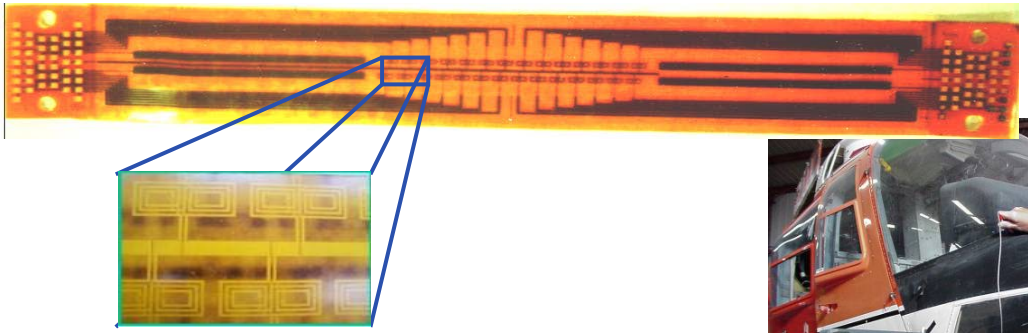
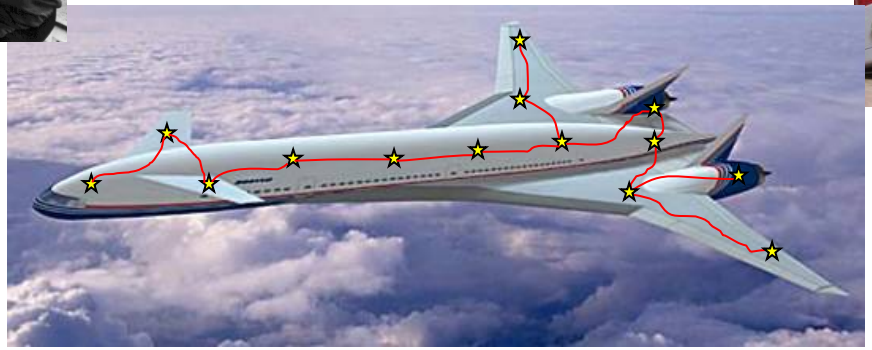
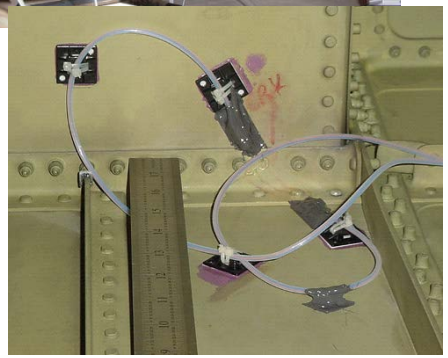
Validation of a Structural Health Monitoring (SHM) System and Integration Into an Airline Maintenance Program (Part 1)







Dennis Roach
Tom Rice
Stephen Neidigk
Sandia National Labs
FAA Airworthiness Assurance Center

David Piotrowski
John Bohler
Alex Melton
Delta TechOps

John Linn
Boeing

Paul Swindell
FAA

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Structural Health Monitoring – Integration into Routine Maintenance

Sandia National Laboratories

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Stephen Neidigk

Paul Swindell
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DELTA TechOps

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John Bohler, Joe Reeves
Chris Coleman, John Hays

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STRUCTURAL MONITORING SYSTEMS

Toby Chandler
Andy Chilcott

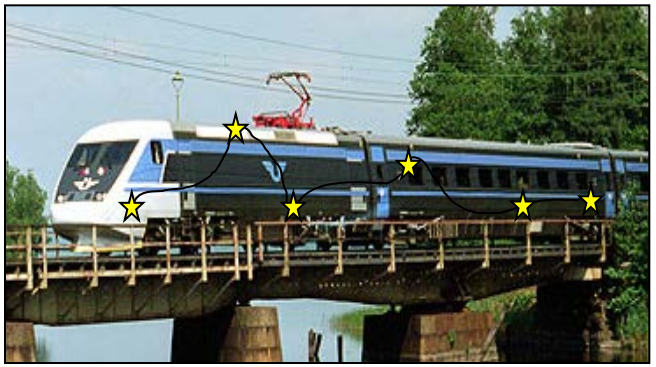
AEM ANODYNE ELECTRONICS MANUFACTURING CORP.

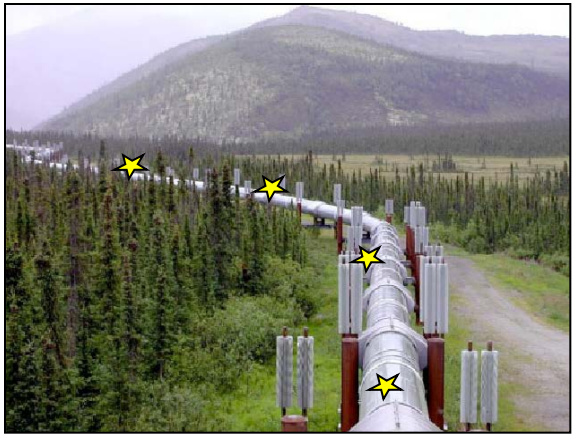
Trevor Lynch-Staunton
Henry Kroker, Brian Shiagec,
Dave Veitch

Distributed Sensor Networks for Structural Health Monitoring

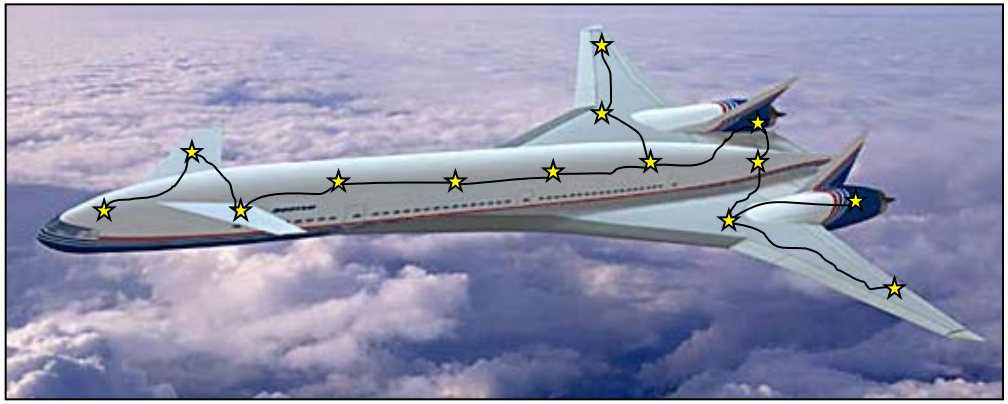
Smart Structures: include in-situ distributed sensors for real- time health monitoring; ensure integrity with minimal need for human intervention

- **Remotely monitored sensors allow for condition-based maintenance**





- **Automatically process data, assess structural condition, & signal need for maintenance actions**



NDI vs. SHM – Definition

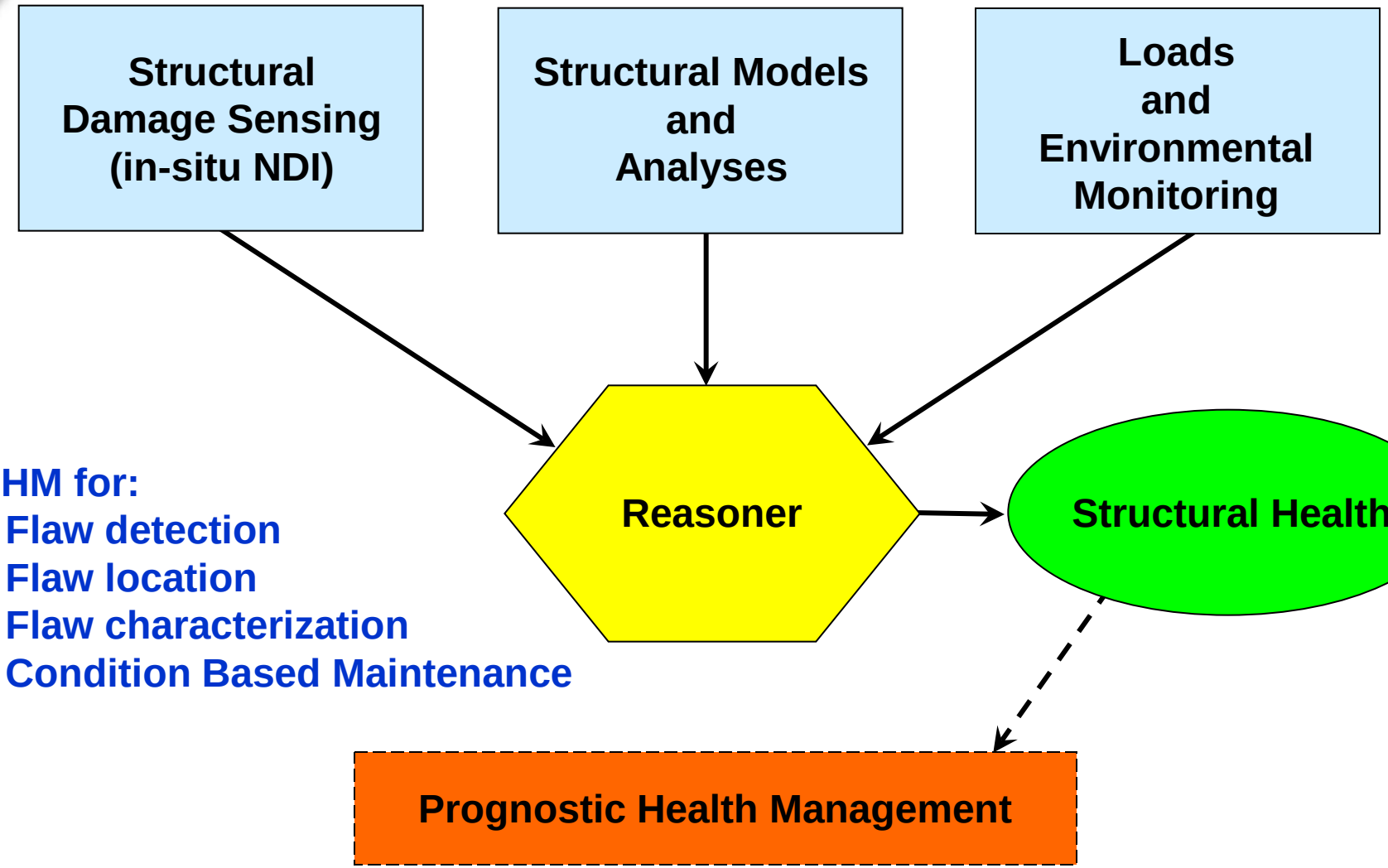
Nondestructive Ins **a material to determine geometry, g technology that does not affect its fu**

- **High degree o**
- **Local, focused**
- **Requires acce select intervals)**

Structural Health M **ctures;" use of NDI principles coupl r rapid, remote, and real-time conditi goal is to reduce operational costs an tructures**

- **Greater vigil needs**
- **Overcome a geometries, depth of hidden da**
- **Eliminate co ssembly**
- **Minimize hu analysis**
- **Reduce mai**
- **Early flaw detection = enhanced safety & less costly repairs**
- **Condition-based maintenance practices**

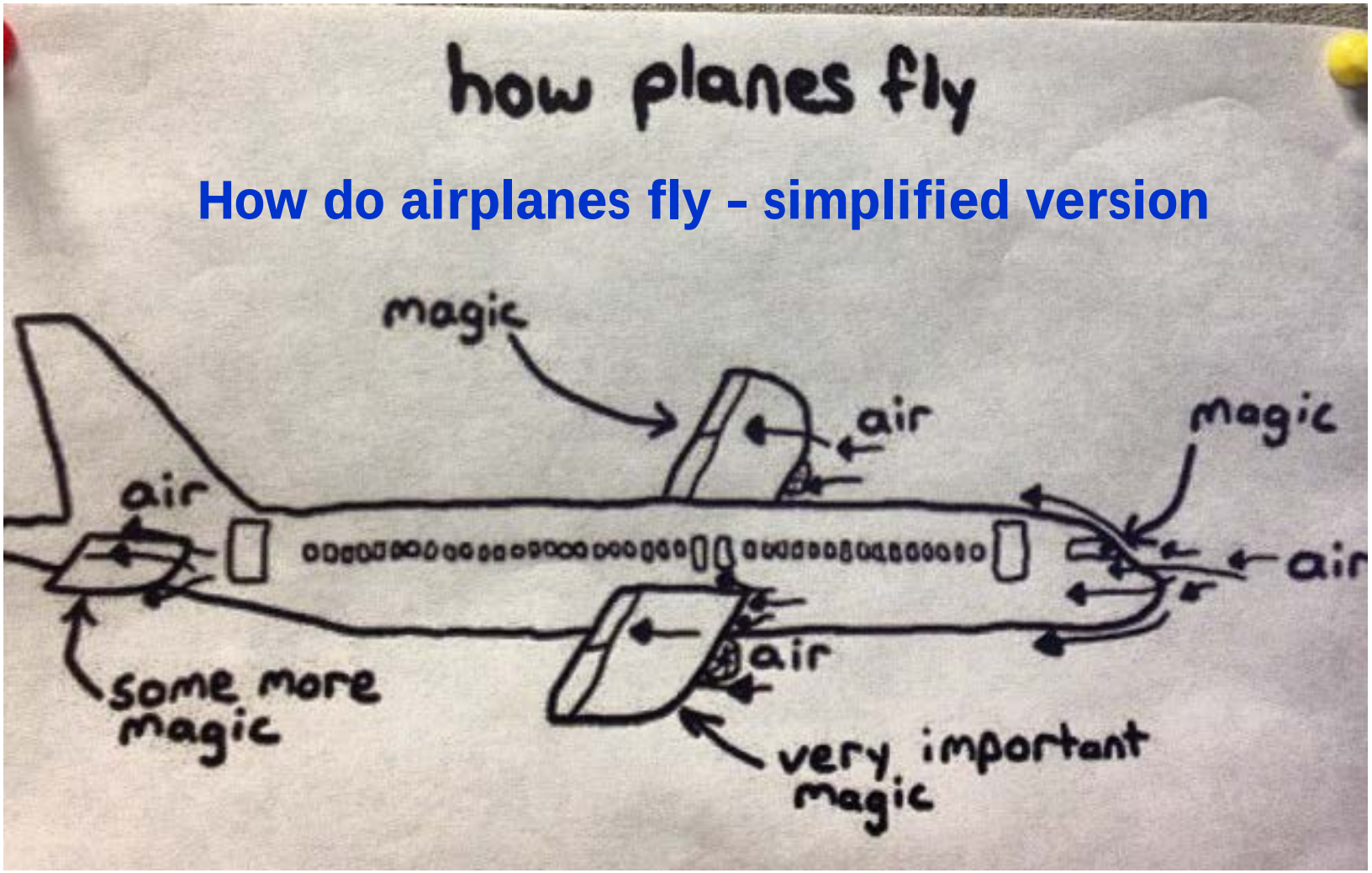
Structural Health Monitoring



SHM for:

- Flaw detection
- Flaw location
- Flaw characterization
- Condition Based Maintenance

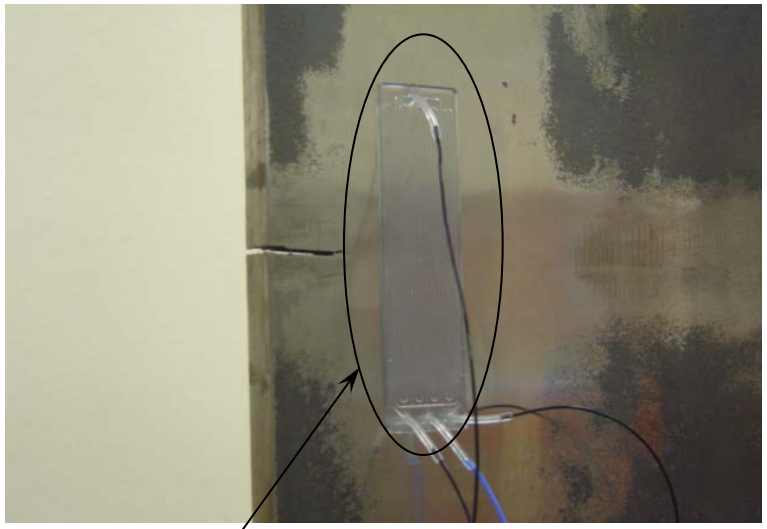
SHM Integration Timeline – Performance & Safety Assessment and Approval Process



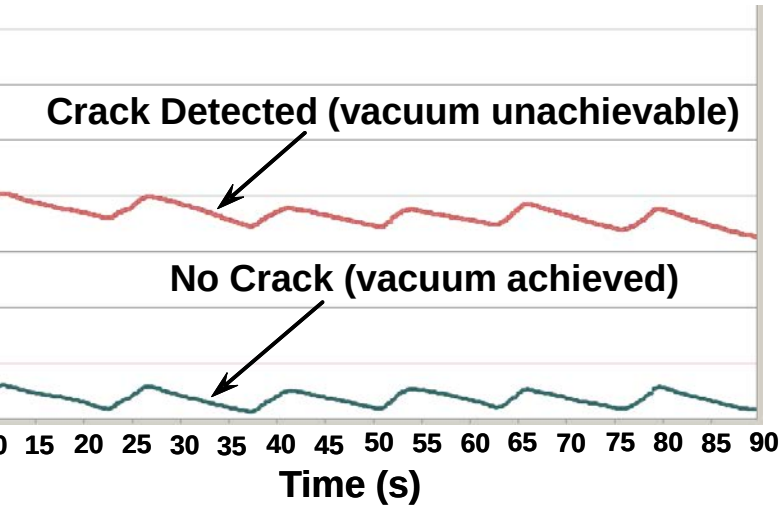
How do airplanes fly - simplified version

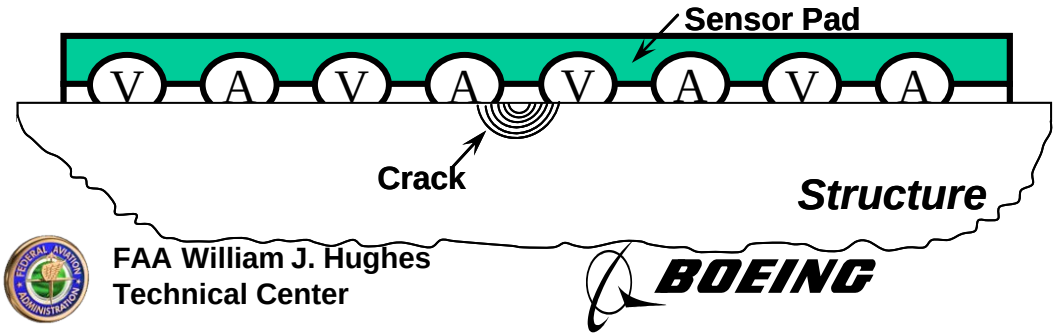
Comparative Vacuum Monitoring System

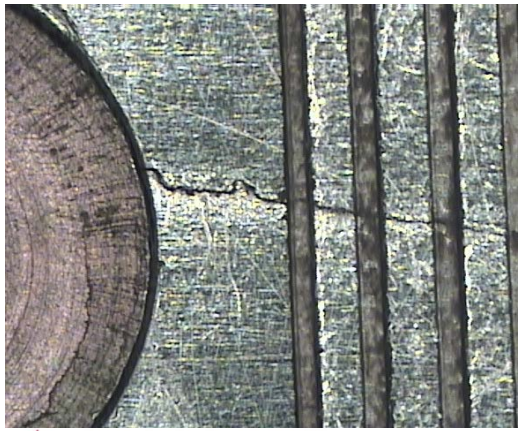
- Sensors contain fine channels - vacuum is applied to embedded galleries **(crack detection < 0.1” for alum. < 0.1” th.)**
- Leakage path produces a measurable change in the vacuum level
- Doesn’t require electrical excitation or couplant/contact



CVM Sensor Adjacent to Crack Initiation Site







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In-Situ Health Monitoring for Aircraft Using Comparative Vacuum Monitoring Sensors

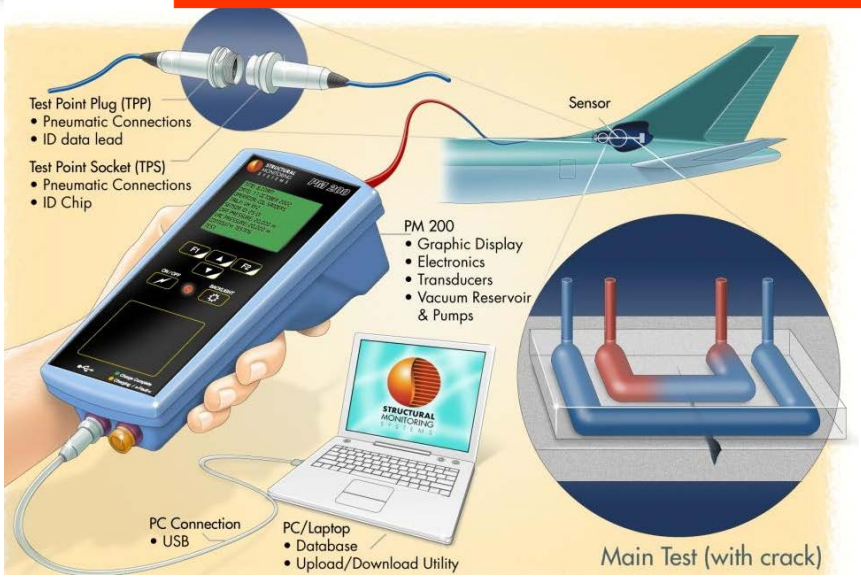
Laboratory and Field Evaluation Program for Modification of Boeing NDT Standard Practices Manuals

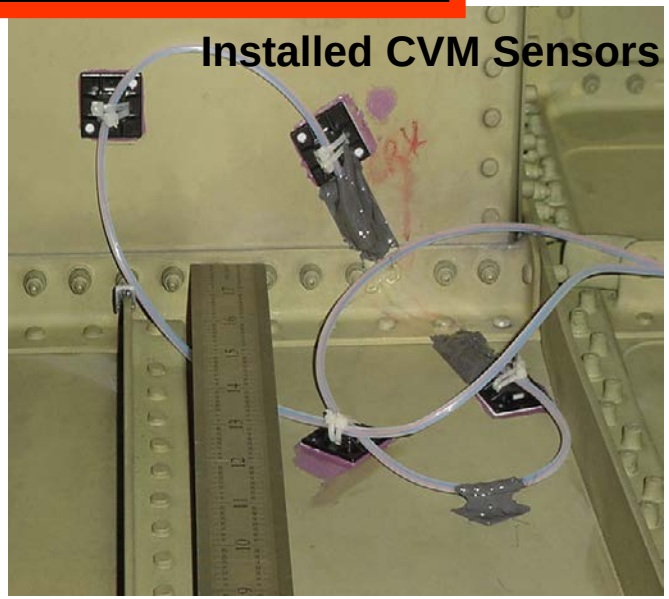
Drivers for Application of CVM Technology

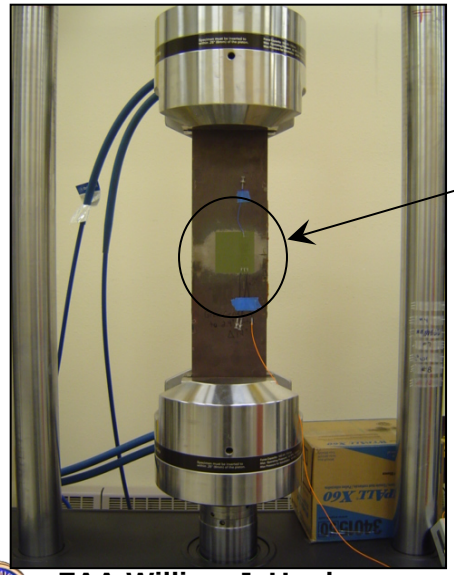
- Overcome accessibility problems; sealed parts
- Improve crack detection
- Real-time information or more frequent, remote interrogation
- Initial focus – identified problem areas (hot spot monitoring)
- Long term possibilities – distributed systems; remotely monitored sensors allow for condition-based maintenance

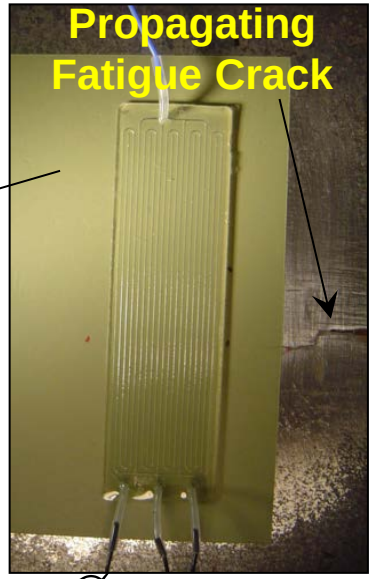
Team: Jeff Kollgaard, John Linn – Boeing, Seattle; Masood Zaidi – Boeing, Long Beach; Dennis Roach, Floyd Spencer – Sandia Labs FAA AANC; John Bohler, Dave Piotrowski, Alex Melton – Delta Air Lines; Dave Galella – FAA; Kyle Colavito, Erdrogan Madenci – Univ. of Arizona

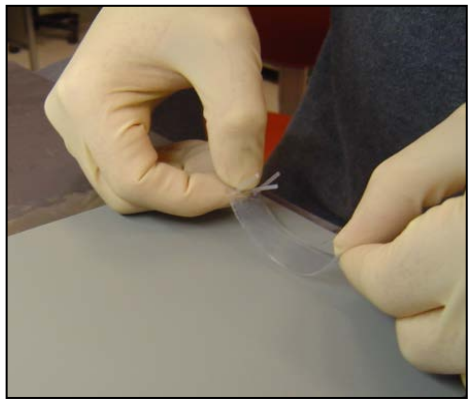
Crack Detection Via CVM System and Test Installation of Sensors











CVM Sensor Installation & Crack Growth Monitoring

For 0.040” th. Skins

90% POD Level	False Calls
0.021"	0

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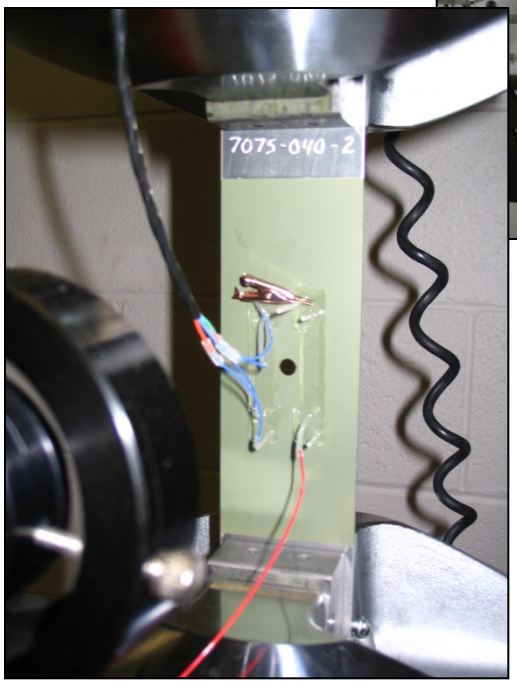
Test Matrix to Quantify Probability of Crack Detection

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



CVM Validation - Crack Detection Results (cont.)

All POD levels listed are for 95% confidence

Description: 0.100 inch thick panel (primer surface)

2024-T3 Alum.

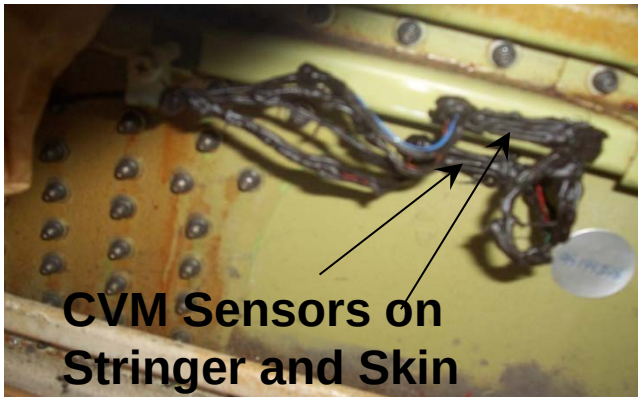
PHASE 2 TESTS						
Panel	**Fastener Crack Site**	**Distance from Fastener (inches)**	**Crack Length at CVM Detection (growth after install in inches)**	**SIM-8 Reading ΔPa (Pasm)**	**PM-4 Read-out**	**PM-4 Indicate Crack (Y or N)**
1001	5L	0.350	0.065	773-825	1713	Y
1001	7R	0.206	0.054	697-722	1768	Y
1001	8R	0.115	0.060	560-600	1609	Y
1003	8L	0.044	0.068	297-320	1410	Y
1003	7L	0.086	0.058	342-386	1411	Y
1003	8L	0.187	0.069	~1800	3391	Y
1003	6L	0.061	0.065	476-500	1846	Y
1003	6L	0.131	0.076	800-946	2117	Y
1003	8R	0.160	0.045	380-420	1508	Y

90% POD Level	**False Calls**
0.090"	0

[all panels are 2024-T3 alum. (AMS-4040, 41, QQ-A-250/5) with 0.0005" th. clad]

Field Evaluation of CVM Sensor Applications – Decal Mode

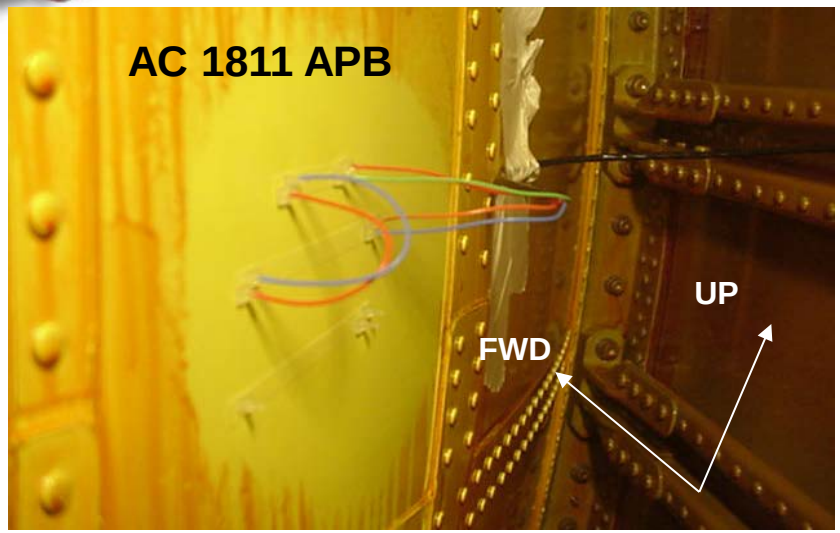
Environmental Durability Testing - To assess the long-term viability of CVM sensors in an actual operating environment, 22 sensors were installed on DC-9, 757 & 767 aircraft for functional evaluation:

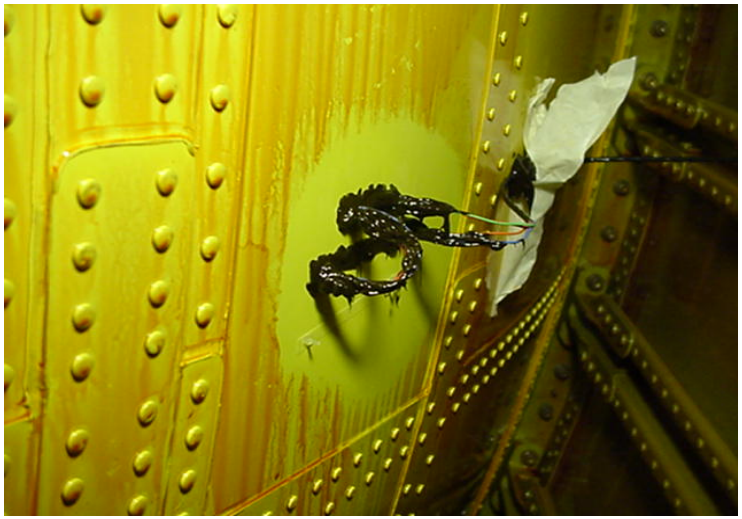


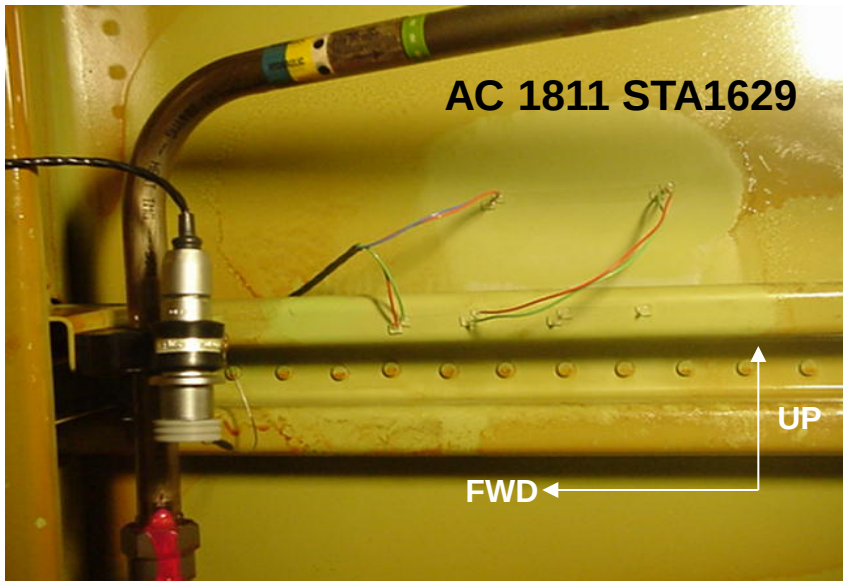
SLS connector routed to access panel

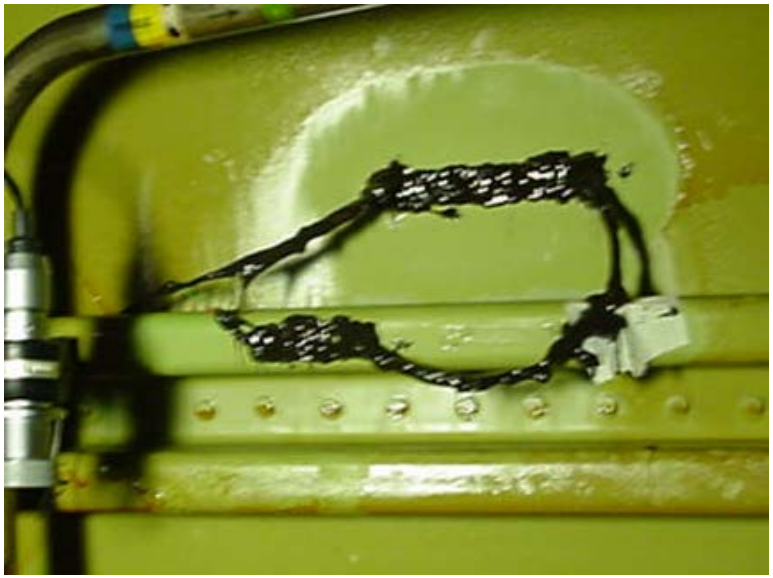
Monitoring CVM

Delta Air Lines Field Installations

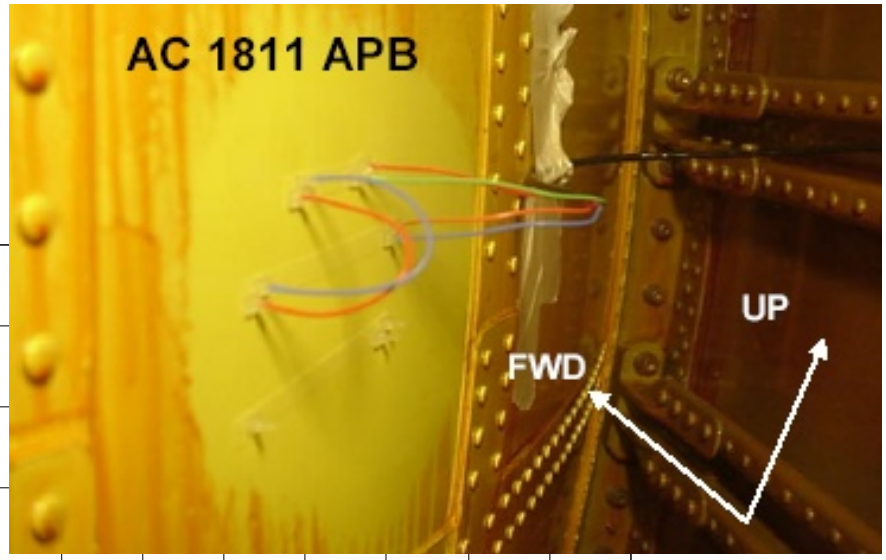






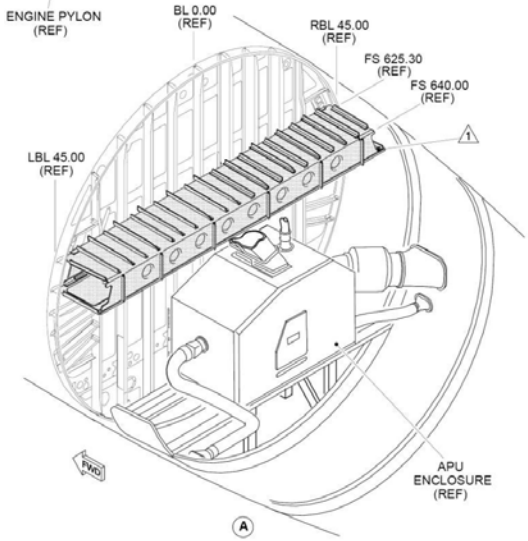


Delta - 767
Aft Pressure Bulkhead - Unpressurised (AC1181)

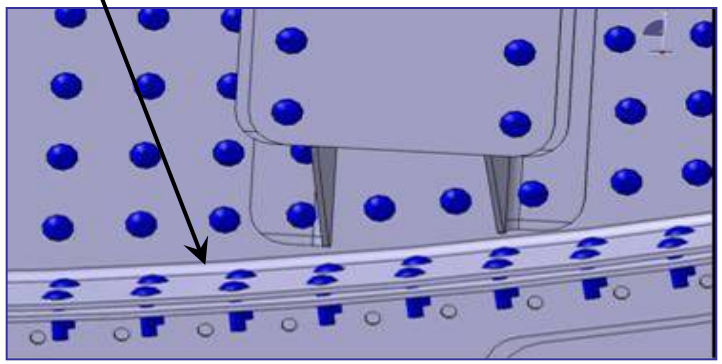


CVM Success on CRJ Aircraft

Pilot program with Bombardier and Air Canada



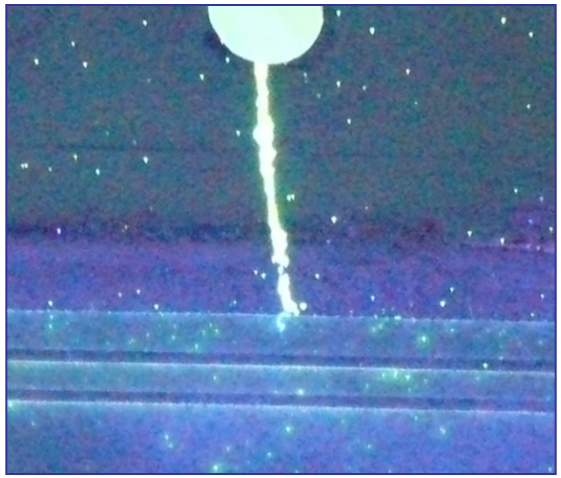
Inspect in the radius



Sensor Issues:

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

Aft Equipment Bay

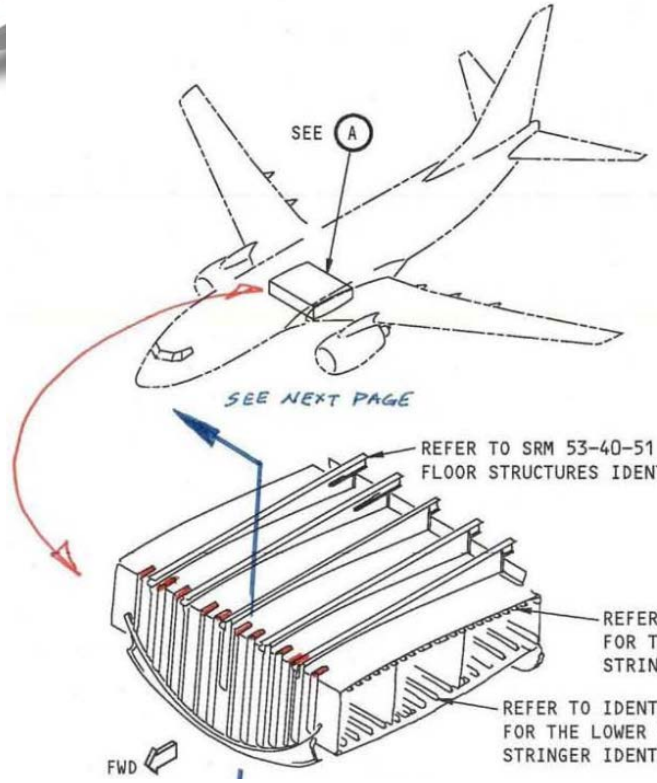


SHM Certification & Integration Activity

Delta-OEM-FAA-AANC joint effort to leverage airline activities

- **Certification/usage effort intended to investigate, exercise and evolve the SHM certification path – address all "cradle-to-grave" issues for airlines, OEMs, and regulators**
- **Identify SHM applications – assess positive cost-benefit analysis**
- **Customize SHM system to the selected application(s)**
- **Develop validation/certification plan – utilize precedents from existing sensors**
- **Complete SHM indoctrination and training for Delta personnel (engineering, maintenance, NDI) and FAA as needed**
- **Hardware specifications, installation procedures, operation processes, continued airworthiness instructions**
- **Complete modifications to Delta maintenance program as a result of SHM use**
- **Assess aircraft maintenance depots' ability to adopt SHM and the FAA support needed to ensure airworthiness**

737NG Center Wing Box, Front Spar Shear Fitting



Boeing 737 SB:

- **Cracking between 21K-36K cycles**
- **Visual/eddy current inspection for crack detection**

FRONT SPAR AND WING CENTER SECTION

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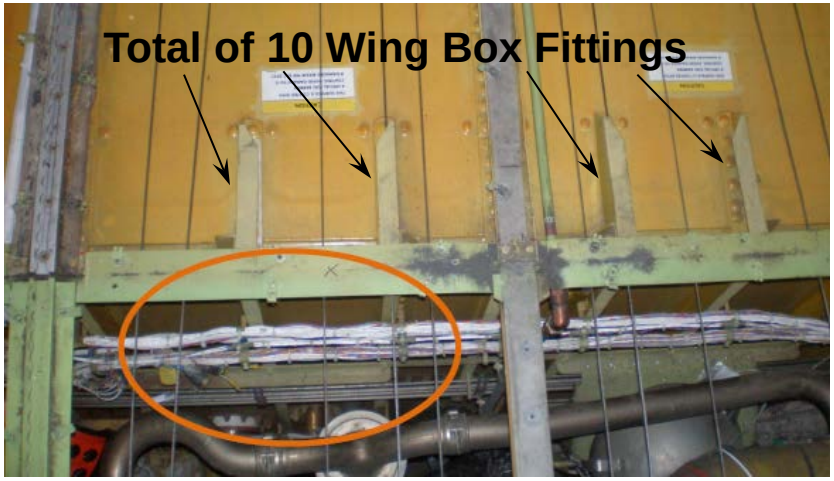
737NG Center Wing Box – CVM Installation & Operation Workshop

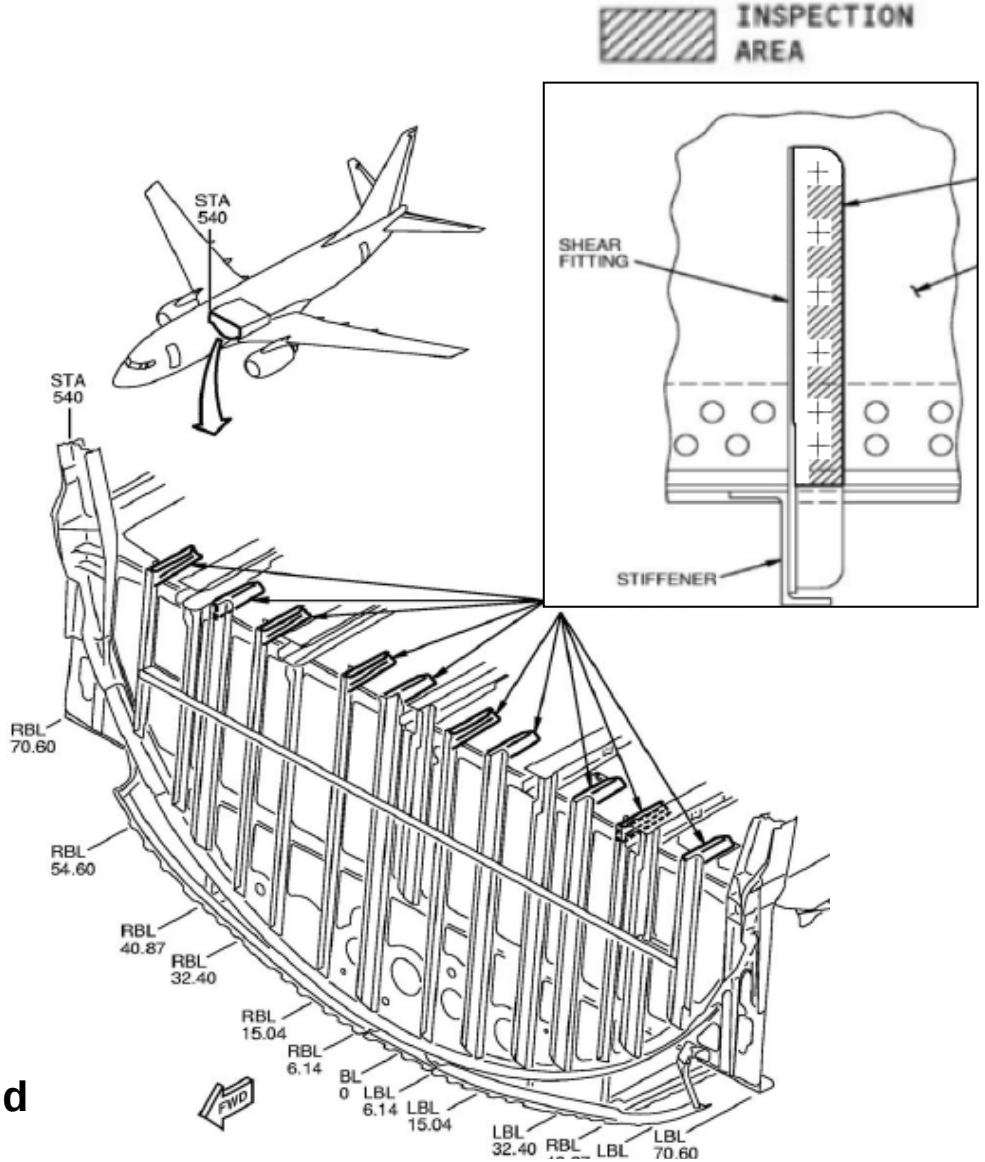
- Workshop conducted in anticipation of on-aircraft flight test program
- Attendees included: Boeing, Delta Air Lines, AAR MRO, SMS, AEM, Sandia Labs
- Details on sensor placement, sensor lead routing, tie-downs and logistics (e.g. kits) were determined
- Facilitate Action Authorization (generation of job/task cards) & Delta incorporation of CVM installation and operation documents into maintenance program

737NG Center Wing Box – CVM Flight Tests

- Acquire successful flight history – 7 aircraft, 70 sensors, 7 weeks
- Step through formal process of integrating SHM into airline maintenance program (e.g. management education/approvals, Job Cards, training)
- Develop guidelines for safely adopting SHM solutions

737NG Center Wing Box – CVM Flight Tests





CVM Sensor on 737NG Wing Box Fitting and Top View of SLS Mount Location

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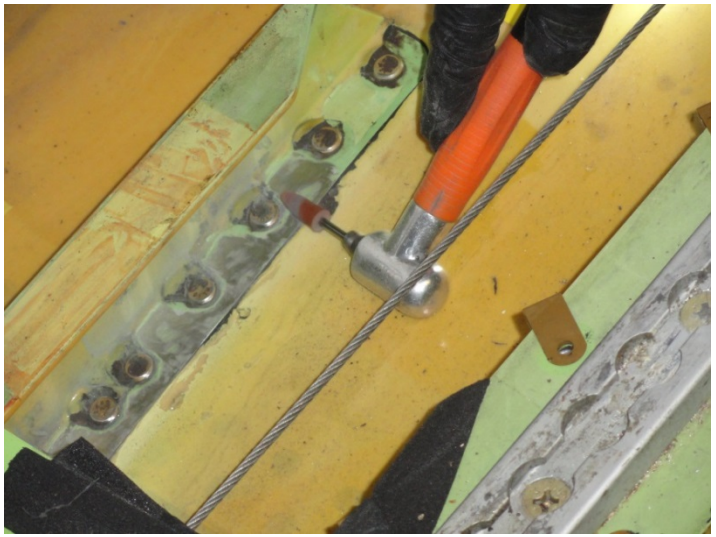
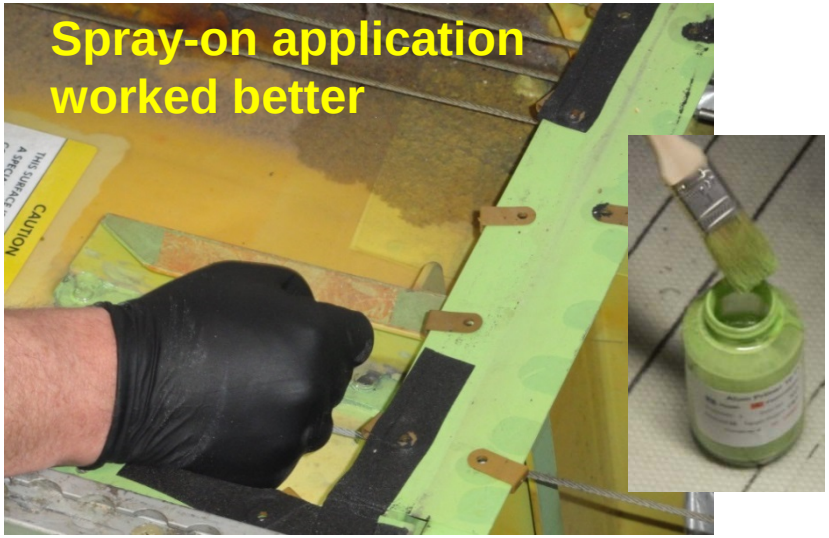
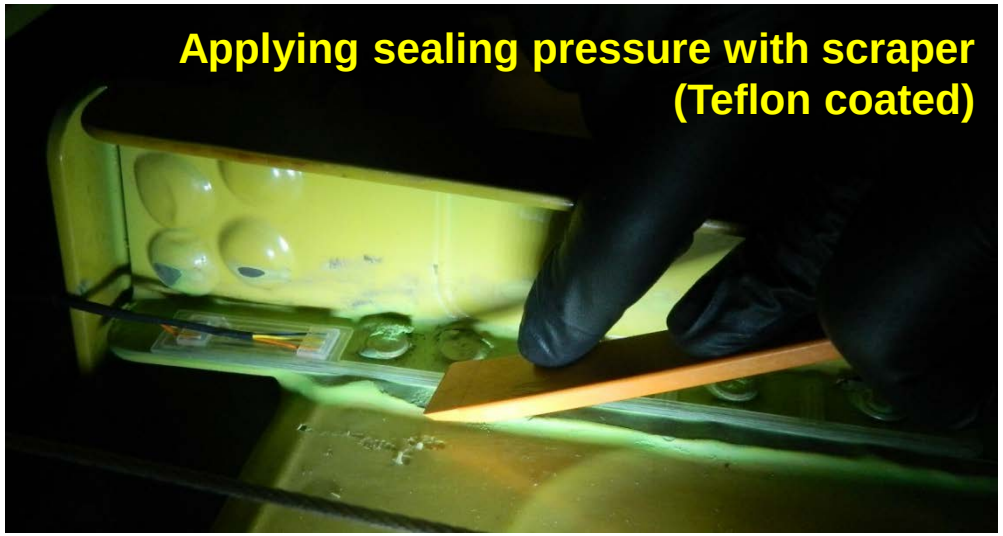
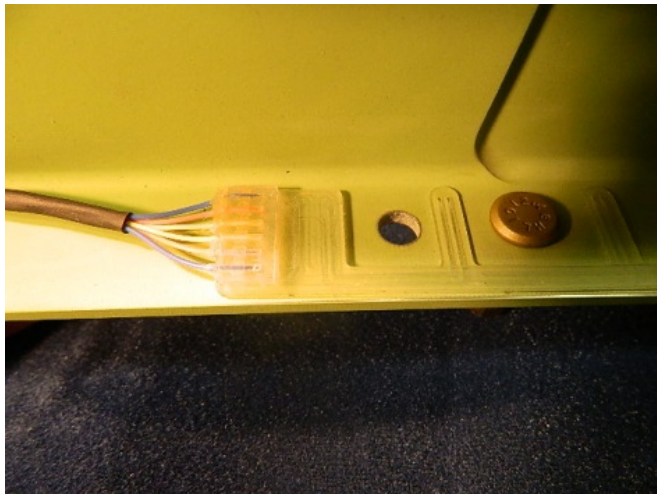
1) Remove rivet head sealant , fuel vapor barrier and primer 2) Inspect for cracks with HFEC, 3) Re-prime surface



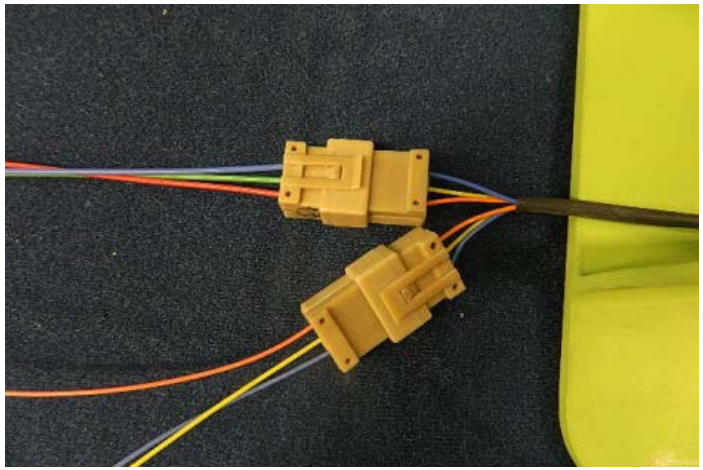


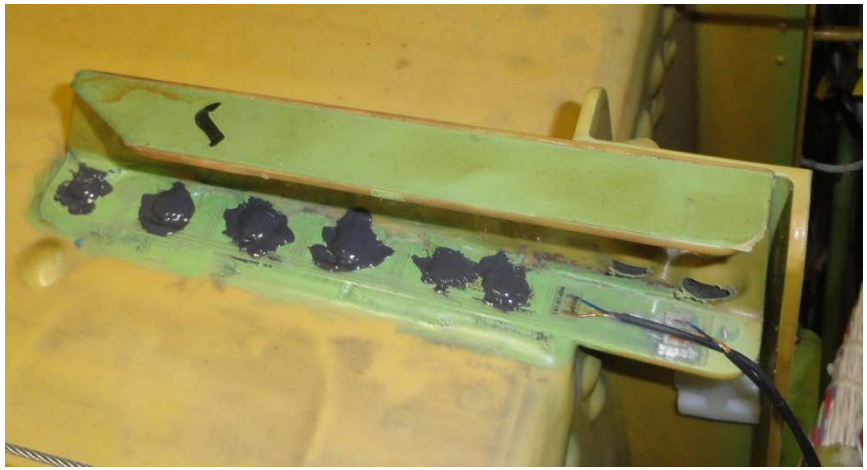
4) CVM surface prep (sandpaper, acetone & deionized water), 5) CVM sensor placement on wing box fittings

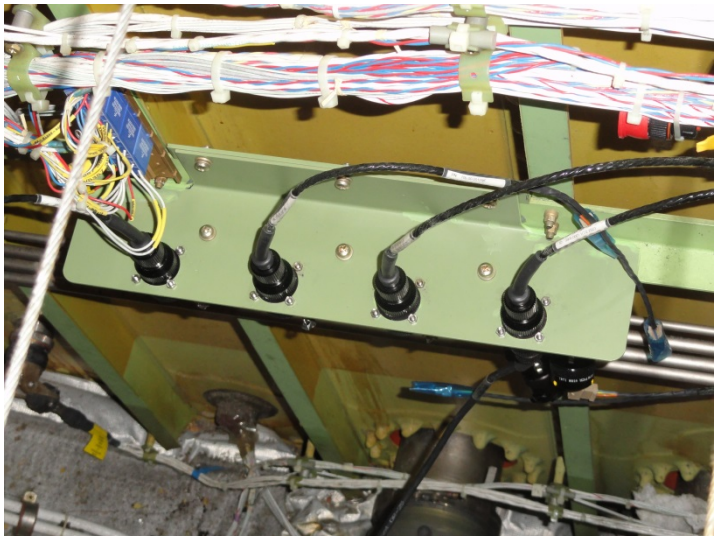




6) Seal CVM to surface & daisy-chain with Snap-Clicks, 7) Reapplication of rivet head sealant and fuel vapor barrier, 8) Installation of SLS connector set



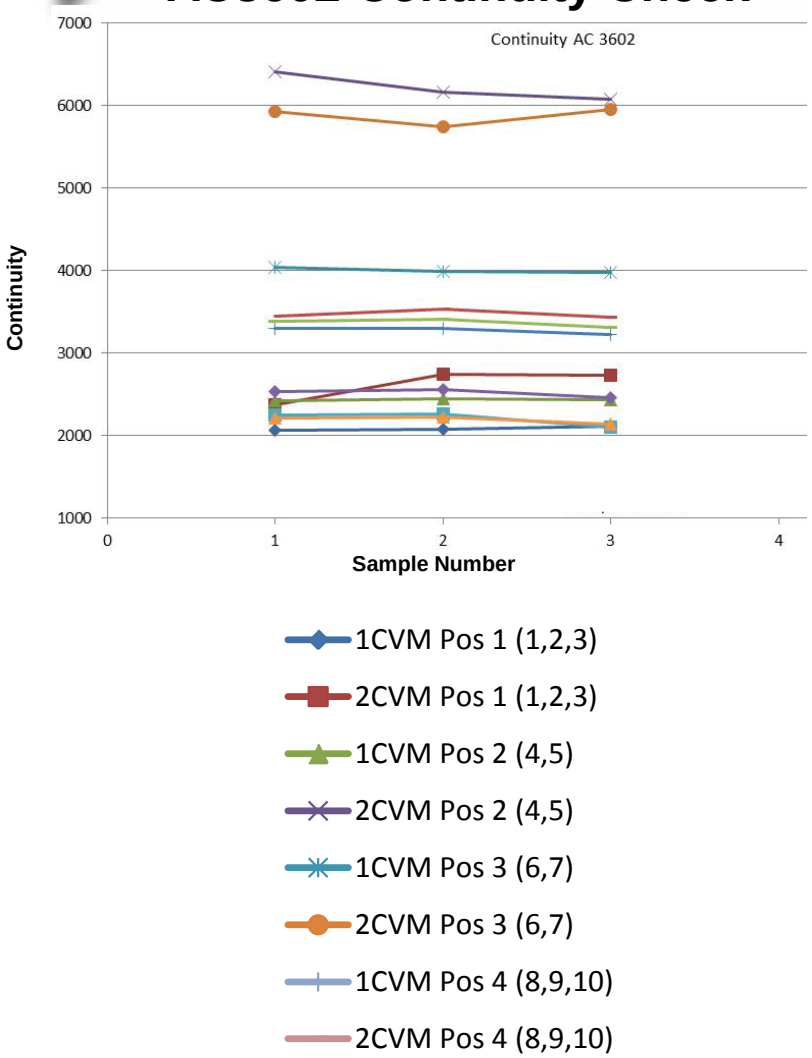




9) Connection of multiple CVM sensors to individual SLS connectors and 10) Monitoring CVM with PM-200 device

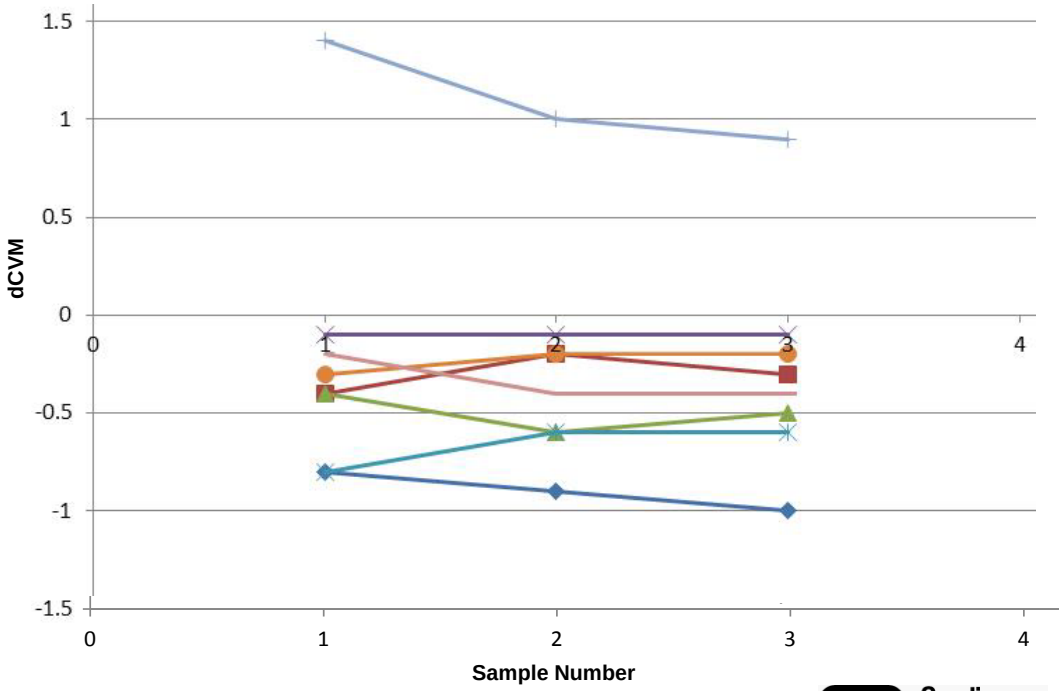
Sample CVM Flight Test Data

AC3602 Continuity Check

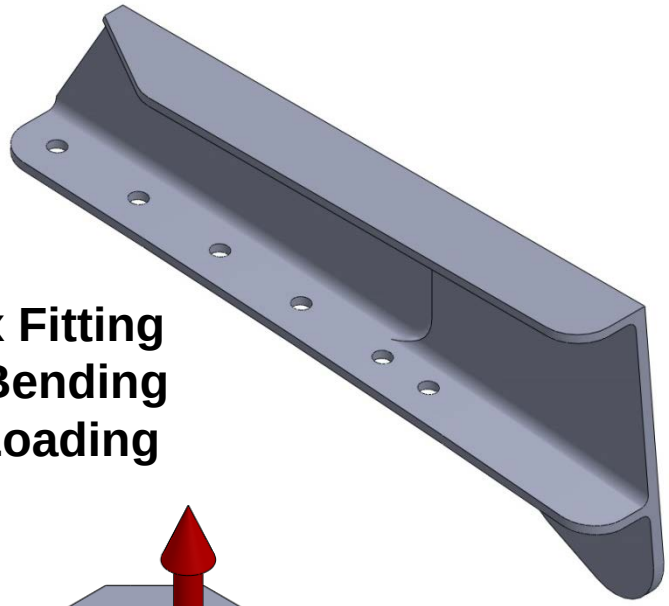


- Fail-safe check – want continuity (flow) high
- Crack detection – dCVM (vacuum) low = no crack
- Conductivity Index = flow

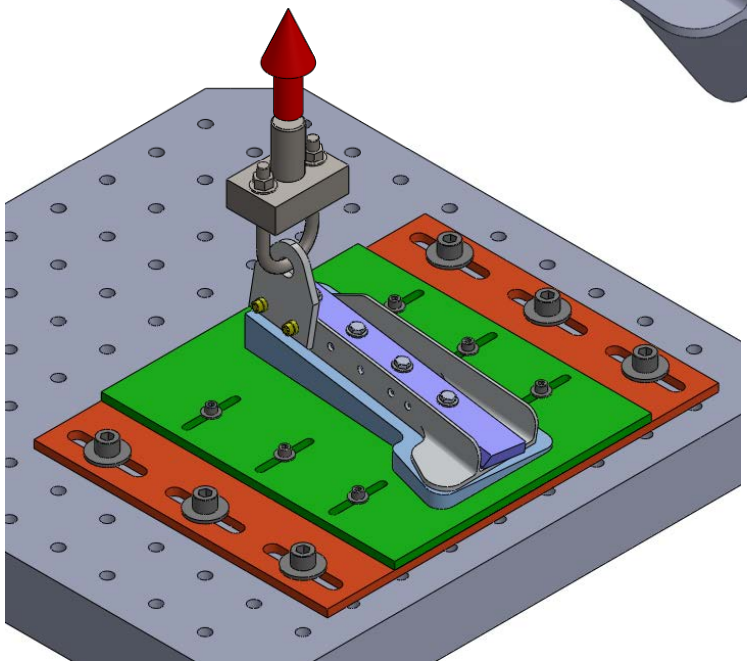
AC3602 CVM Readings

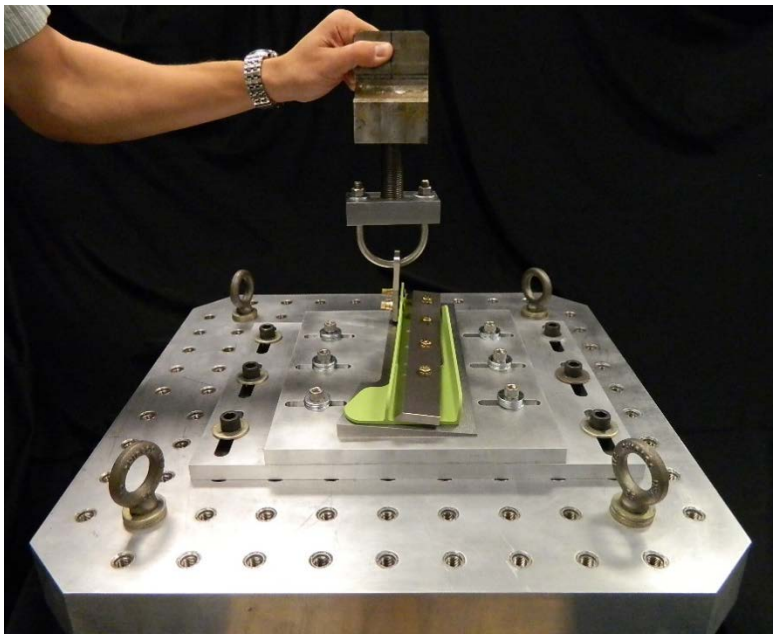


737NG Center Wing Box – CVM PerformanceTests



Wing Box Fitting
Tension-Bending
Fatigue Loading

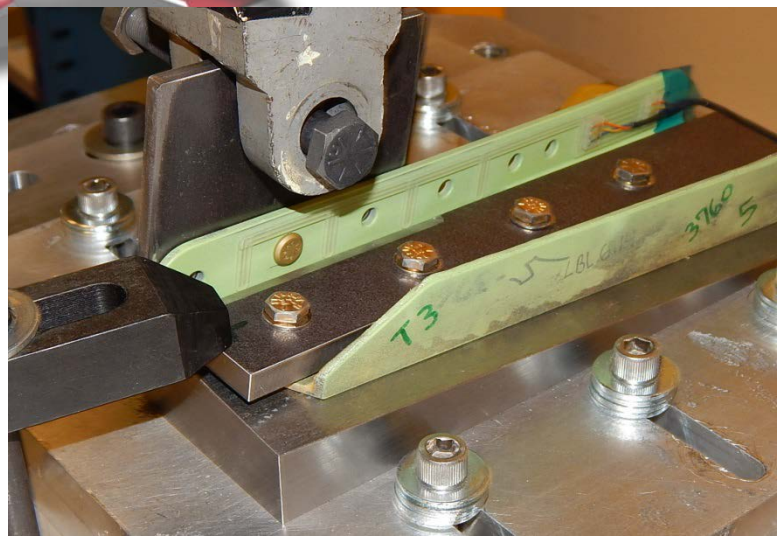




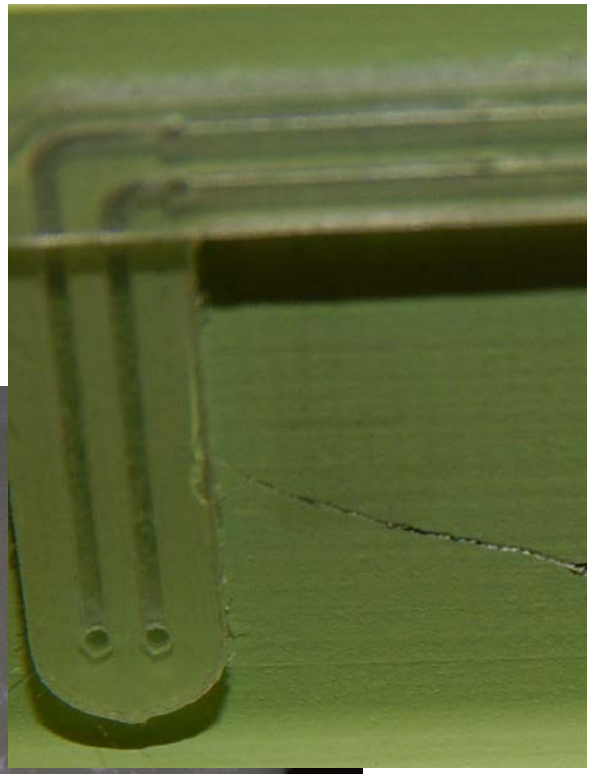
737NG Center Wing Box – CVM PerformanceTests

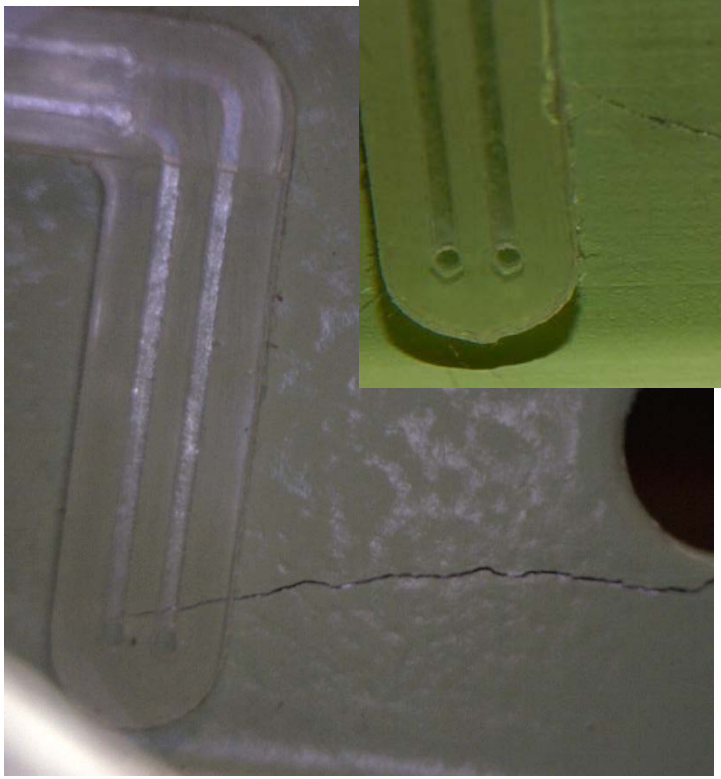
Sim-8 for real-time monitoring and PM-200 for final confirmation of CVM crack detection

737NG Center Wing Box – CVM PerformanceTests



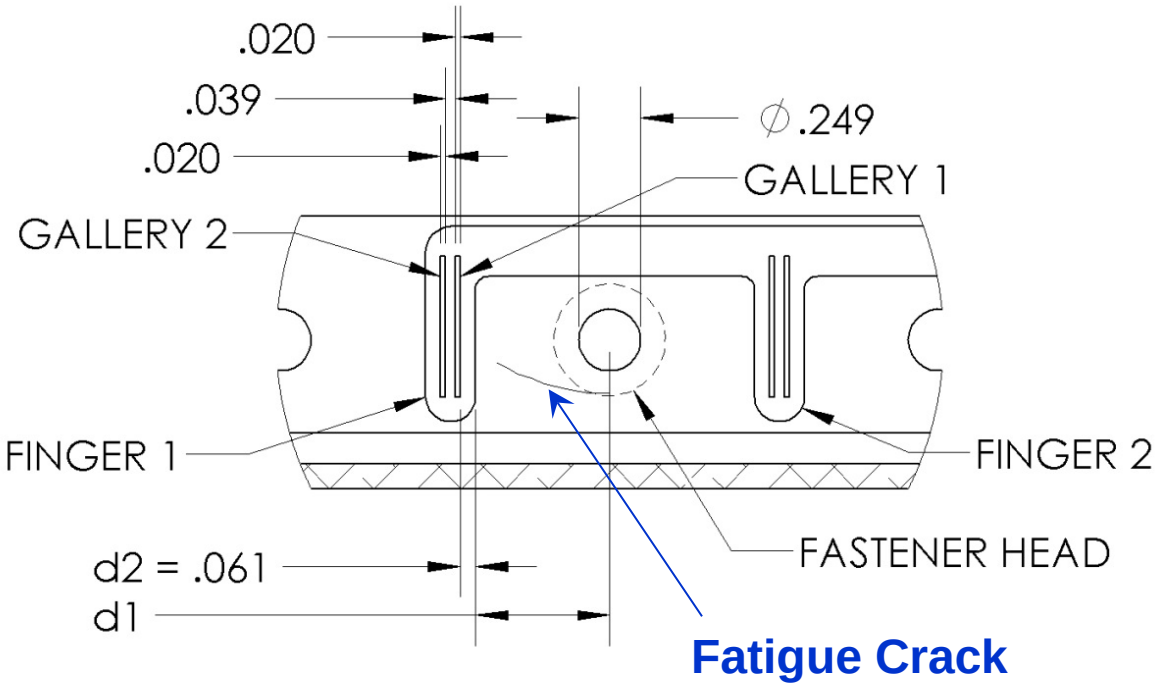
Fatigue crack intercepting dual gallery arrangement





737NG Center Wing Box – CVM PerformanceTests

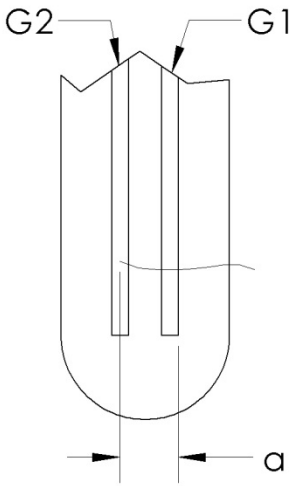
- Bending crack has increased closure loads
- Monitoring for permanent crack detection – unloaded, unfastened and multiple day lag in readings
- Sealant (FVB) applied to determine crack detection when entire surface is sealed
- POD $_{[90/95]}$ for 1st & 2nd gallery; S/N > 10



Fatigue Loaded Crack Engaging CVM Gallery.wmv

737NG Center Wing Box – CVM PerformanceTests

CVM Sensor Wing Box Fitting Performance Tests					
Test No.	CVM Finger Location	Sensor Distance from Fastener d_1 (In)	Crack Length at CVM Detection a (In)	SIM-8 Reading (Pa)	PM200 Reading (dCVM)
T1	2	0.488	0.084	282	7.4
T2	1	0.524	0.109	496	35.5
T3	1	0.550	0.089	2017	157.5
T4	1	0.570	0.094	330	14.4
T5	1	0.574	0.084	285	8.9
T6	1	0.580	0.079	2901	264.8
T7	2	0.546	0.124	318	22.5
* Final values being confirmed					
** Detection for unloaded state with sealed crack and sensor					



Crack Length: a = excursion into CVM galleries

Validation of CVM Sensors for SHM Crack Detection

- CVM sensor detects cracks in the component it is adhered to
- Inspection process and diagnosis is fully automated – remote
- Early detection = less costly repairs
- CVM system is fail-safe (inert sensors produce an alarm)
- General lab performance & multi-year flight test program completed – specific ones (application) are underway
- Integration of CVM in NDT Standard Practices Manuals
- Actual application on commuter (CRJ) aircraft successful; additional applications being pursued
- AMOC for SBs and ADs – safety driven use is achieved in concert with OEMS & regulatory agencies
- Certification & regulatory framework is being addressed

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