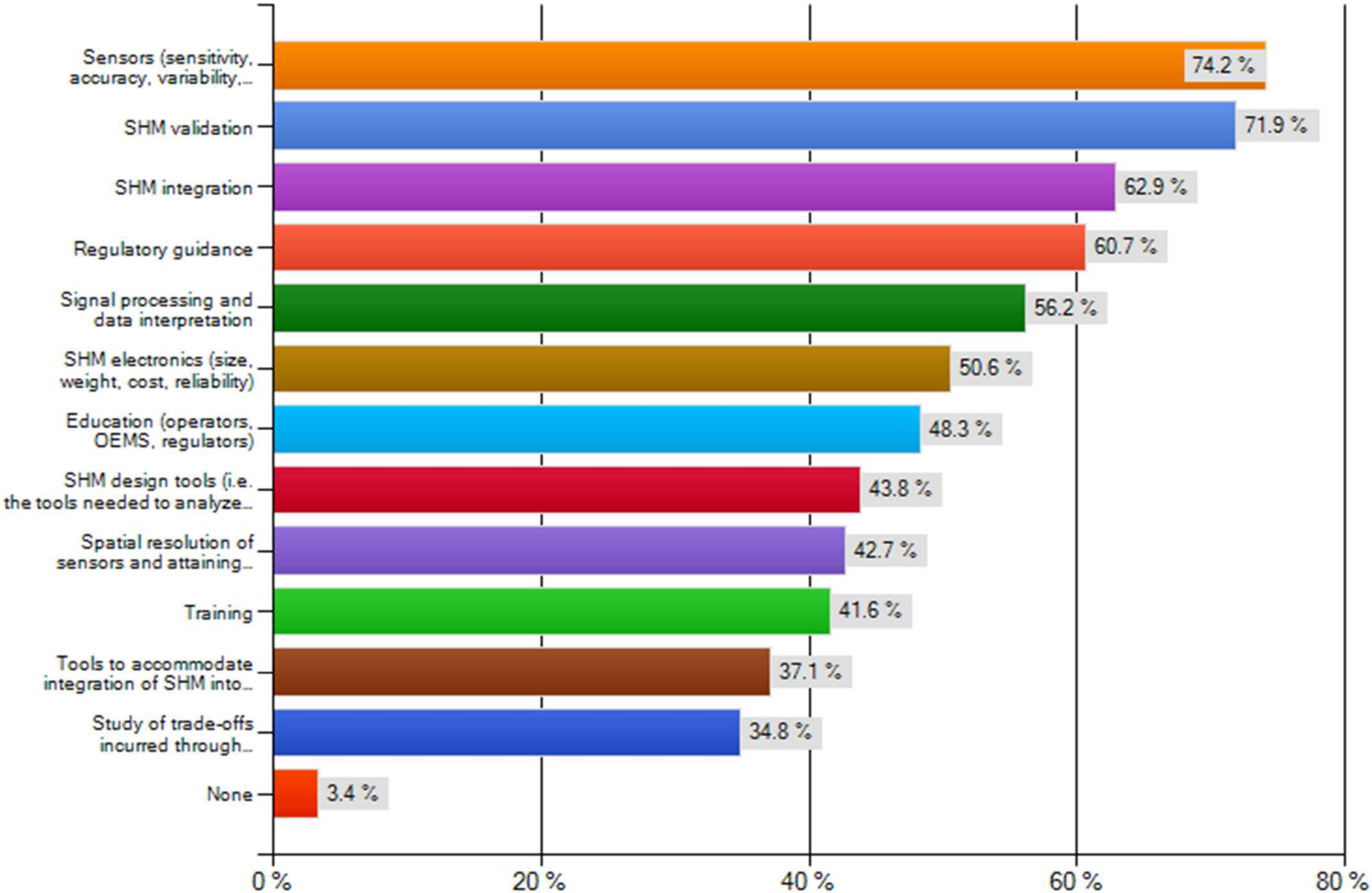


Would you accept performance data from operators/vendors /industry groups/military or require the regulatory agency/ OEM to be involved in a formal test program?

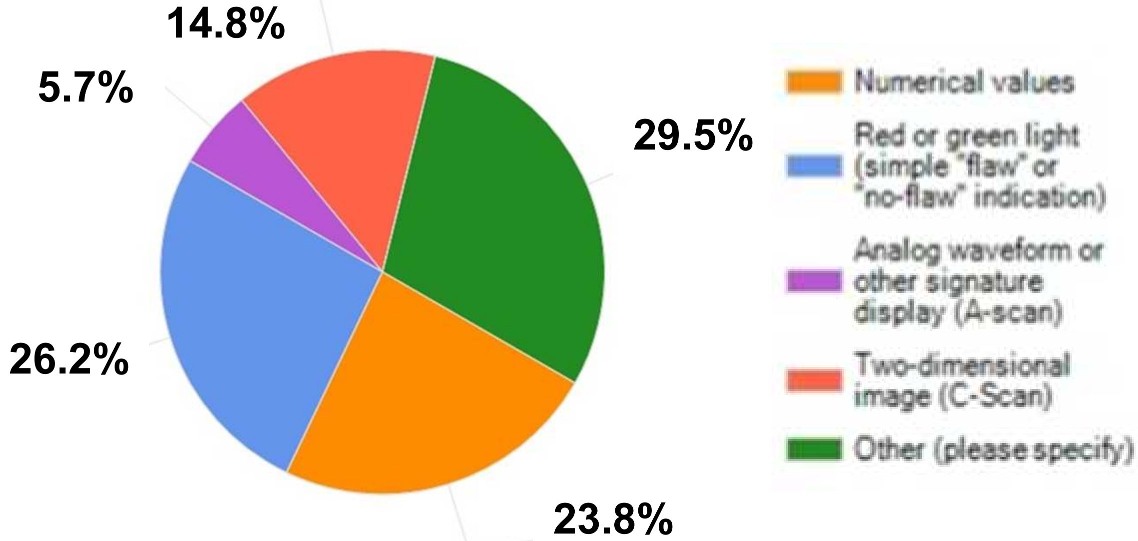
Where do OEMs and Owners/Operators think Standardization and Guidelines are Needed and Feasible?



What Type of Research and Development do OEMs and Owners/Operators think is needed to evolve SHM systems to where they can be used on aircraft?

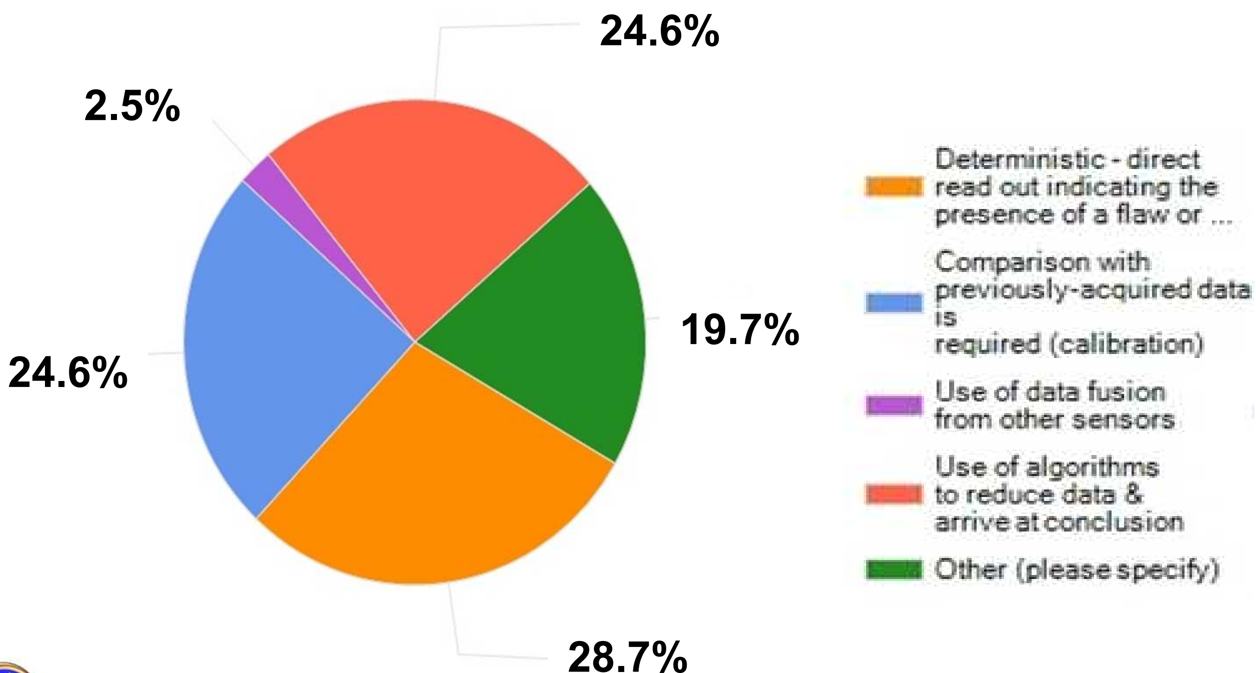


What the Industry Survey Revealed on Sensors



How are the results presented to the operator?

How much data interpretation is required of the sensor output?



Smart Patch Sensor System

Some Survey Results from Sensor Developers

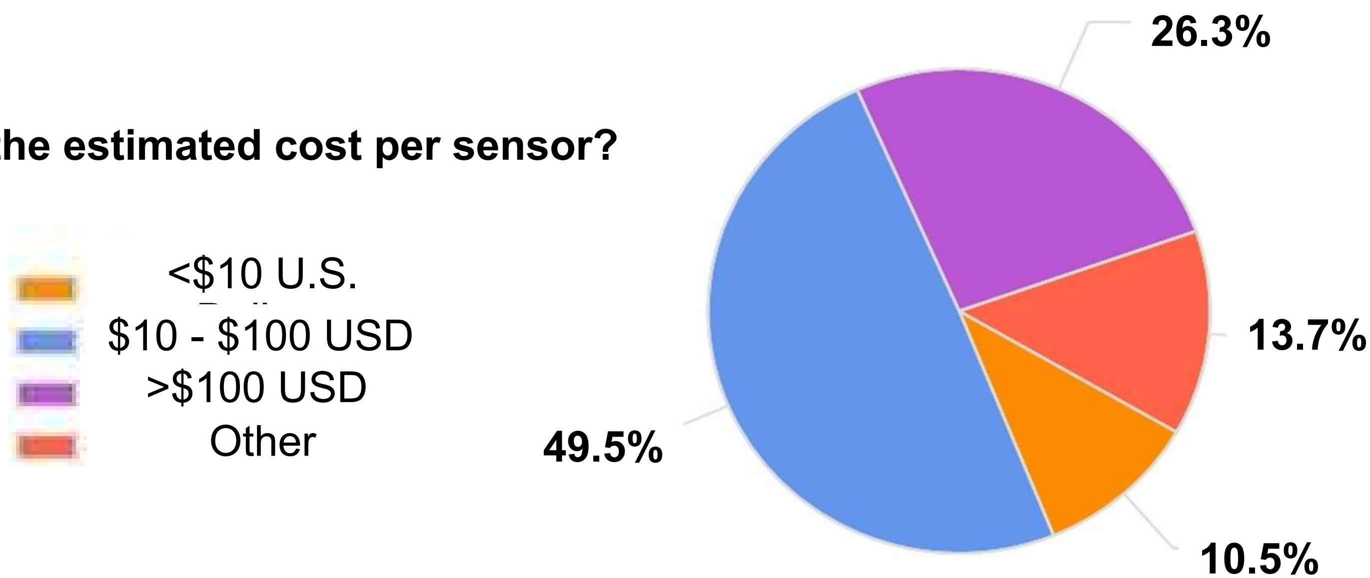
Does the sensor have a fail-safe feature which will prevent the acquisition of faulty data from a damaged or failed sensor?

52% Yes
48% No

Does the system contain a built-in self-diagnostic capability to automatically interpret the data?

60% Yes
40% No

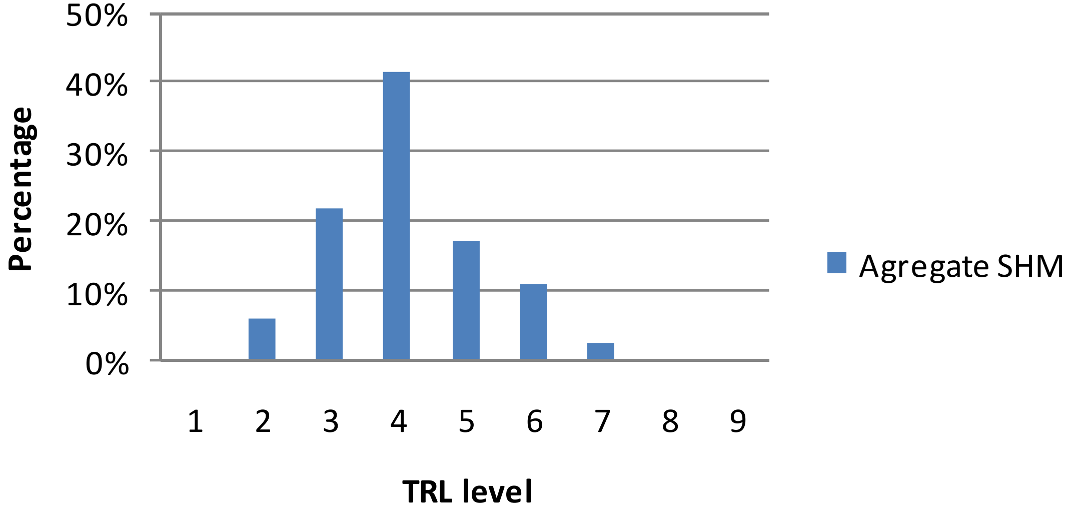
What is the estimated cost per sensor?



Technology Readiness Level (TRL)

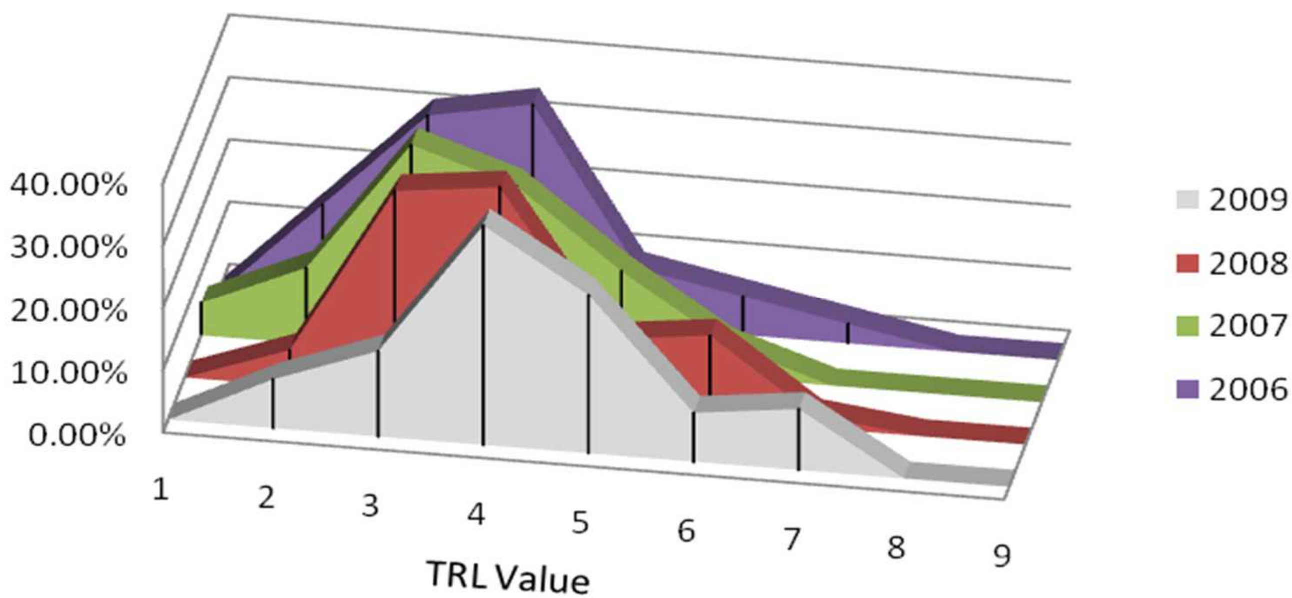
- TRLs were adopted as a method for ranking technology/systems through the development stages
- Mimics TRLs used by NASA & military - this classification system clearly defines benchmarks, direction and maturity of emerging technologies
  - **TRL 1** - *Physical principles are postulated with reasoning*
  - **TRL 2** - *Application for physical principles identified but no results*
  - **TRL 3** - *Initial laboratory tests on general hardware configuration to support physical principles*
  - **TRL 4** - *Integration level showing systems function in lab tests*
  - **TRL 5** - *System testing to evaluate function in realistic environment*
  - **TRL 6** - *Evaluation of prototype system*
  - **TRL 7** - *Demonstration of complete system prototype in operating environment*
  - **TRL 8** - *Certification testing on final system in lab and/or field*
  - **TRL 9** - *Final adjustment of system through mission operations*

Overall SHM TRL Distribution



TRL currently peaks at 4 (centered around 3-6) - some technologies have reached full prototype systems designed for use on aircraft (7)

TRL Distribution vs Year



Shift in TRL (lft to rt) –shows advancing SHM technology; some should arrive at TRL 7-9 in the next 3-5 years

Overview of SHM Readiness

- Overall, there is a strong interest in SHM – multitude of applications covering all aircraft structural, engine, and systems areas
- Industry's main concern with implementing SHM on aircraft is achieving a positive cost-benefit & time to obtain approval for SHM usage
- Research and development efforts should be focused on: global systems, sensor technology, system validation and integration, and regulatory guidance
- Standardization and guidelines are needed in certification, laboratory and field validation, and sensor design with aviation in mind
- SHM should run in parallel with current NDI inspections for a period of time
- Industry would use SHM to detect cracks, delaminations, disbonds, corrosion and impact among others
- There is a wide variety of SHM sensors currently developed that have shown potential in aircraft applications. SHM maturity has grown exponentially so desired usage and need for certification is expected to rise rapidly.

FAA Regulatory Guidance & Aircraft Certification Process

- Use of SHM can be fostered through the addition of SHM solutions in FAA and OEM documents –
  - Federal Aviation Regulations (FARs),
  - Advisory Circulars (ACs)
  - Airworthiness Directives (ADs)
  - Service Bulletins (SBs)
  - Advisory and Rulemaking Committee Orders
  - Supplemental Type Certificate (STC) - issued by FAA to accommodate design mods; can be airline or someone other than holder of TC
  - Alternate Means of Compliance (AMOC)
  - Supplemental Structural Inspection Documents
- Validation requirements established by FAA, OEM, airline, and other agency teams – goals, usage and approach to be determined up front

SHM Validation – Certification and Future Use

How is SHM Being Used - Future applications for SHM go beyond S-SHM and into prognostic and condition-based health monitoring. The ATA and industry team is currently determining the guidance needed to modify scheduled maintenance via the introduction of P-SHM and C-SHM. Such a shift to predictive and continuous monitoring will require extensive validation and successful in-service experience so that regulatory agencies and operators can acquire confidence in these SHM approaches.

A/C Maintenance Practices
Deployment – operational performance
Regulatory actions – depends on certification process (AMOC, NDT SPM, SB/AD, STC)

Aerospace Industry Steering Committee on Structural Health Monitoring (AISC SHM)

First meeting of AISC-SHM
Stanford University
Palo Alto, CA
October 2006

Recognized need for guidance and standardization

20th meeting of AISC-SHM
OGMA MRO
Lisbon, Portugal
April 2016

Vision and Motivation of AISC-SHM

- The AISC – SHM is an international team comprising industry, government and academic participants with a collective vision to efficiently and effectively implement structural health monitoring for a wide variety of commercial and military aerospace applications through the development of standards, procedures, processes and guidelines for implementation and certification of SHM technologies.

- The AISC-SHM operates as a Technical Committee within SAE International's Aerospace Standards Program (G-11 SHM)

- International efforts among various organizations:
  - OEMs: aircraft manufacturers
  - Airlines/Operators and their representatives
  - Regulatory Authorities
  - System Integrators
  - Developers / Research organizations
  - Military

Sample Members:
Airbus (EADS)
Air Force
BAE Systems
Boeing
Bombardier
Cranfield Univ.
Delta Air Lines
EASA
Embraer
FAA
GE
Honeywell
NASA
Navy
RIMCOF
Sandia Labs
Sikorsky
Stanford Univ.
Univ. of Tokyo

AISC-SHM Organization and Responsibilities

G-11 SHM

Aerospace Industry Steering Committee for Structural Health Monitoring

Committee structure

AISC -SHM Main Technical Committee

Operators /end users, Regulatory agencies, OEMs, Systems integrators and SHM Suppliers, Research organizations /institutions, other interested parties

AISC -SHM Executive Management Board (EMB)

Officers, industry/ institutional representatives, chairs of working groups, plus SAE representative.

A4A (ATA) interaction

SAE Administration

Working Groups

- **Commercial Aviation Working Group**
- **Military Aviation Working Group**
- **Rotorcraft Working Group**
- **SHM Reliability Working Group**

AISC-SHM Mission

- **The mission of the AISC-SHM is to provide an approach for standardizing integration and certification requirements for SHM of aerospace structures, which will include system maturation, maintenance, validation and introduction into accepted maintenance practices.**

- **The focus is the <u>development of cross-industry guidebooks</u> describing approaches to safely deploy SHM systems on fixed wing aircraft and rotorcraft and guidelines for the proper validation and certification of SHM solutions.**

- **SAE International Aerospace Recommended Practices document: ARP6461 “Guidelines on the Implementation of Structural Health Monitoring on Fixed Wing Aircraft” (September 2013)**

SAE Aerospace An SAE International Group	AEROSPACE RECOMMENDED PRACTICE	SAE ARP6461 Issued Proposed Draft 2012-11-28

Guidelines for Implementation of Structural Health Monitoring on Fixed Wing Aircraft

DRAFT

RATIONALE

The development of Structural Health Monitoring (SHM) technologies to achieve Vehicle Health Management objectives in aerospace applications is an activity that spans multiple engineering disciplines. It is also recognized that many stakeholders: Regulatory Agencies, Airlines, Original Equipment Manufacturers (OEM), Academia and Equipment Suppliers are crucial to the process of certifying viable SHM solutions. Thus a common language (definitions), framework of solution types, and recommended practices for reaching those solutions, are needed to promote fruitful and efficient technology development.

TABLE OF CONTENTS

ARP6461 “Guidelines on the Implementation of Structural Health Monitoring on Fixed Wing Aircraft”

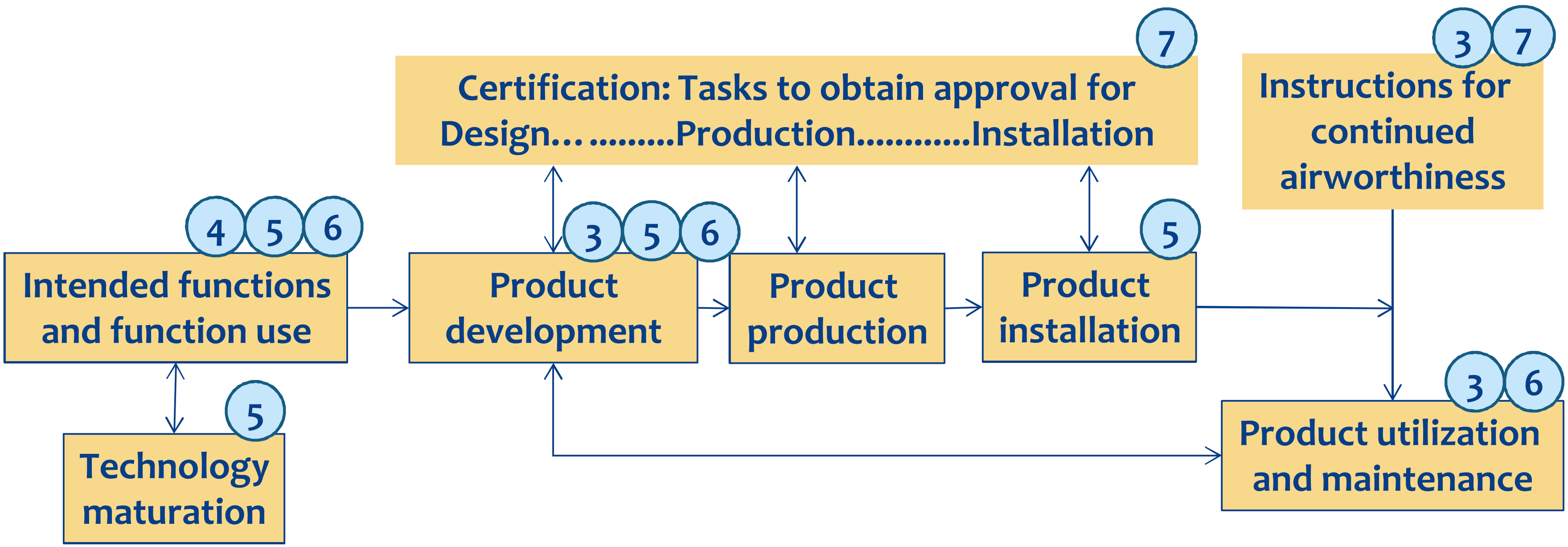
Contents of Guidelines

AISC-SHM Guidelines in Process

1. AIR 6892: “Structural Health Monitoring Considerations and Guidance Specific to Rotorcraft”
2. AIR XXXX: “Perspectives on Integrating Structural Health Monitoring Systems into Military Aircraft”
3. AIR/ARP TBD: “Methodologies for Determining the Performance and Reliability of Structural Health Monitoring Systems

ARP6461 "Guidelines on the Implementation of Structural Health Monitoring on Fixed Wing Aircraft"

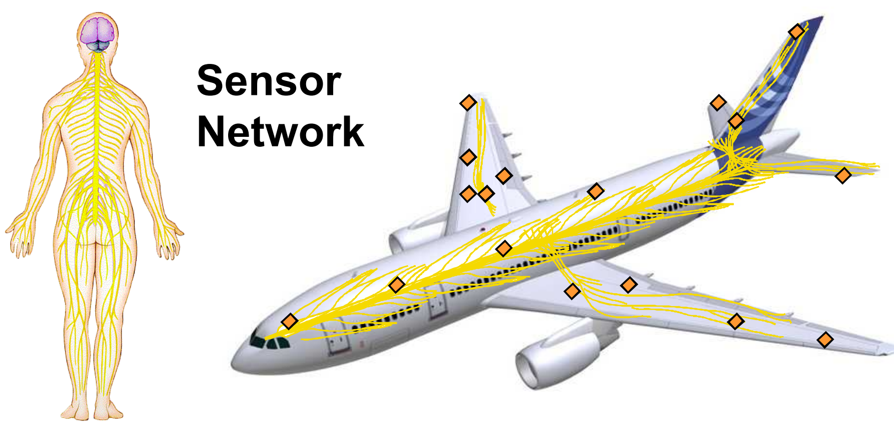
Organization of ARP6461 Document



1. Scope
2. Applicable Documents
3. Introduction to Aircraft Structures Design and Maintenance
4. Essential Aspects of Structural Health Monitoring
5. SHM System Requirements
6. Validation and Verification
7. Certification

Airbus SHM Activities & Perspectives

Generation 0	Generation 1	Generation 2	Generation 3
• Structure testing application • Benefit: - Structure analysis & testing (e.g. A380)	• In-service aircraft, off-line sensor systems (TR: 2009) • Benefit: -maintenance	• In-service aircraft, on-line sensor systems (TR: 2013) • Benefit: -weight saving component level -maintenance	• In-service aircraft, fully integrated sensor systems (TR: 2018) • Benefit: -weight saving aircraft level -maintenance



→ Stepwise approach towards SHM development
→ Global integration: Airlines/Authorities/Suppliers

Embraer SHM Activities & Perspectives

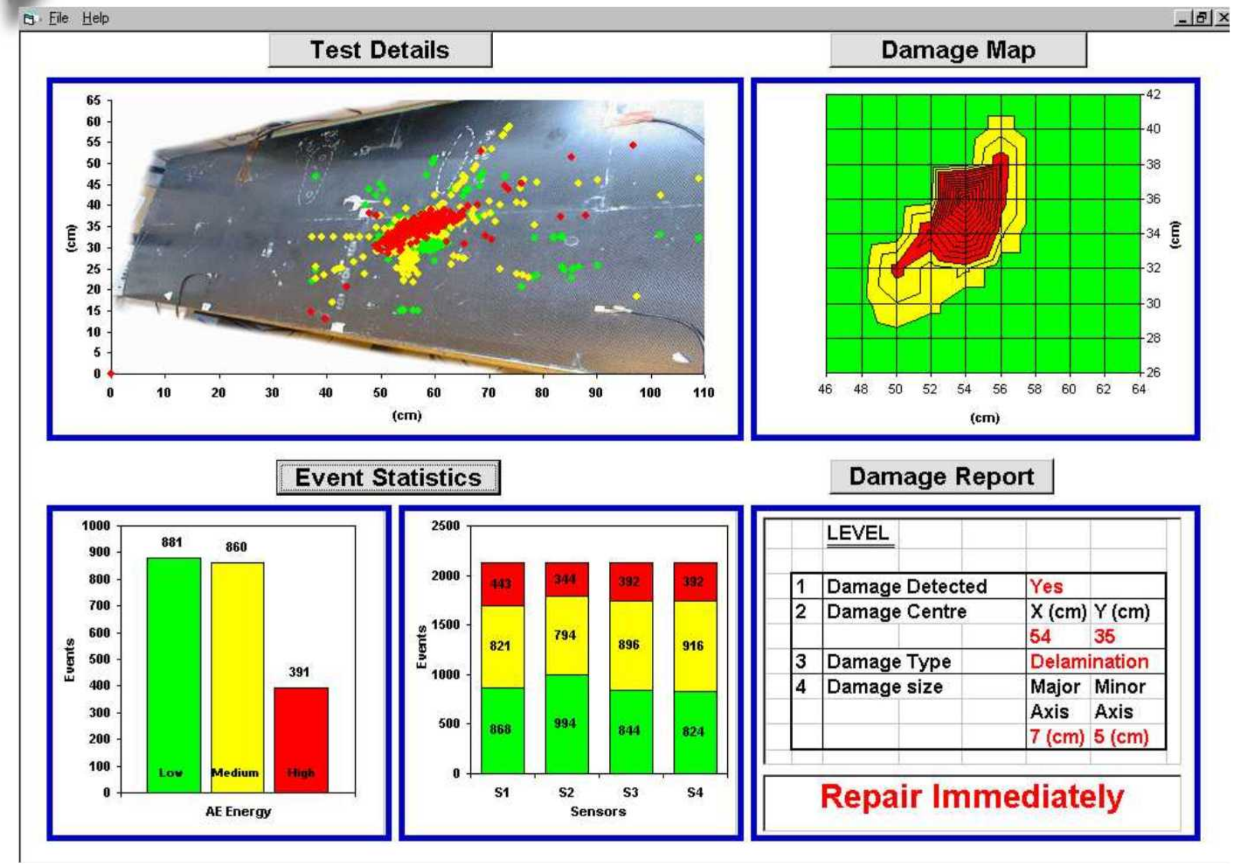
Coupon Tests	Definitions and standardization for SHM. Guidelines for POD, confidence and POFA analysis. Guidelines for equipment calibration.
Sub-Components	Guidelines for installation, operation and maintenance of SHM systems.
Full Scale Fatigue Test	
Prototype	Guidelines for hardware and software testing, qualification and integration (accuracy, durability, MTBF, DOs, HA, Zonal Analysis, etc.).
Operational	Guidelines for continued airworthiness, ATA MSG-3.

Boeing SHM Activities & Perspectives

Implementation in Phases

- Initial Discovery
- Testing/Algorithm Development
- Working Group Development (AISC)
- Phase I – Passive Damage Detection (on ground) and Flight Parameter monitoring
- Phase II – Active Damage Detection (in Flight)

Progression of SHM Approach

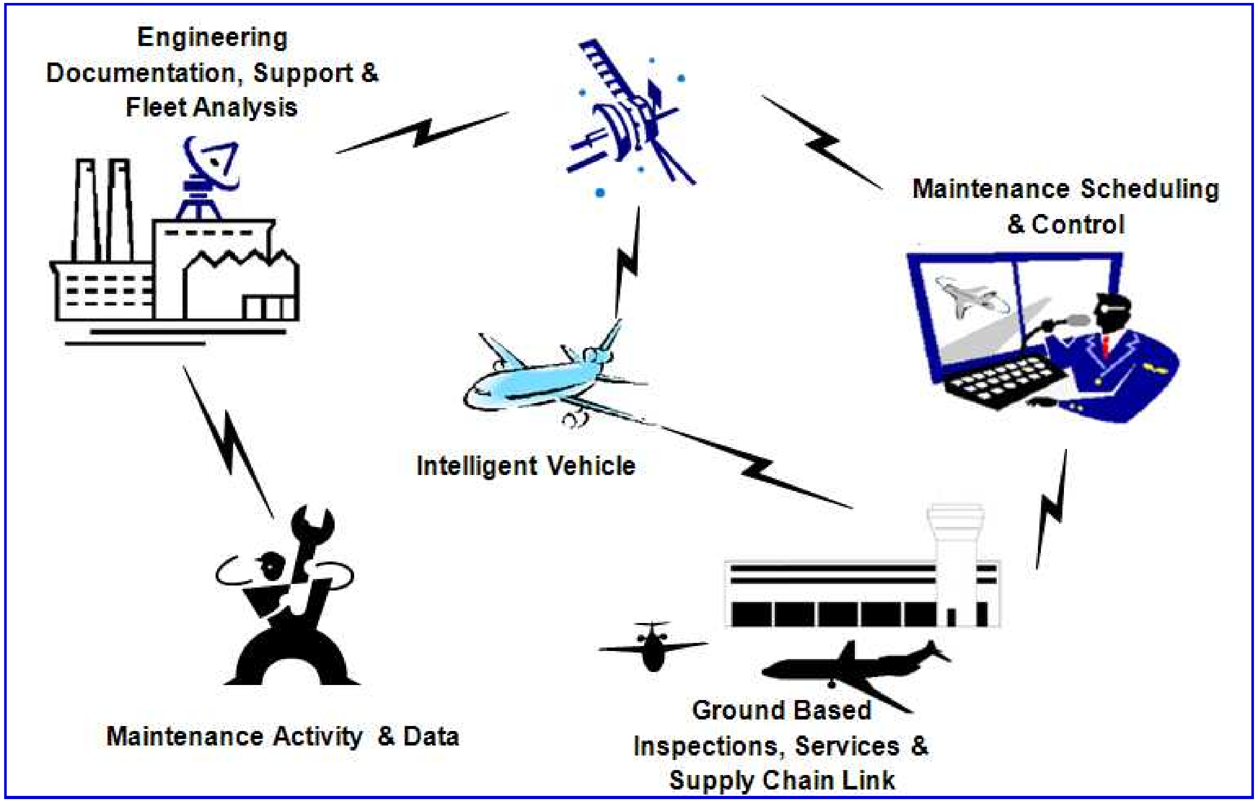


Allows for inspection without dismantling

<u>SHM Concept</u>: ground crew interrogates the on-board SHM and receives immediate diagnosis. Network enabled systems could link with maintenance and ground support systems to automate resulting actions.

SHM – Future Prospects

In-Situ NDI → Condition Based Maintenance → Prognostic Health Management



<u>Changing Design Methodology</u>: Weight reduction may be achieved by having higher levels of probability of detection & confidence, and by decreasing time between periodic inspections

Structural Health Monitoring – Future Look

What can be done?

Progression of SHM Approach

Defining Maintenance Credits: the benefits of SHM.

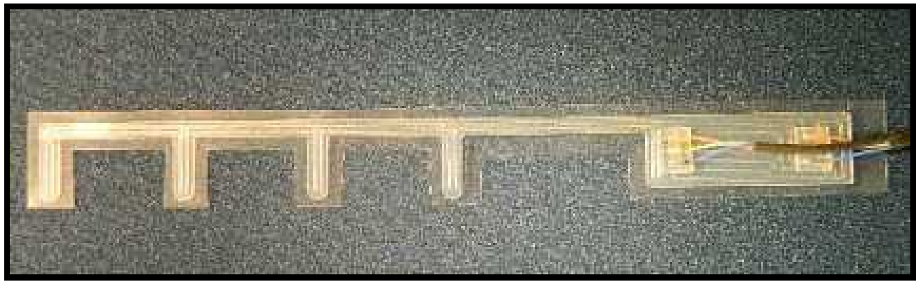
Introduction of the technology is only worthwhile if cost-benefits or increased safety and reliability result.

Condition based maintenance perspective:

- **Reduced intervention, fewer intrusive inspection, less reliance on inspection triggered by subjective assessments from aircrew or ground-crew following suspected exceedances.**
- **Extended time between overhauls based on component condition.**
- **Avoidance of unnecessary replacement. The replacement of structural items would depend on actual condition rather than scheduled replacement according to duration in service, irrespective of condition.**
- **Avoidance of unnecessary modification. Structural items are only modified if their condition warrants modification.**

Part 4 – Introduction to SHM Validation and Performance Assessment

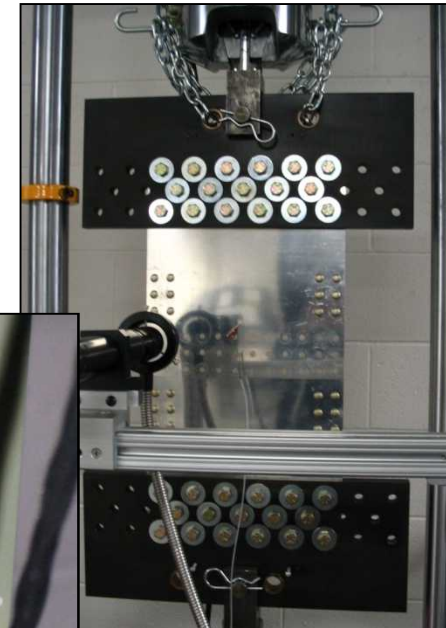
Validation of a Structural Health Monitoring (SHM) System and Integration Into an Airline Maintenance Program

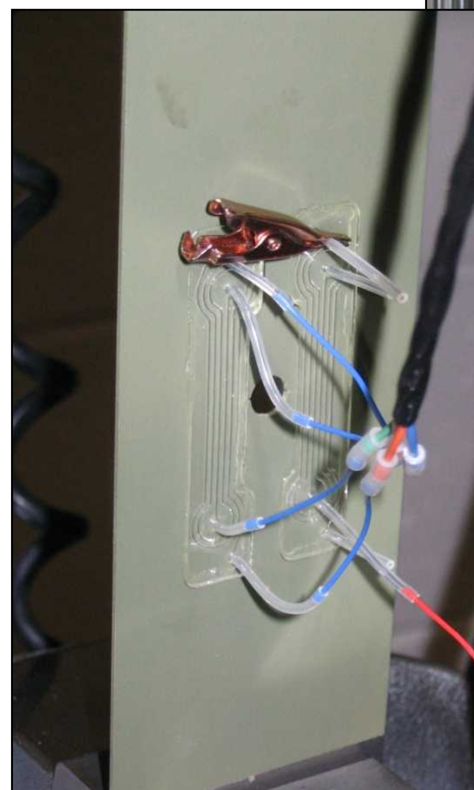


Test Matrix to Quantify Probability of Crack Detection

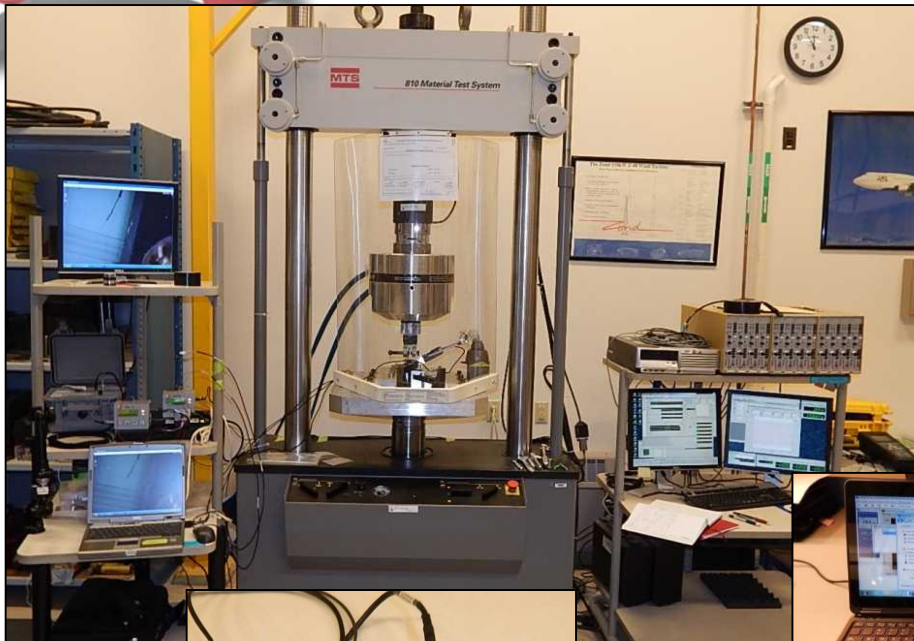
Test Scenarios:

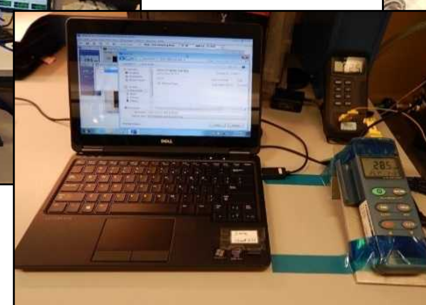
Material	Thickness	Coating
2024-T3	0.040”	bare
2024-T3	0.040”	primer
2024-T3	0.071”	primer
2024-T3	0.100”	bare
2024-T3	0.100”	primer
7075-T6	0.040”	primer
7075-T6	0.071”	primer
7075-T6	0.100”	primer





737NG Center Wing Box – CVM Performance Tests





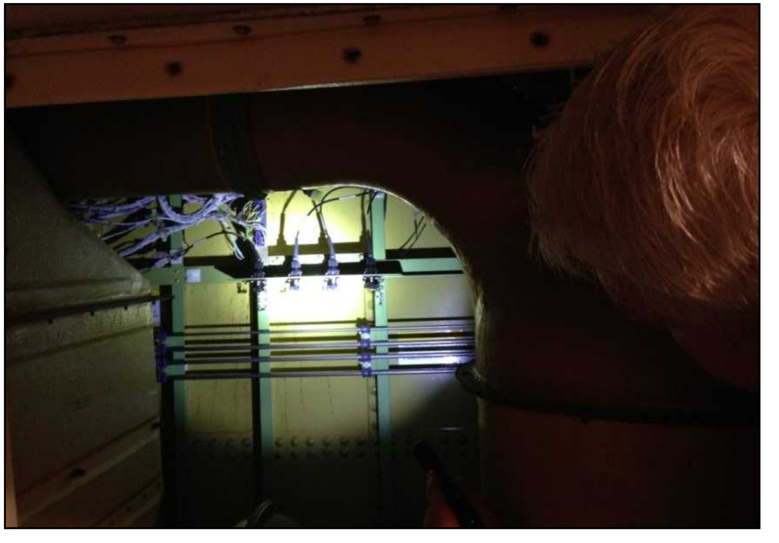
FAA William J. Hughes
Technical Center

Sandia National Laboratories

737NG Center Wing Box – Accumulating Successful Flight History

Aircraft Parked at Gate After Final Flight of the Day

Access to SLS Connectors Through Forward Baggage Compartment



Removal of Baggage Liner to Access 4 SLS Connectors Mounted to Bulkhead

737NG Center Wing Box – CVM Sensor Monitoring

Connecting SLS Leads and Running PM-200 to Monitoring Device to Check Sensor Network

Logging Inspection Completion at Aircraft Gate

Other Applications Identified by Delta Air Lines

Other Potential SHM Applications

Some Potential SHM Applications:

- 737 aft pressure bulkhead
- 737 center wing box spar fitting
- 747 fuselage
- MD-88 and DC-9 substructure
- MD-88 belly skin
- MD-88 and 90 Stringer Cracking
- 767 frames
- MD-88 and MD-90 vertical & horizontal stabilizers

No shortage of ideas for sensor usage

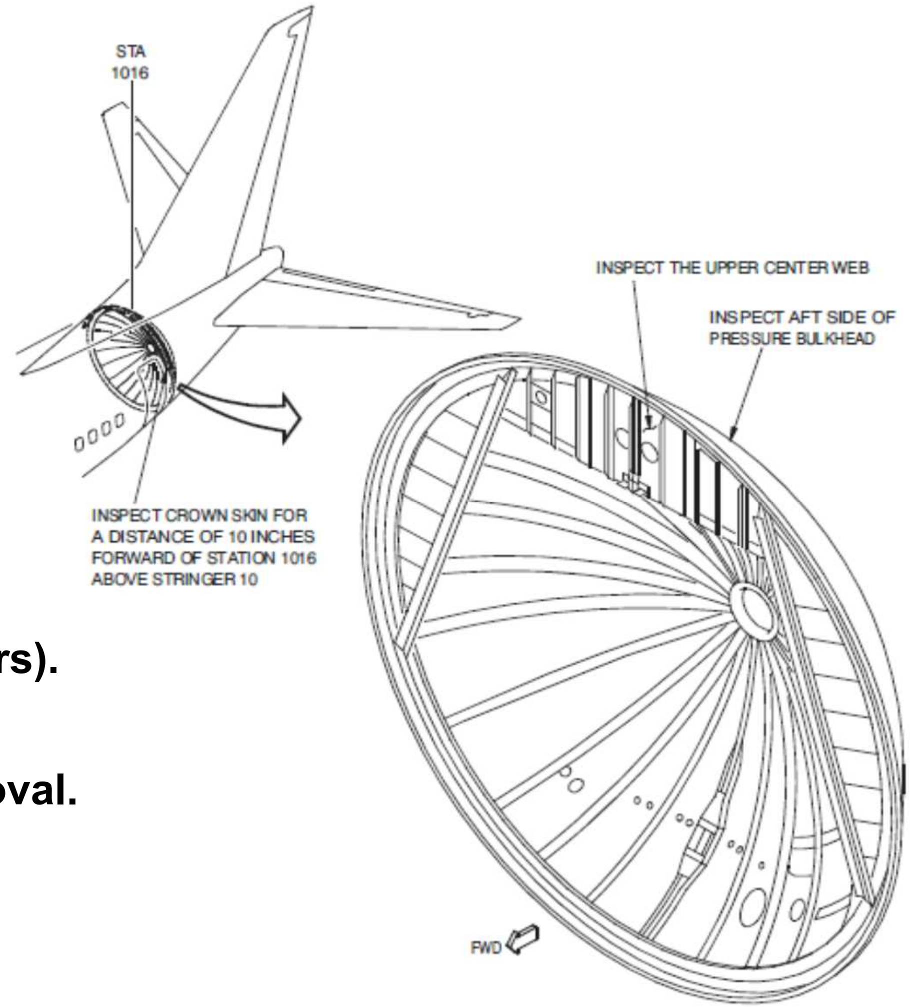
Delta SHM Application – 737NG Aft Pressure Bulkhead

SB 737-53A1238/AD 01-21-51:

- **Visual for cracking.**
- **Incorporated into AMM Ch 5 for:**
  - –Hard Landing
  - –Overweight landing
  - –Severe Turb
  - –Tail strike
- **Inspect Fwd side if aft side LFEC damage.**
  - –Galley removal = 150 mhrs/insp
- **Potential sensor on aft side (Human Factors).**

Pros:
- **Big savings, avoiding open-up/galley removal.**

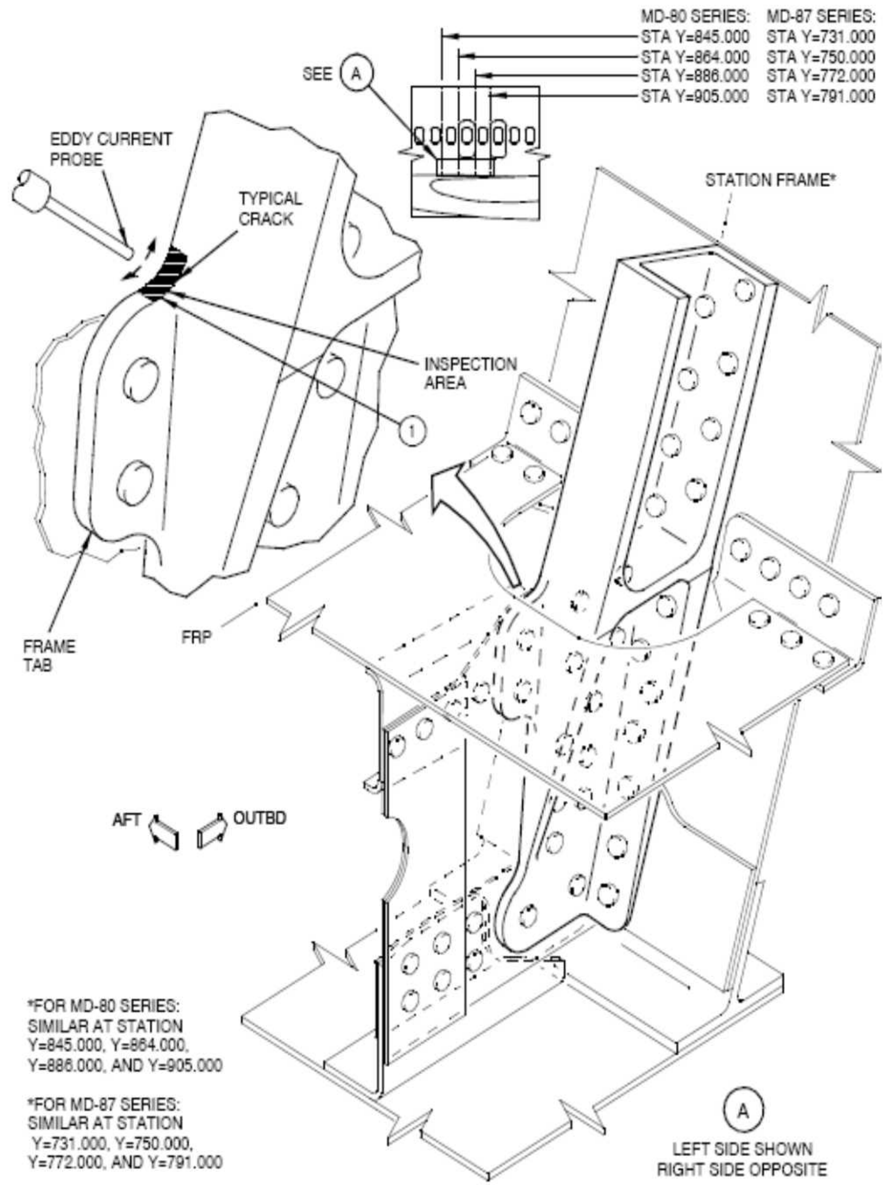
Cons:
- **Unknown Payback period (event driven).**
- **Up-front cost.**
- **AD, requires AMOC.**



Delta SHM Application – MD88/90 Overwing Frames

SB MD80-53A301:

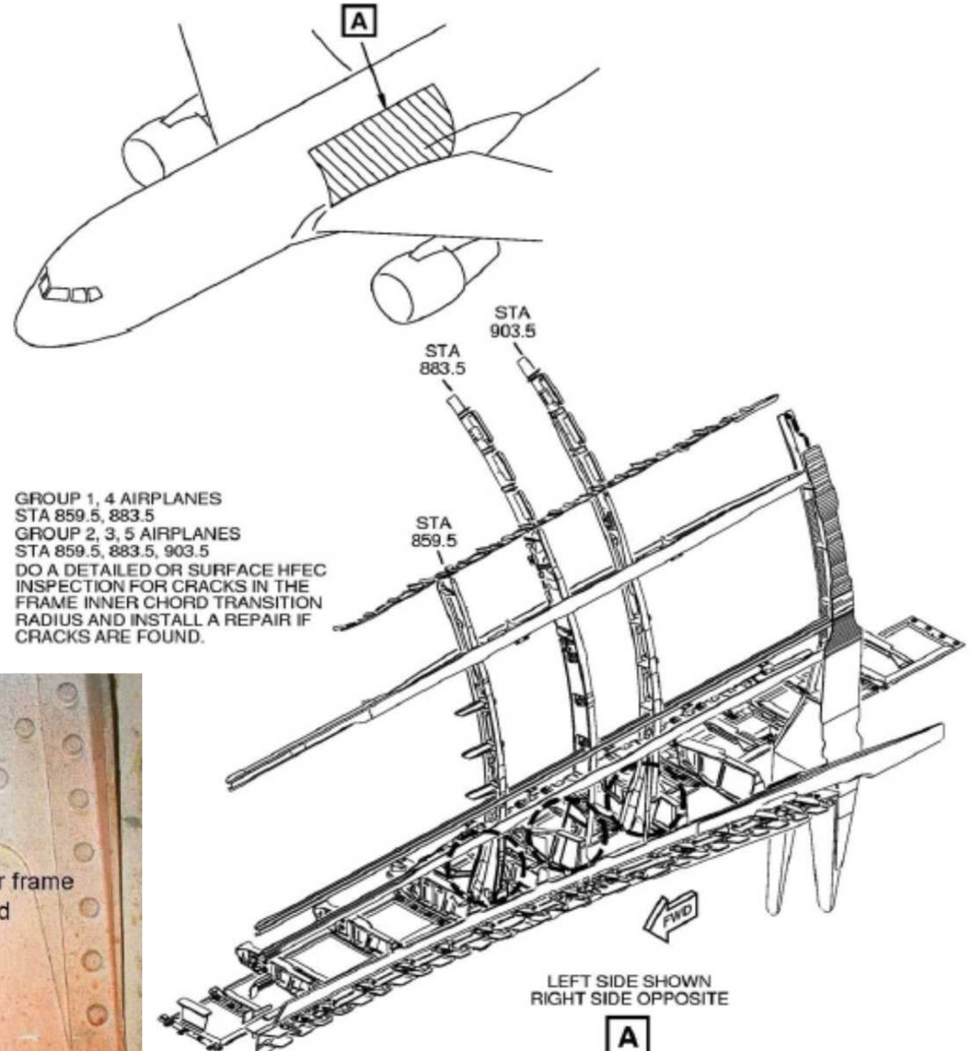
- Visual and HFEC of Overwing Frames
- Threshold: 20,000 cycles or 24 months, whichever occurs first
- Repeat inspection: 9,300 cycles (4 ½ to 5 years based on usage)
- 4 operators, 6 instances of cracking (found visually at HMV).
- Handful of findings at Delta.
- Major impact to fleet (2/3 special schedule).
- AD, requires AMOC.

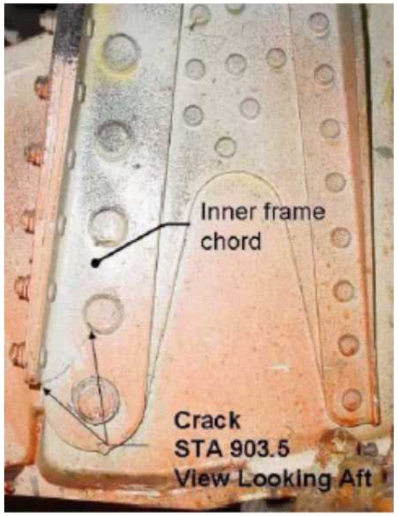


Delta SHM Application – 767 BS 903.5/883 Frame Inner Chord

SB 767-53A-0209:

- Visual and HFEC of 3 frames
- Threshold: 14,000 cycles or within 3K of SB release
- Repeat inspection: 3,000 cycles if DVI, 6,000 if HFEC
- Post repair inspection 12K cycles after installation
- 25 man-hours to accomplish inspections
- Affects AD 2003-18-10
- Required for Winglet mod
- Lots of findings at Delta





OVERVIEW

FAA Webinar Series on Structural Health Monitoring

Module 2 – SHM Validation and Approval for Routine Use

Part 1 – SHM System Requirements Drive Validation & Verification Tasks
Part 2 – SHM Performance Assessment
Part 3 – SHM Durability Assessment: Reliability & Environmental Effects
Part 4 – SHM Flight Testing: Durability & Integration into Maintenance Programs

SHM Validation Considerations

- **Declared Intent** - application is for credit (replaces task or leads to changes in the requirements for a task); criticality describes the severity of the result of an SHM application failure or malfunction
- **Usage Mode for SHM System**
  - "Hot spot" or local monitoring (S-SHM)
  - Prognostic and condition-based health monitoring (P-SHM and C-SHM) - shift to predictive and continuous monitoring will require extensive validation and successful in-service experience so that regulatory agencies and operators can acquire confidence in these SHM approaches.
- **Aircraft Maintenance Practices** – change in programs; how to adopt
- **Deployment** – operational performance & repeatability
- **Regulatory Actions and Industry Acceptance** – depends on certification process (AMOC, NDT SPM, SB/AD, STC)

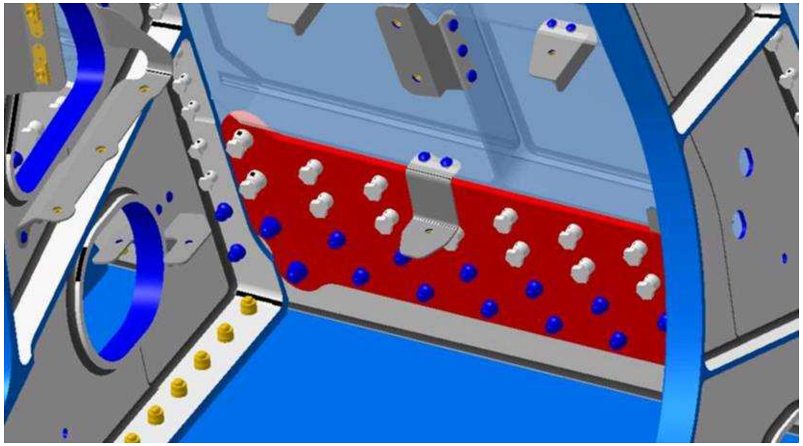
SHM Validation Considerations (cont.)

- Key element in an SHM system is a calibration of sensor responses so that damage signatures can be clearly delineated from sensor data produced by undamaged structures
- Commercial implementation of SHM needs to be proven through statistically-viable lab performance data and successful field operation data
- Data requirements need to be established for determining the applicability of SHM (boundaries) and to address certification requirements.
- Educational initiatives with key players – understanding of SHM, its usage and its limitations

SHM Validation Process Must Account for All Factors That Can Affect Performance

- **SHM Method** - SHM solution, device, sensor spacing, data acquisition process, data analysis method, data interpretation (thresholds, S/N), use of baselines
- **Structural Configuration** – geometry, material type, number of layers, fastener types and spacing, hole geometry, assembly specifics (fit/gaps), surface condition, coating changes
- **Flaw/Damage Condition** – type, X-Y location, depth, orientation, dimensions, morphology, presence of by-products
- **Environmental Conditions** – load scenario to generate damage, impact, environment to generate damage & establish durability

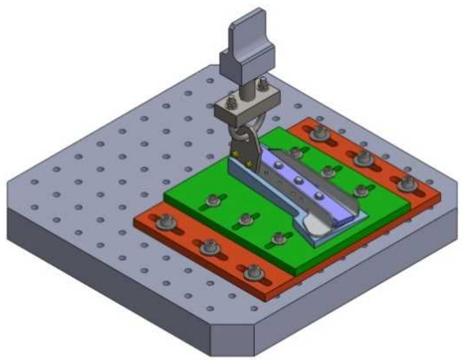
Complex Structure Requires Detailed SHM Validation

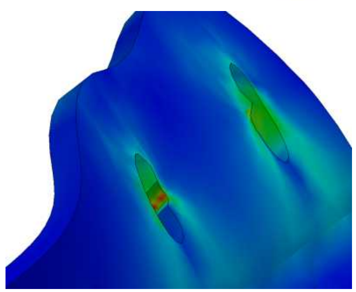


Validation of SHM Capability – Certification for Use

Laboratory Tests

- Quantify performance
- Env/durability
- POD – statistically relevant evaluation
- Reliability/repeatability





Flight Tests

- Incomplete response statistics – lack of damage
- Deployed with airlines
- Need suite of monitoring data points (how many?, access to aircraft)
- Establish ability of current tech base to properly deploy SHM
- Establish ability of maintenance program to adopt SHM – admin obstacles

Validation to Approve SHM Usage

- **Strong interest in SHM – multitude of applications**
- **Industry's main concern with implementing SHM on aircraft is achieving a positive cost-benefit & time to obtain approval for SHM usage**
- **SHM should run in parallel with current NDI inspections for a period of time**
- **SHM performance – lab & multi-year flight test programs are needed**
- **SHM training and education - workshops**
- **AMOC & new SBs– safety driven use is achieved in concert with OEMS & regulatory agencies**
- **Approval through regulatory framework is the final formality to be addressed - standardization and guidelines are needed for certification and field validation**

Validation of a Structural Health Monitoring (SHM) Systems and Integration Into Airline Maintenance Programs