FAA Structural Health Monitoring Research Program: In-House Chemical Mill Line Testing

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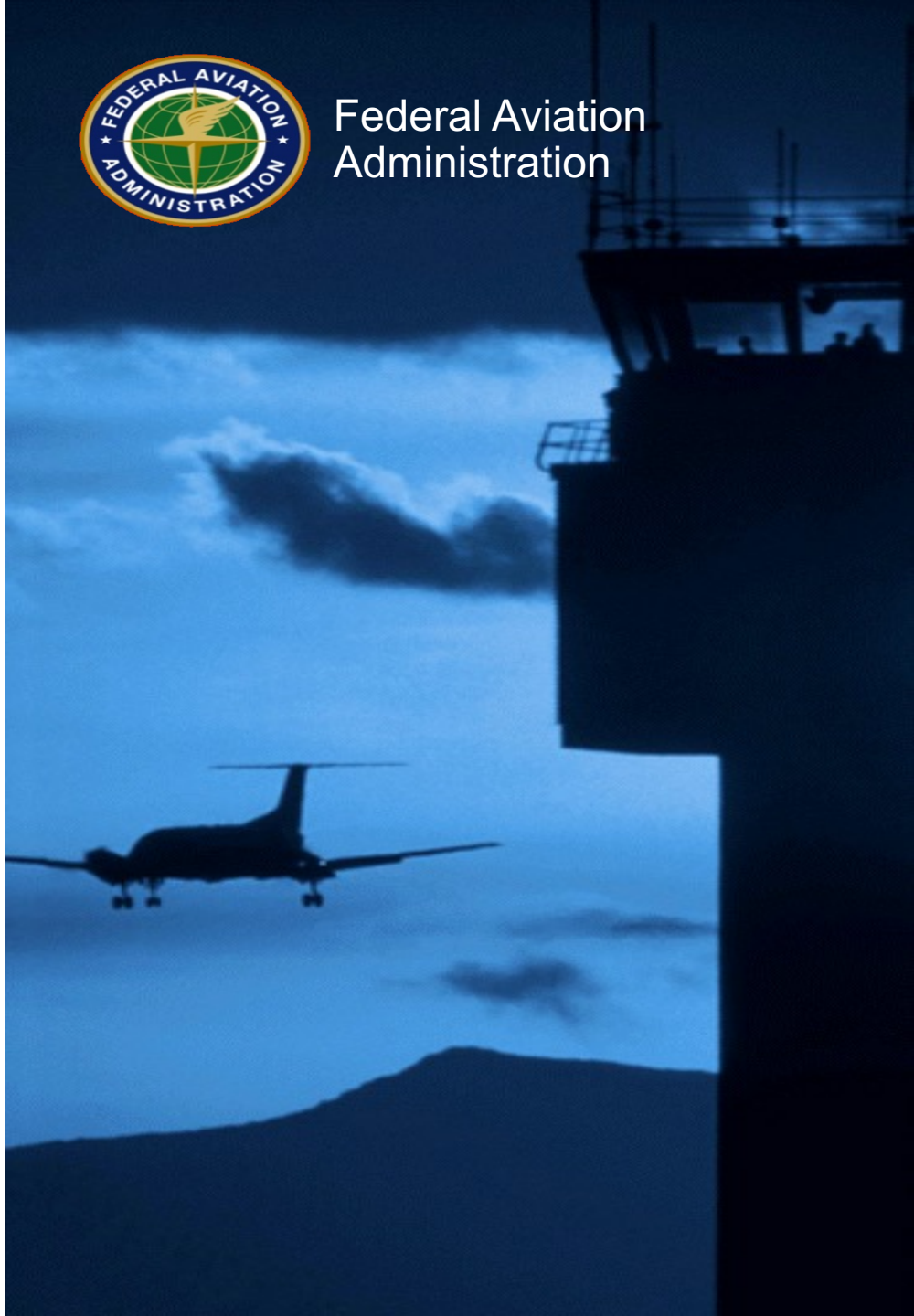
Danielle Stephens, FAA
danielle.stephens@faa.gov

Structures and Materials Section, ANG-E281
FAA William J. Hughes Technical Center
Atlantic City Int'l Airport, NJ 08405

Federal Aviation Administration



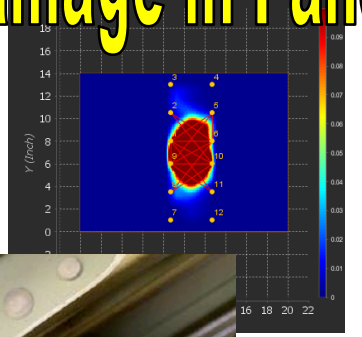
FAA SHM PROGRAM AGENDA

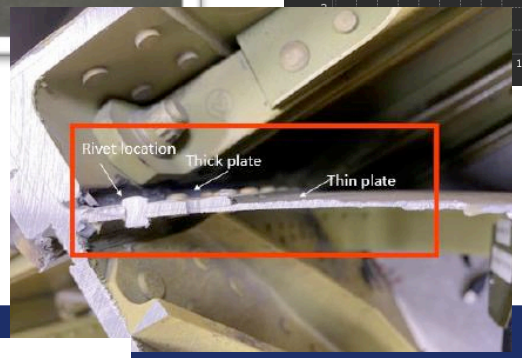
Structural Health Monitoring (SHM) Application on Chemical Mill Line Crack Inspection – In-House Testing

- **Research Program Background**
- **Full-Scale Aircraft Structural Test Evaluation and Research (FASTER): Aluminum Lithium skin structure**
  - **Panel 3 - Chem Mill Line Testing Phase 1 (completed)**
  - **Panel 3 - Chem Mill Line Testing Phase 2 (testing completed, data being analyzed)**
- **Summary**

FAA Structural Health Monitoring (SHM) – In-House Research

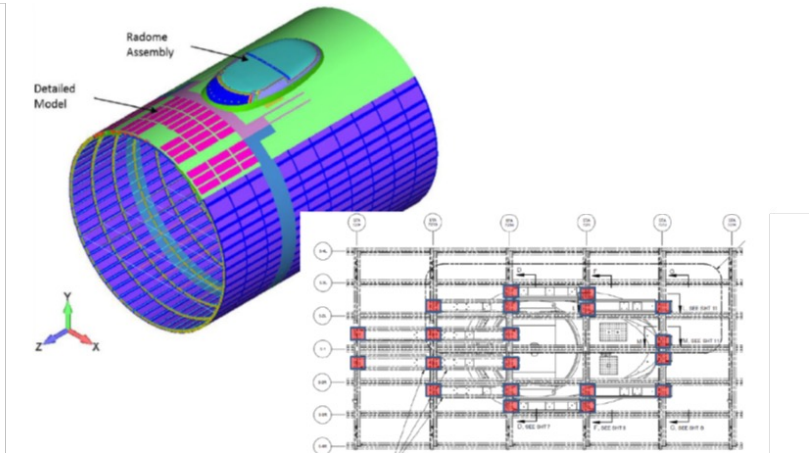
- Research Question: How to certify that SHM systems provide the same level of safety as traditional inspections?
- Objective: Assess commercially available SHM systems to detect damage formation
- Partnerships: Established Agreements with Acellent, Metis, Simmonds (Collins Aerospace), Embraer, and Boeing; Pending agreement with DFinder
- Highly collaborative; strong industry partnerships; active with the SAE Aerospace Industry Steering Committee (AISC) for SHM
- Outcome: Ensure safe implementation of emerging structural technologies





RESEARCH PURPOSE

- Fill knowledge gaps via collaborative R&D programs with industry
- Collect data for SAE AISC committee
  - Help develop reliability methodology
  - Validate ARP being developed
  - Common data set for industry use

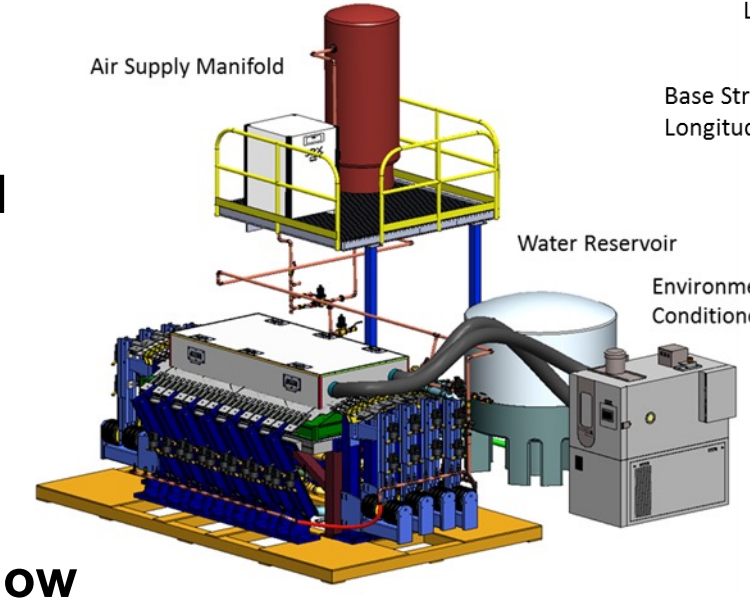


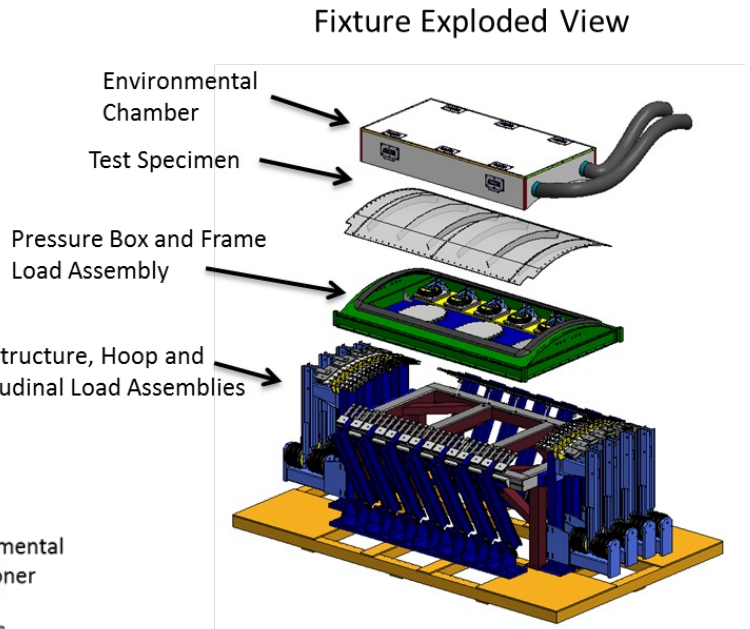
- Assess commercially available SHM systems to monitor and record damage formation

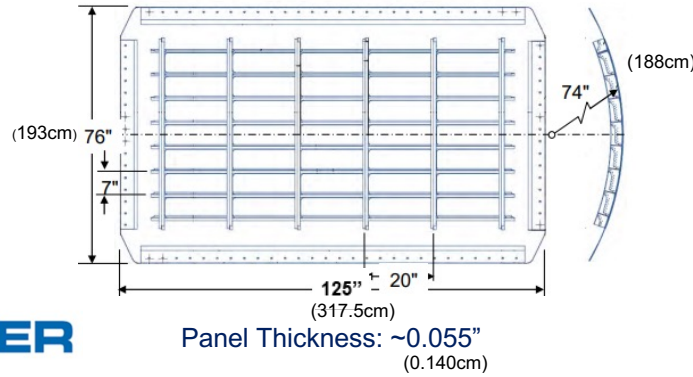
➢ Data to FAA Sponsors- applicants starting for FAA review/approval

Full-Scale Aircraft Structural Test Evaluation and Research (FASTER)

- **Purpose: Assess damage tolerance of emerging metallic structures technologies for fuselage applications**
- **Test emerging technologies**
  - **Al-Li skins/frames/stringers**
  - **Fiber Metal Laminate Reinforced**
  - **Bonded stiffeners**
  - **Multisite damage**
- **Partners: Arconic/Embraer**
- **Panels 1 and 2 complete, testing 3 now**
- **Panels 4 and 5 will be last panels for this phase of testing**







Panel Thickness: ~0.055" (0.140cm)

ARCONIC EMBRAER

FASTER - Inspection

- Strain gauges, Digital Imaging Correlation
- NDI: EC and Detailed Visual Inspection (DVI)
- SHM: PZT (Acellent and Metis), Carbon Nanotube (Metis), and Fiber Optic (FOI) (Luna and DFinder)
- Well characterized crack growth with frequent inspection opportunities

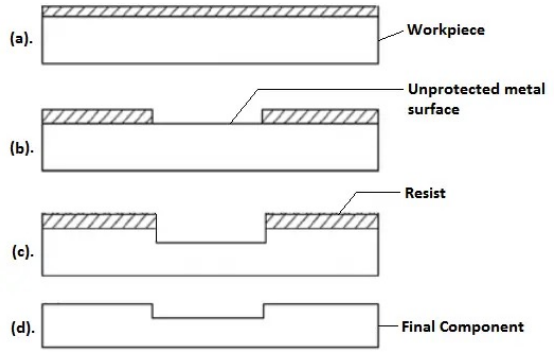
Chemical Mill Line Testing - Background

- Chemical Milling: In aircraft manufacturing, to remove material from the surface of metal components, such as skin panels, to achieve a specific shape or thickness

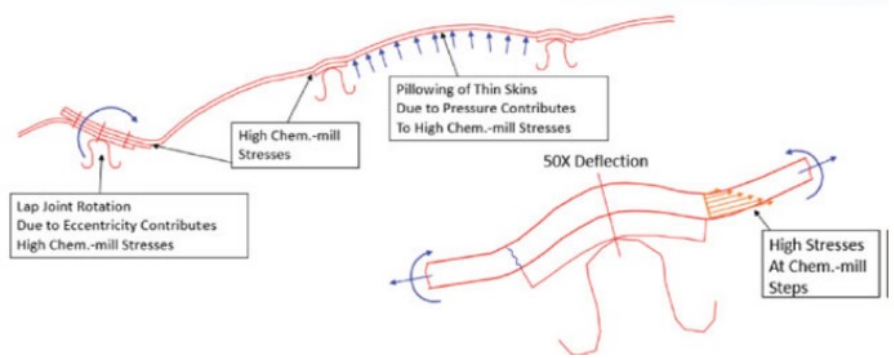
- Several incidents of cracking at the edges of chem milled areas
  - ➢ Result: Issuance of a number of Service Bulletins and Airworthiness Directives requiring inspection at the mill line

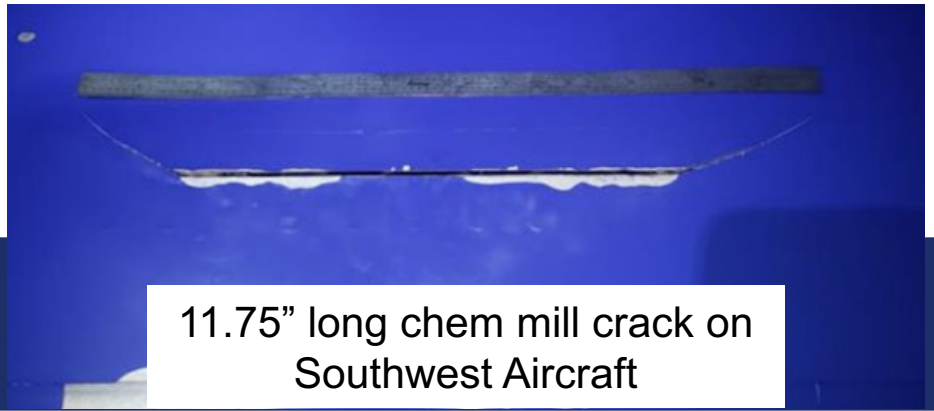
- Operator Concerns:
  - "Shear volume of chem-mills needing inspection" (Piotrowski, Delta Tech Ops)
  - Shortage of qualified NDT inspectors

- Candidate SHM application for future Boeing certification efforts

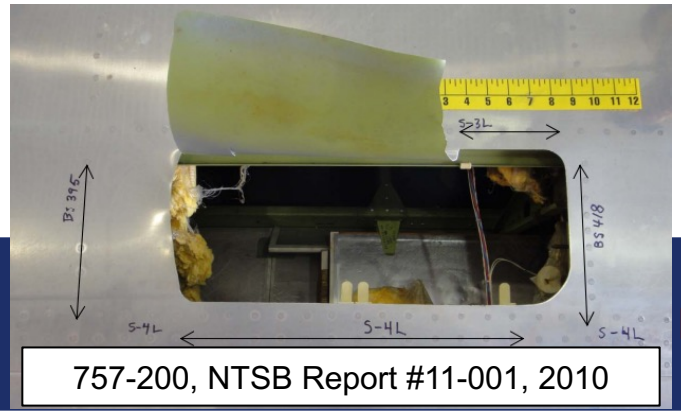


Chemical Milling

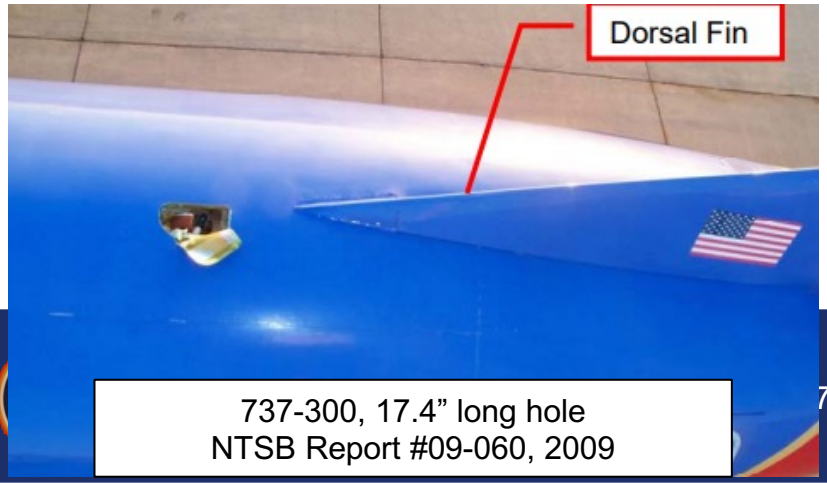




11.75" long chem mill crack on Southwest Aircraft

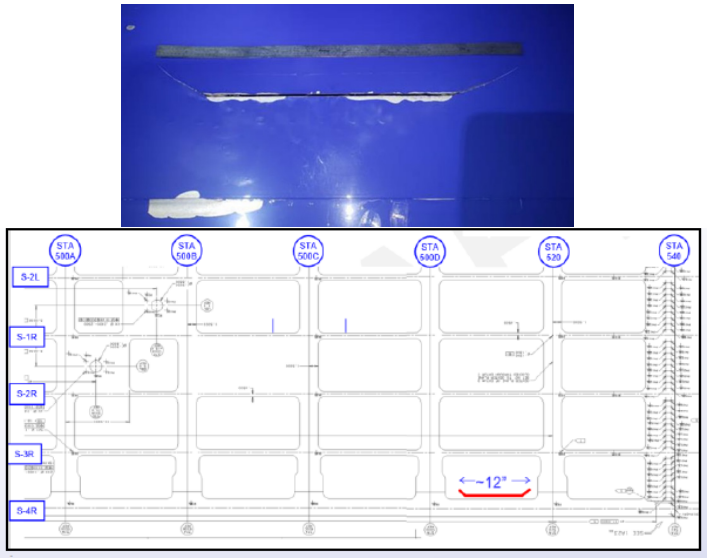


757-200, NTSB Report #11-001, 2010



737-300, 17.4" long hole
NTSB Report #09-060, 2009

Example: 737NG Crown Skin Chem-Mill Crack Between BS 500D-520 Above S-4R



Issue/Background
In March 2020, a 12 inch long skin crack between BS 500D and BS 520, above S-4R common to the chem-mill pocket step caused skin separation during flight, causing the flight crew to descend until the cabin warning indication for low pressure discontinued. The crack was discovered after the uneventful landing of the aircraft.

Root Cause
Boeing has determined multi-site fatigue crack initiations occur along the length of the chem-mill between tear straps, which are caused by fatigue stresses generated by normal skin pressure loads and secondary bending due to lap splice eccentricity and pillowing.

Final Action/Resolution
Production:

- Boeing has accomplished a design change at LN 872 for lap joint and LN 3592 for pocket-pad of the crown skin panels to enhance structural durability and reduce the stresses in the areas where chem-mill pockets are adjacent to non chem-mill areas.

Retrofit:
•Revise 737-53A1232 R3 (LN 1-871 affected) as follows:

Service Bulletins	Reference Location	Description	Original Threshold/Repeat	New Threshold/Repeat
737-53-1309 R0 737-53-1310 R0 737-53-1311 R0 737-53-1312 R1	Para 1.E Table 1	Chem-mill step Inspection	43,000 FC	37,000 FC
	Para 1.E Table 5	Modification Installed before 22,400 FC	NO CHANGE	50,000
	Para 1.E Table 5	Modification Installed between 22,400 -32,000 FC	43,000	41,000
	Para 1.E Table 5	Modification Installed after 32,000 FC	NO CHANGE	5,500 FC after modification installed

Service Bulletin(s)	Inspection	Inspection	Original Threshold/Repeat	New Threshold/Repeat
737-53-1309 R0 737-53-1310 R0 737-53-1311 R0 737-53-1312 R1	Para 1.E Table 1	Option 1 (DET + MFEC/MOI/C-SCAN)	1,500	600
	Para 1.E Table 1	Option 2 (DET+ UTPA)	2,100	1,200

Legend:
DET: Detail Visual Inspection
MFEC: Medium Frequency Eddy Current
MOI: Magnetic Optical Imaging
UTPA: Ultrasonic Phased Array

Chemical Mill Line Testing Phase 1
Collaborators

- Federal Aviation Administration (FAA)
  - Danielle Stephens (SHM)
  - Paul Swindell (NDI/SHM)
  - Yongzhe Tian (Test Engineer)
  - Dave Stanley (Test Engineer)
  - Walt Sippel (Sponsor)
  - Greg Schneider (Sponsor)
  - John Bakuckas (Structures Lead)

❖ Acellent
- Amrita Kumar
- Susheel Kumar Yadav
- Franklin Li

❖ Analog Devices, Inc

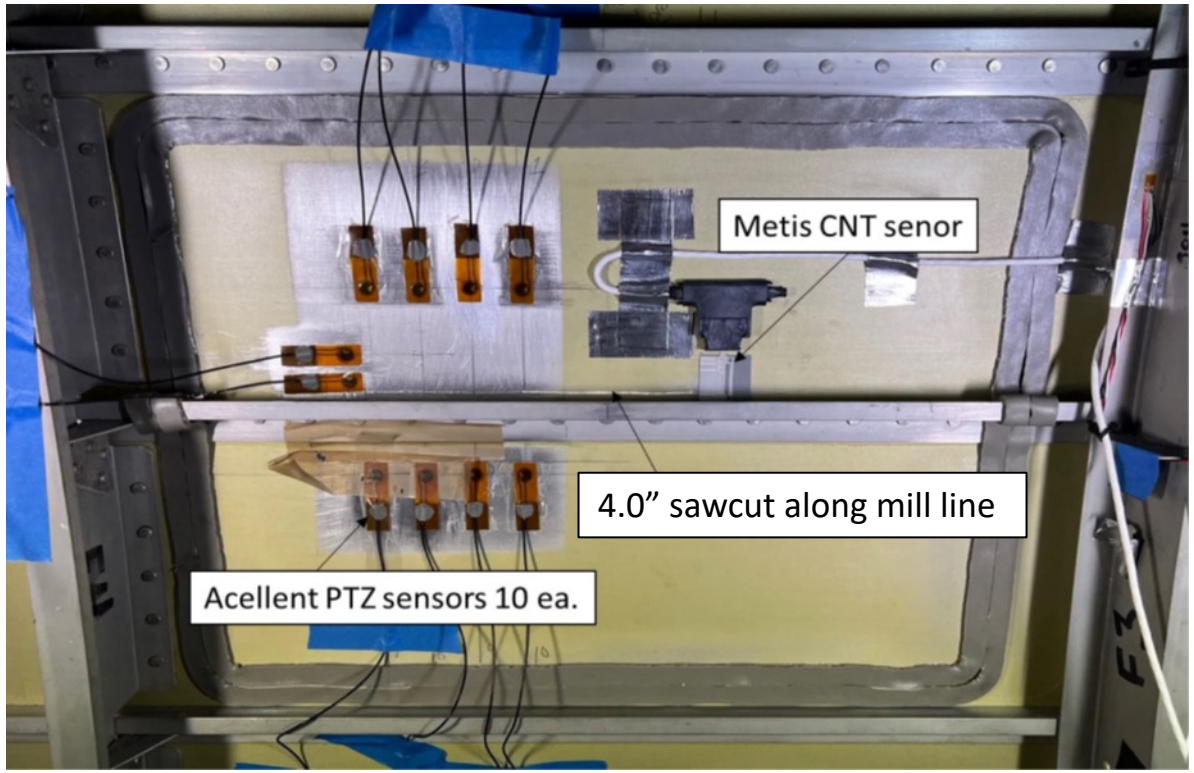
❖ Metis Design
- Seth Kessler

❖ Delta TechOps
- David Piotrowski

Chem mill project (Phase 1) results are the product of a collaborative effort

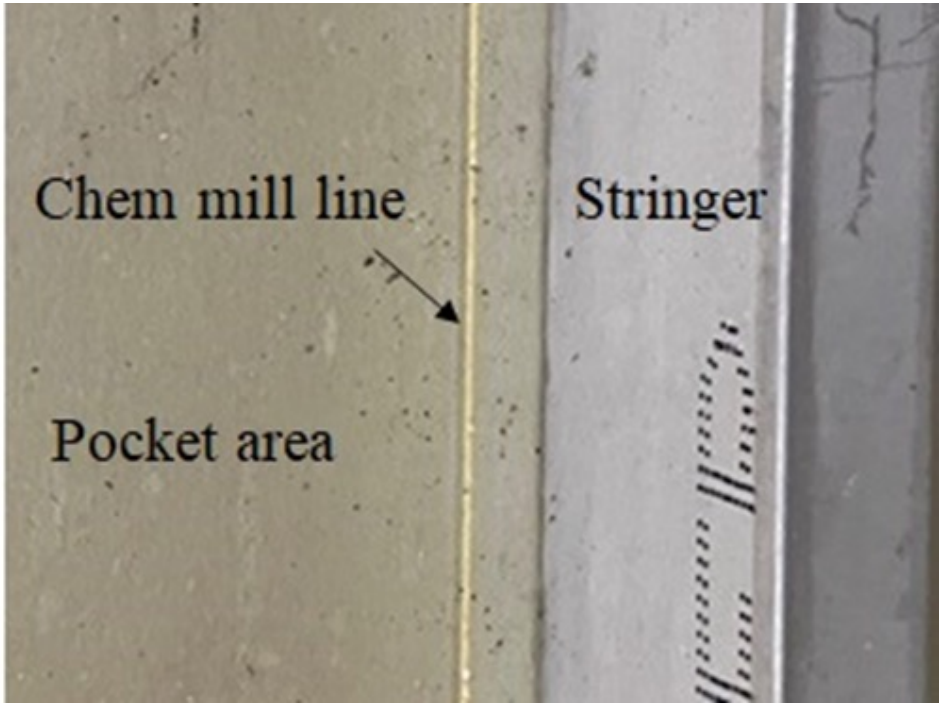
Chem Mill Testing – Phase 1 Installation

“Proof of Concept” Testing



Chem mill line crack and SHM sensors installed on the internal surface of FASTER test panel

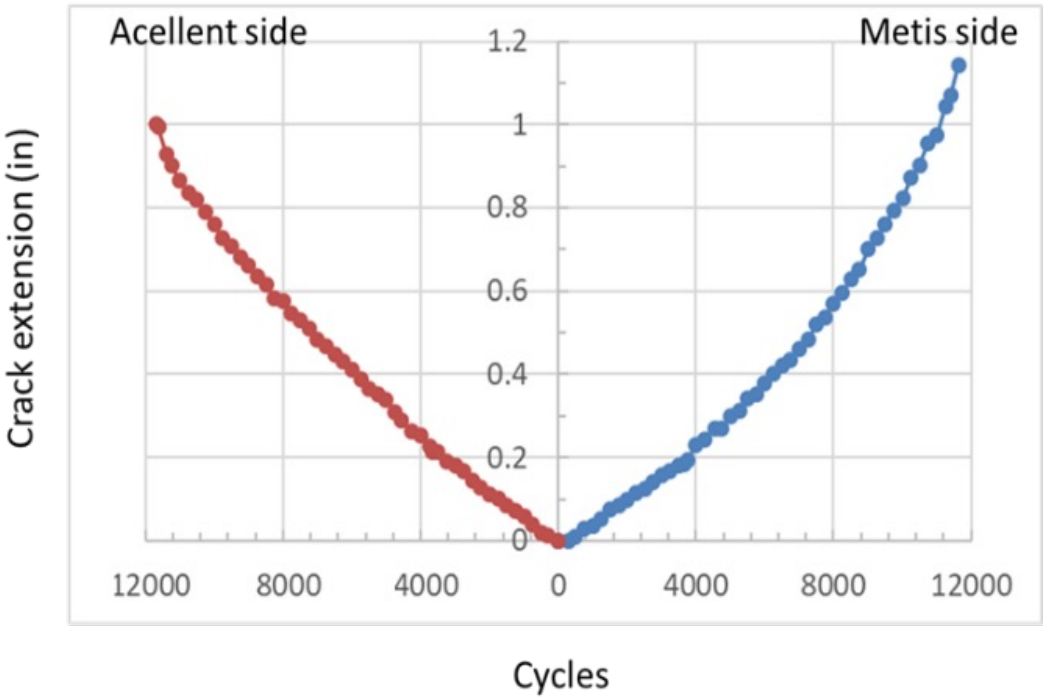
❖**11,700 simulated flight cycles**



Skin chemically milled down from 0.065” to 0.050”

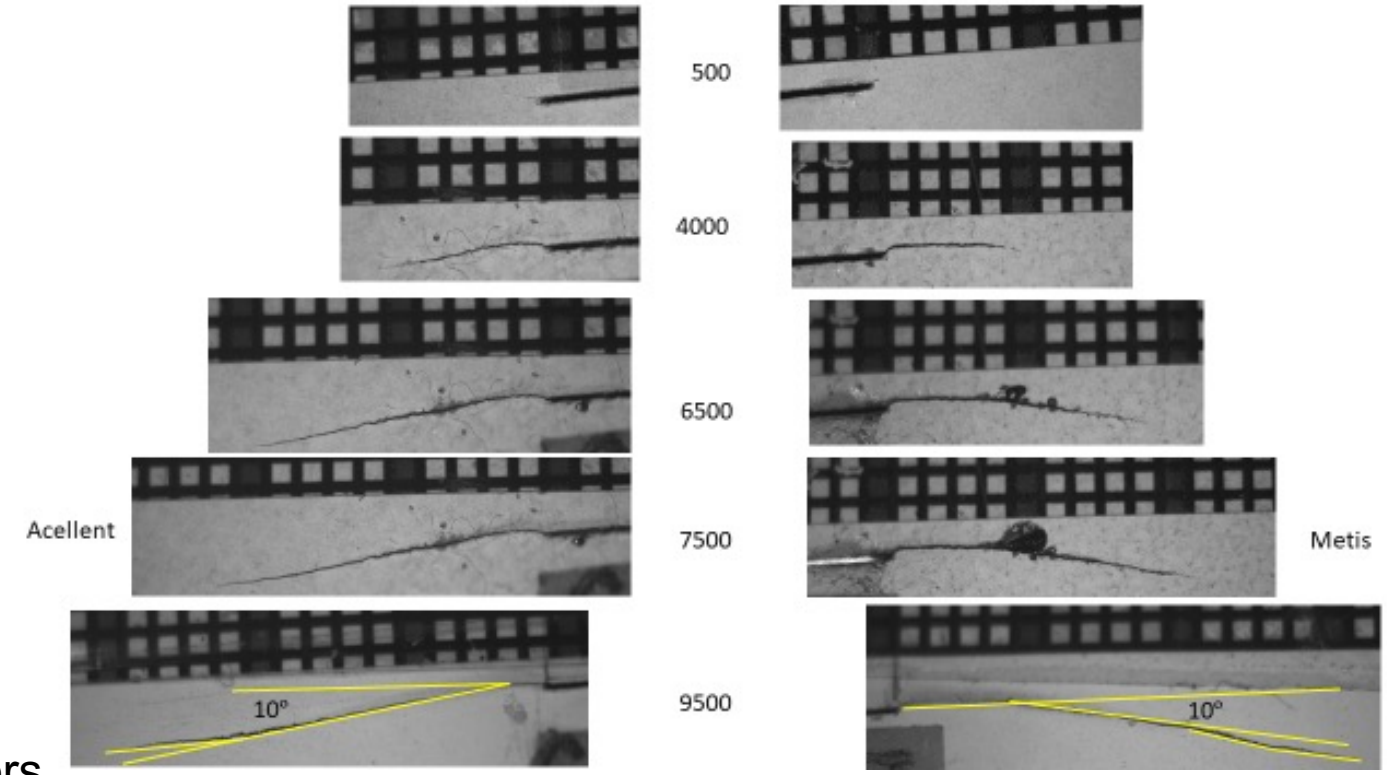
Chem Mill Testing: Crack Growth Data

❖ **11,700 simulated flight cycles**



NDI:

➢ HFEC ➢ Detailed Visual Inspection (DVI)

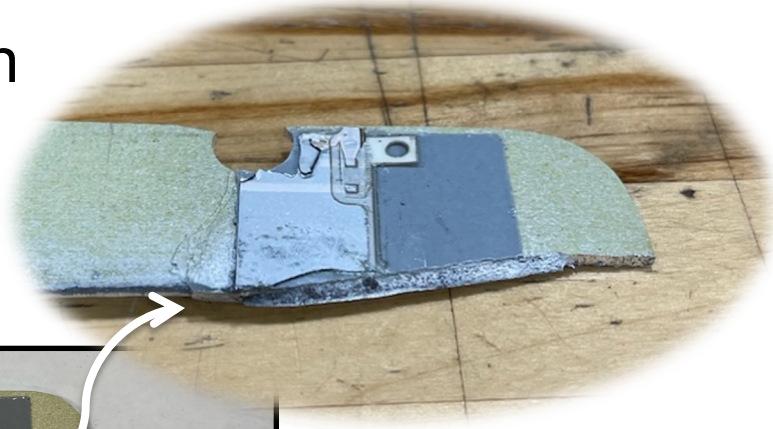


Chem mill line crack extensions through SHM sensors

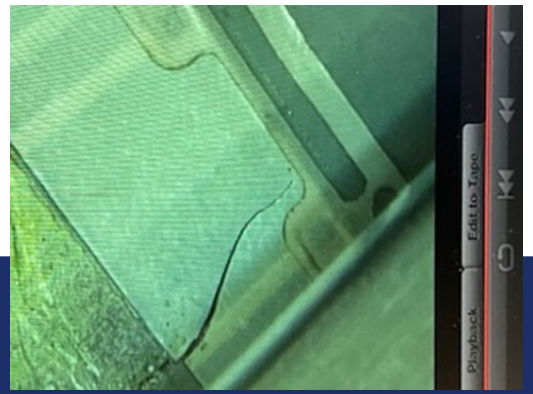
Chem Mill Testing – Metis Design Results

Metis Design Wireless Integrity Sensor Platform (**WISP**)
Carbon Nanotube Sensor

- Note: Installation used a commercial-off-the-shelf version of the sensor due to quick turnaround times to begin testing. Normally, a custom form-factor sensor would be designed specific to the application.



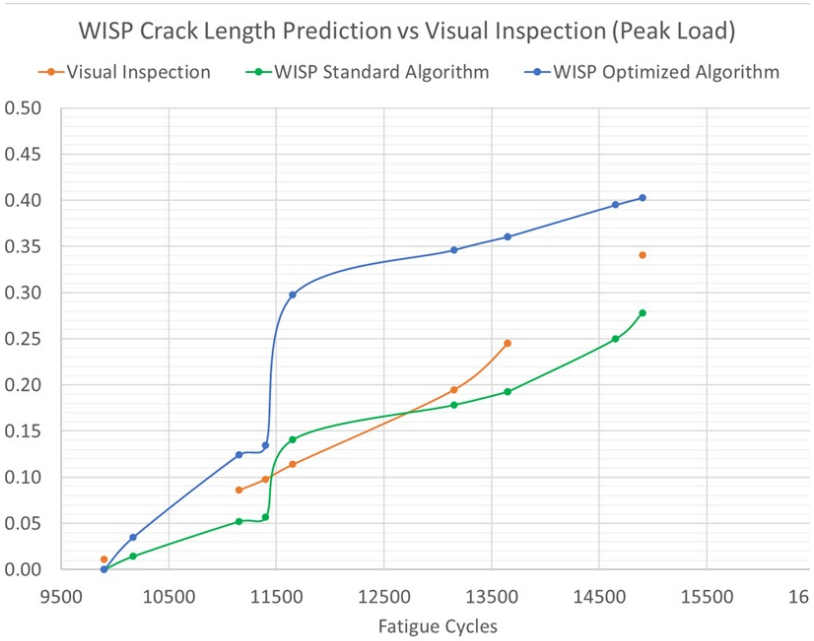
Modification Needed: Custom bonding using an area of thick adhesive about 25x that of the normal bondline thickness

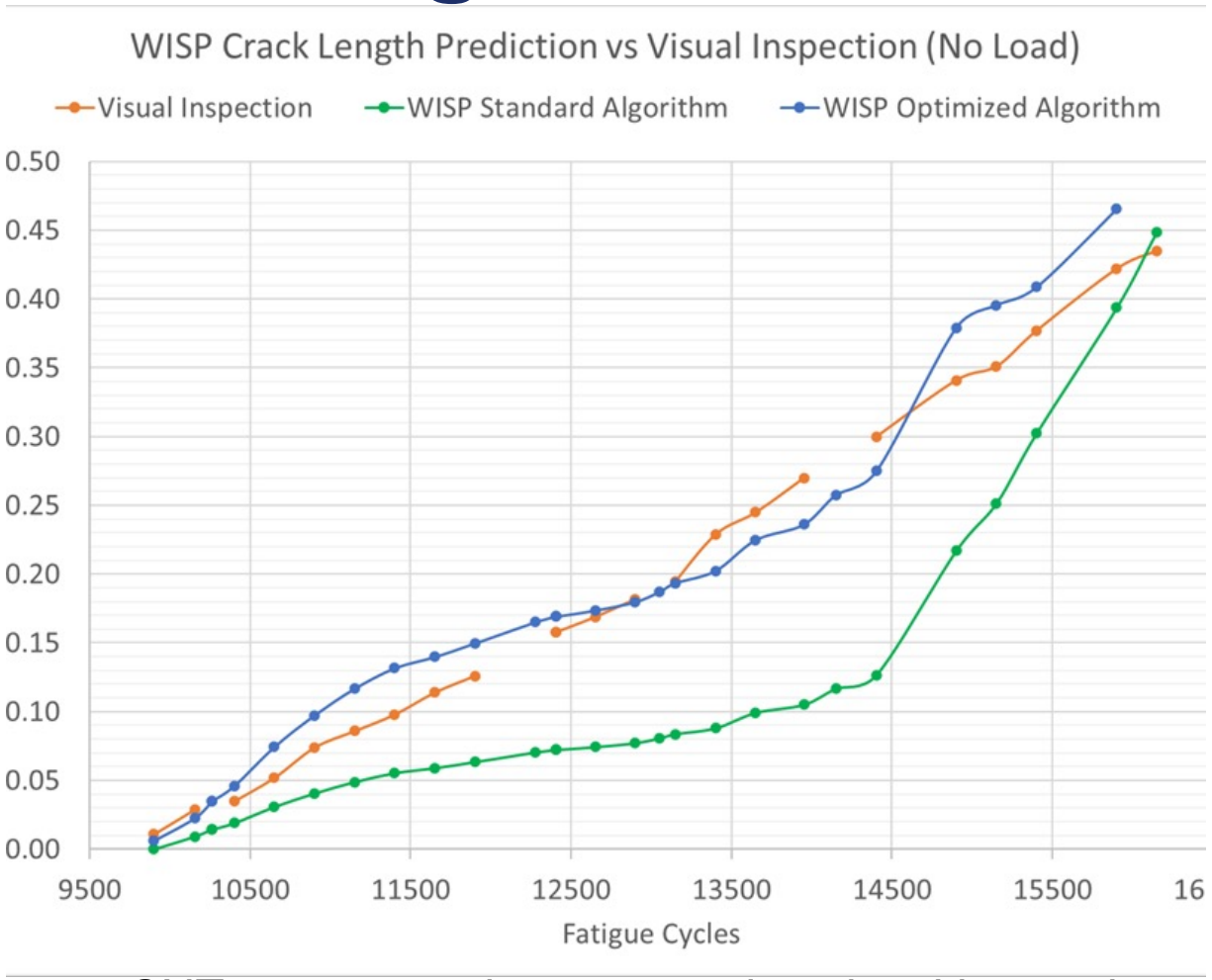


Chem Mill Testing – Metis Design Results

Metis Design CNT Sensors

- Data taken in 250 cycle intervals
- 29 data points
- 0.5” crack extension





CNT sensor results compared to visual inspection

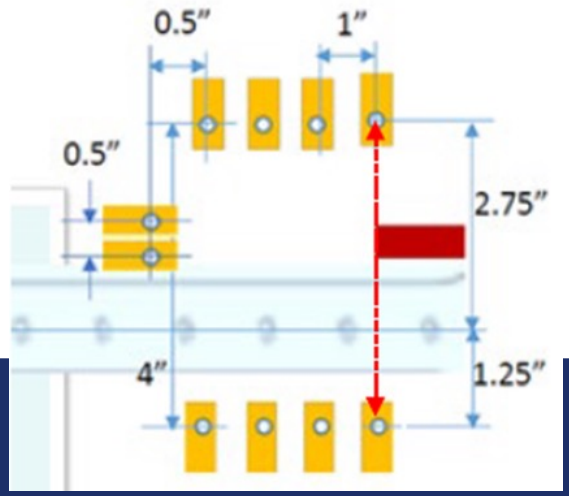
Note: Baseline data was not taken for peak load measurements

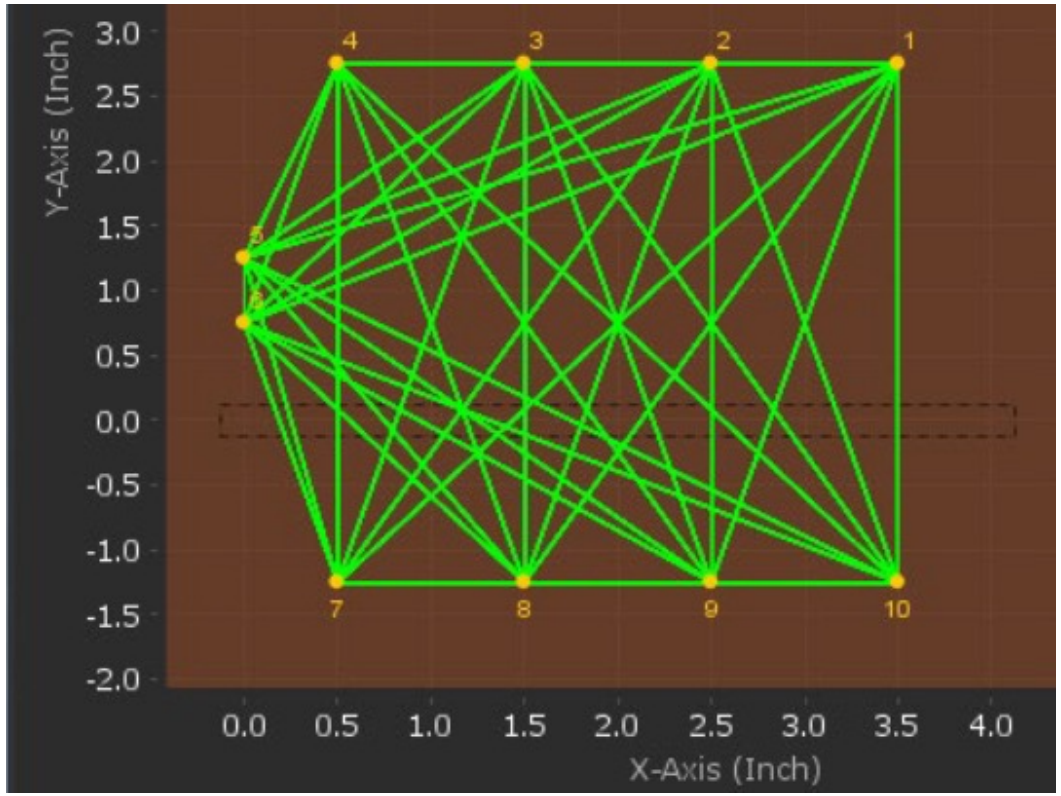
Chem Mill Testing – Acellent Results

Acellent PZT Sensors

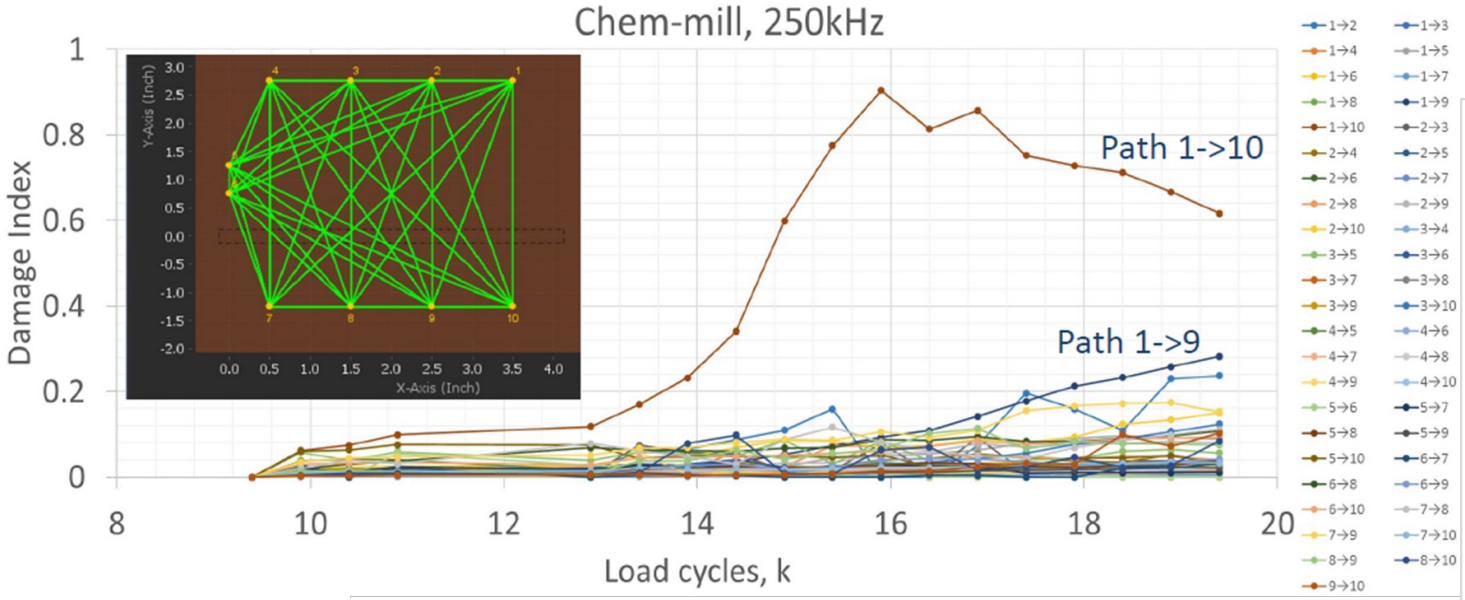
- Data taken in 500 cycle intervals
- 24 data sets
- 45 paths
- 1.0” crack extension

- Frequencies taken:
  - 200-500 kHz at 25 kHz increments

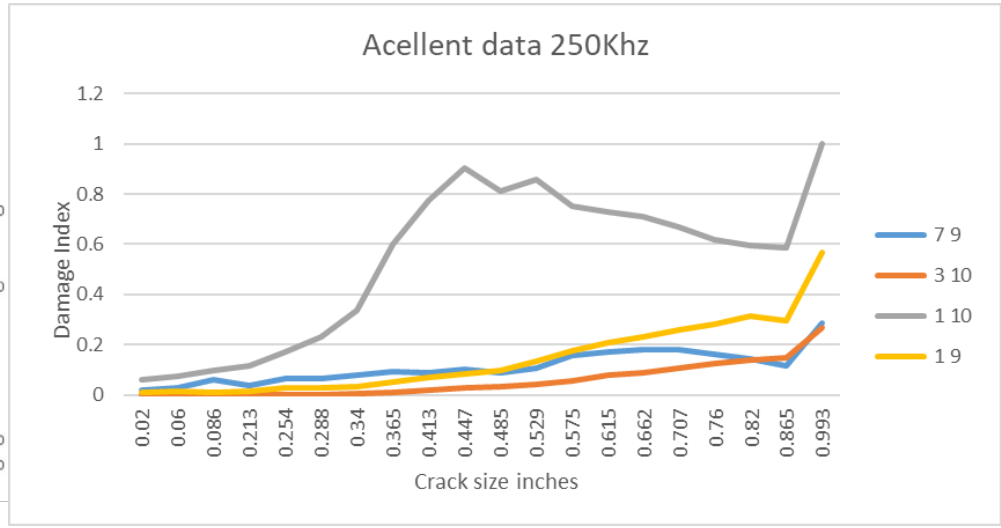


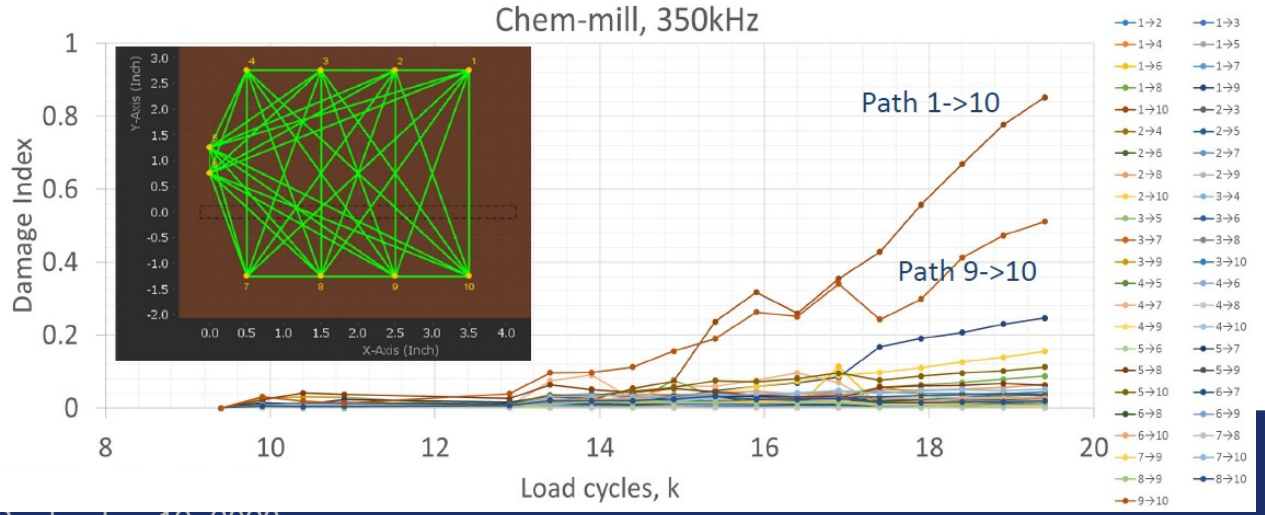


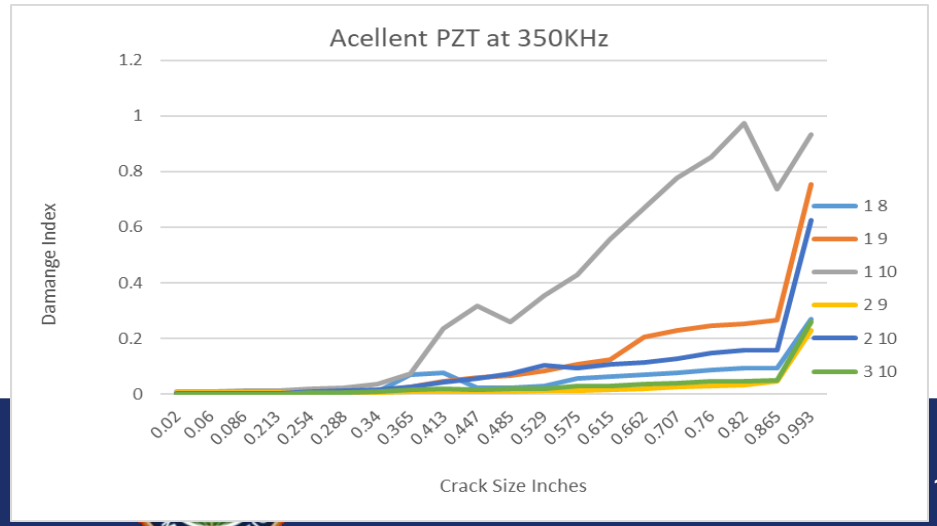
Chem Mill Testing – Acellent Results



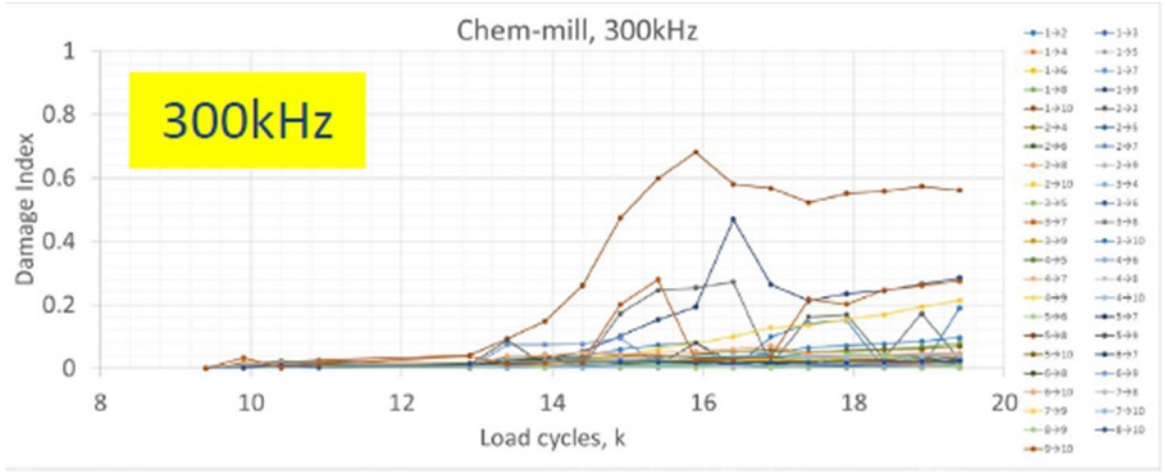
DI > 0.2

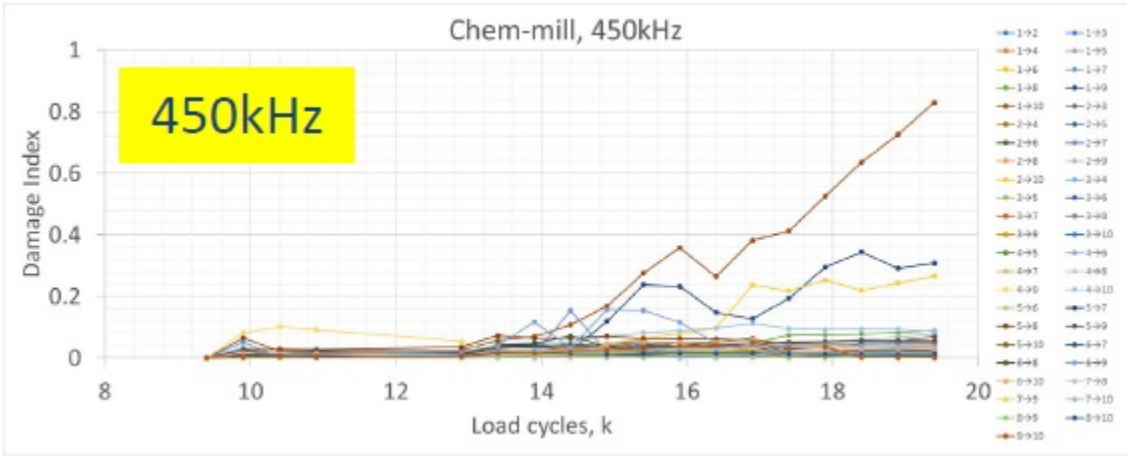


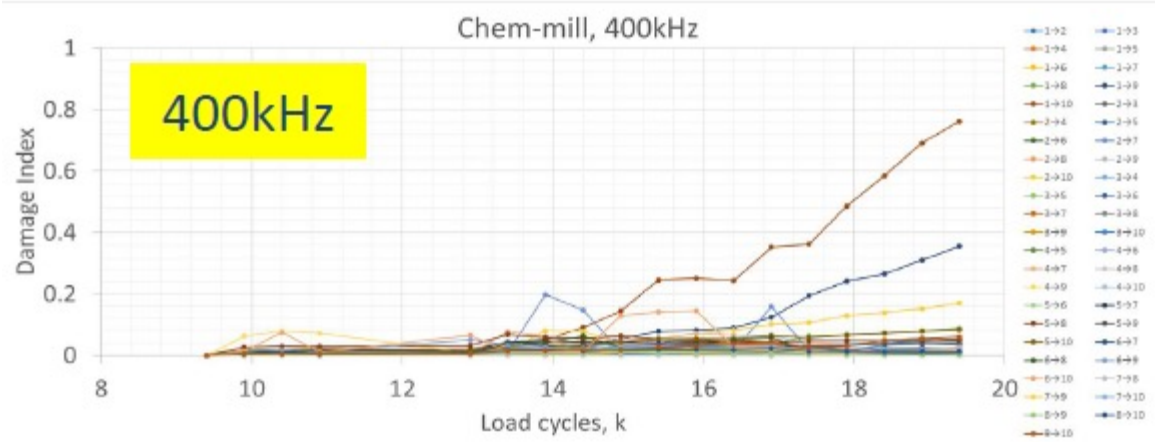


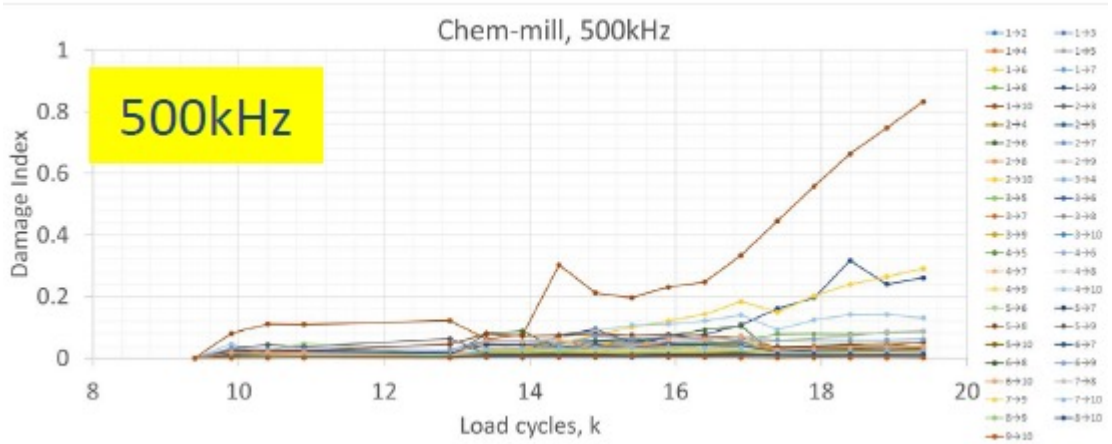


Chem Mill Testing – Acellent Results









FASTER Chem Mill Testing Phase 1 Conclusions

- Within the FASTER panel test setup, both PZT and CNT demonstrated that they were capable of identifying a crack located at the mill line of the chemically milled geometry

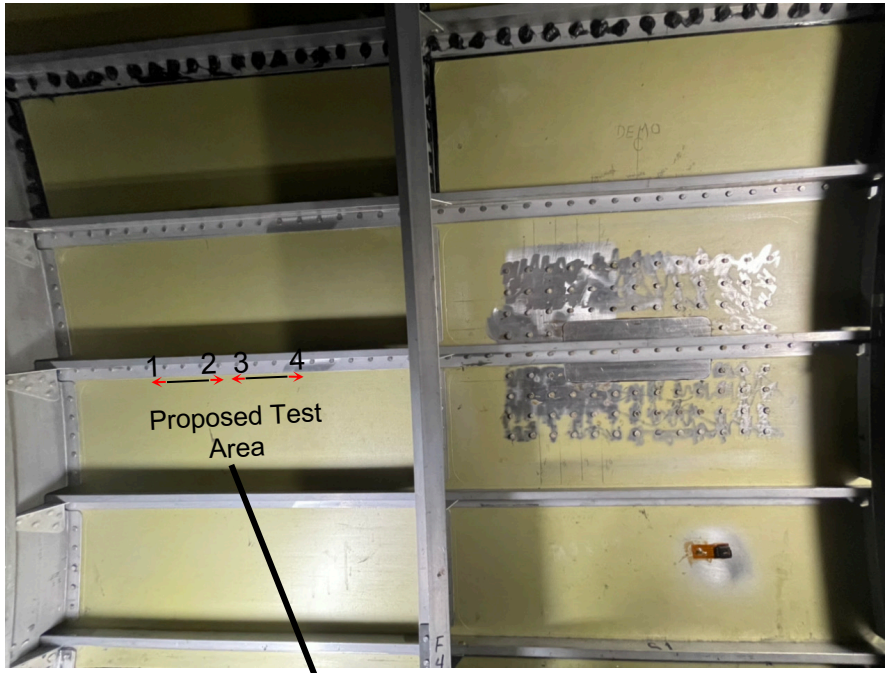
- Metis Design CNT was able to see the crack very early.
- Acellent PZT was capable of finding the crack at ~0.5”.

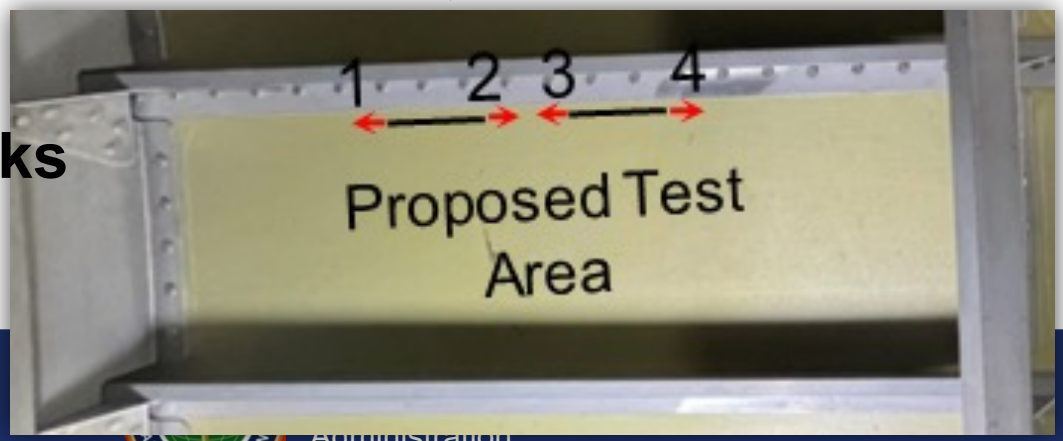
- More tests should be undertaken to further determine each systems’ sensitivity and reliability.

- Potential pitfalls: Boeing has noticed that chem mill cracking doesn’t necessarily originate “neatly” in one area. Has potential to form multi-site cracks and coalesce into large crack.

Chem Mill Line Testing – PHASE 2

- **Initial concerns in chem mill area that were not addressed in initial testing:**
  - **Lap Joints**
  - **Multi-Site Damage**
- **Additional SHM technologies to be explored:**
  - **Acellent PZT – Single Sensors (left sawcut)**
  - **DFinder Fiber Optic (right sawcut and adjacent bays)**
- **Two 4” sawcuts set 2” apart**
- **Cracks growing from ends of sawcut = 4 cracks**





Chemical Mill Line Testing Phase 2
Collaborators

- Federal Aviation Administration (FAA)
  - Danielle Stephens (SHM)
  - Paul Swindell (NDI/SHM)
  - Yongzhe Tian (Test Engineer)
  - Dave Stanley (Test Engineer)
  - Walt Sippel (Sponsor)
  - Greg Schneider (Sponsor)
  - John Bakuckas (Structures Lead)

- Acellent
  - Amrita Kumar
  - Susheel Kumar Yadav
  - Franklin Li

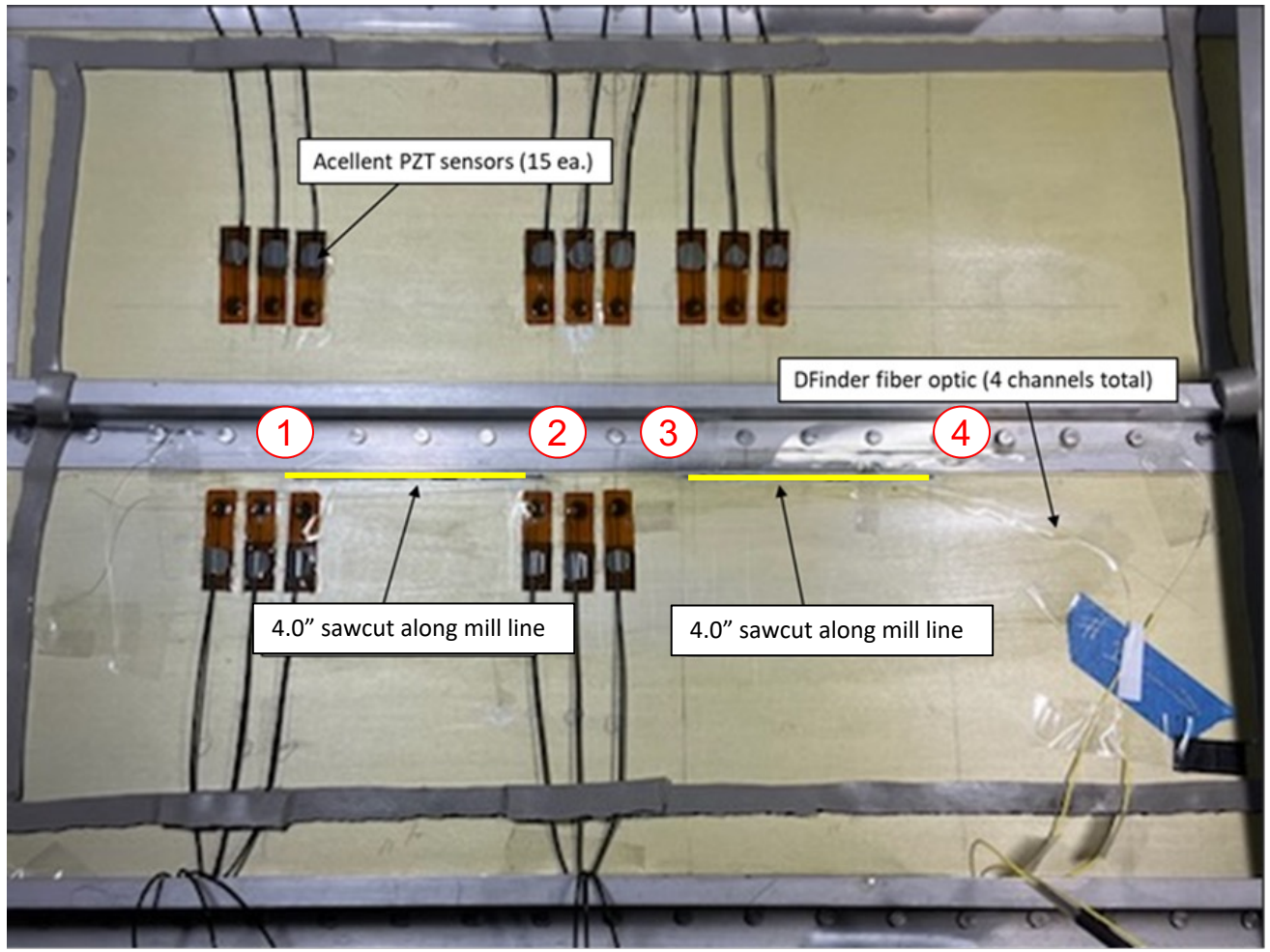
- DFinder
  - Marie-Anne DeSmet
  - Charles Bracoud
  - Luc Benechet
  - Alain Bensoussan

- B-Sens
  - Corentin Guyot
  - Christophe Caucheteur

- Delta TechOps
  - David Piotrowski

Chem mill project (Phase 2) results are the product of a collaborative effort

Chem Mill Phase 2 Testing – Installation



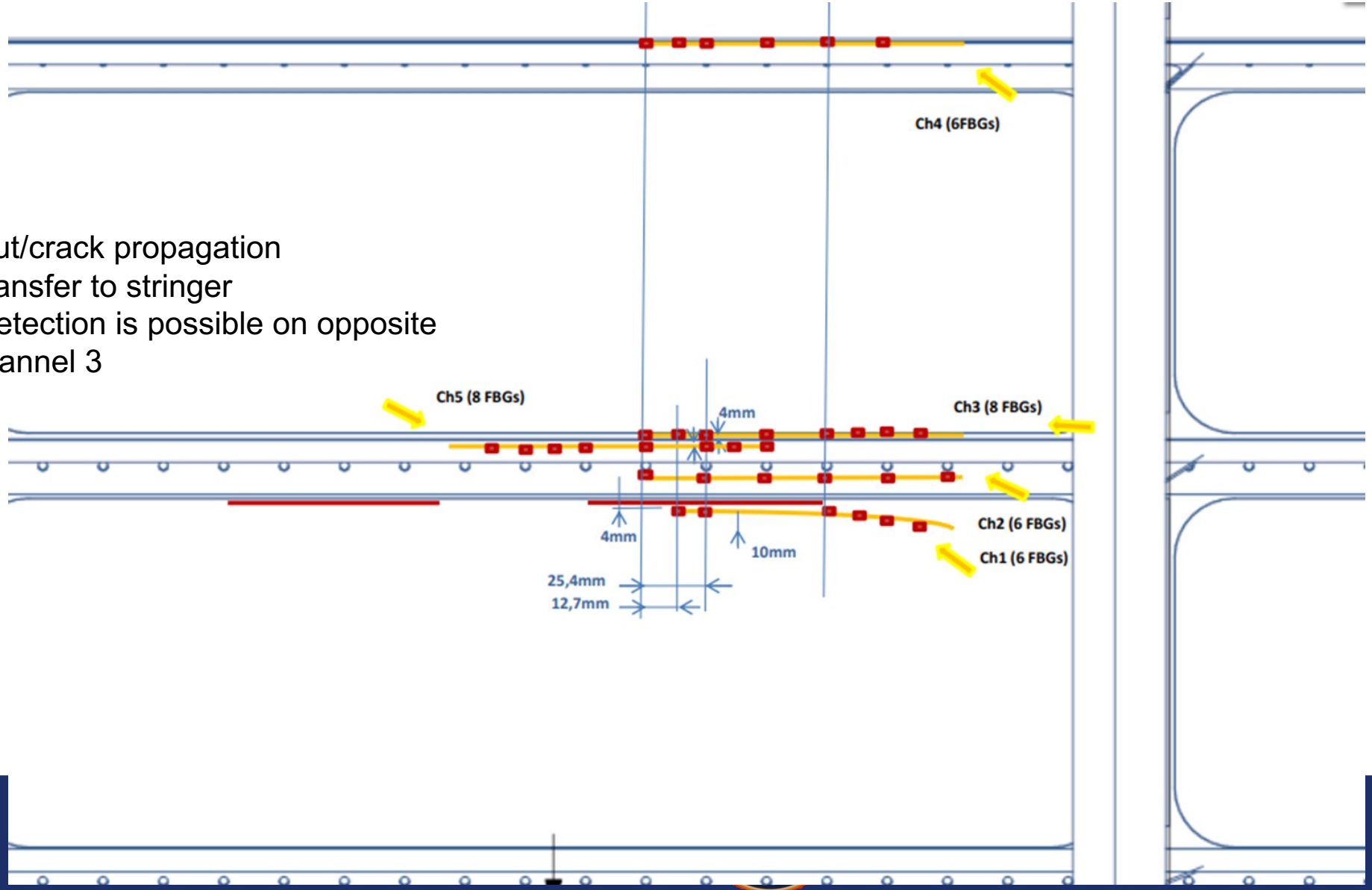
❖ **3,800 simulated flight cycles**

- Two (2) chem mill line cracks and SHM sensors installed on the internal surface of FASTER test panel
- Two 4” sawcuts with 2” space between sawcuts
- Each sensor to monitor at least 2 crack locations

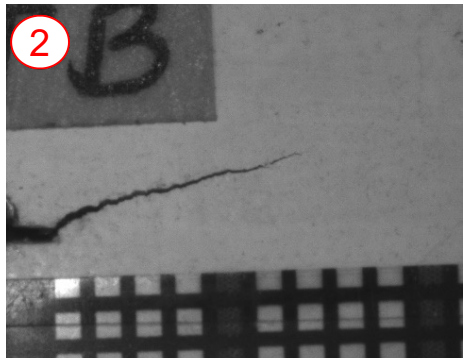
Chem Mill Phase 2 Testing – FBG Locations

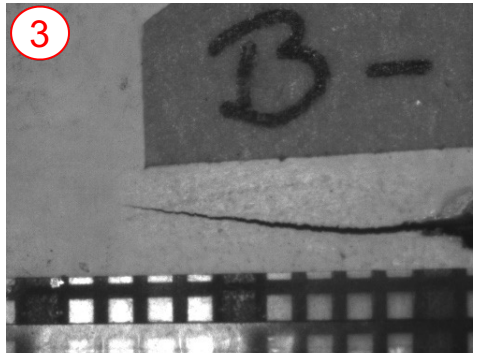
Sensing on 4 Channels

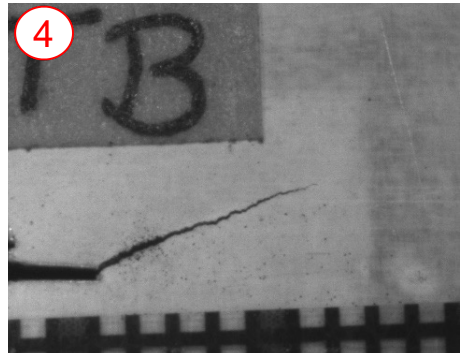
- Channel 1: Nearest to saw cut/crack propagation
- Channel 2: Monitoring any transfer to stringer
- Channel 3: Identify if crack detection is possible on opposite
- Channel 4: Reference for Channel 3

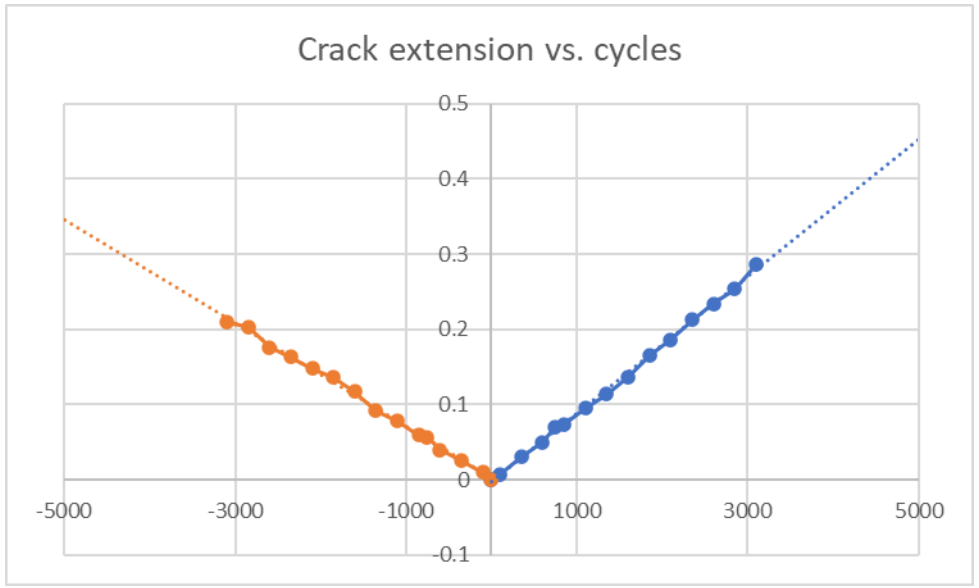


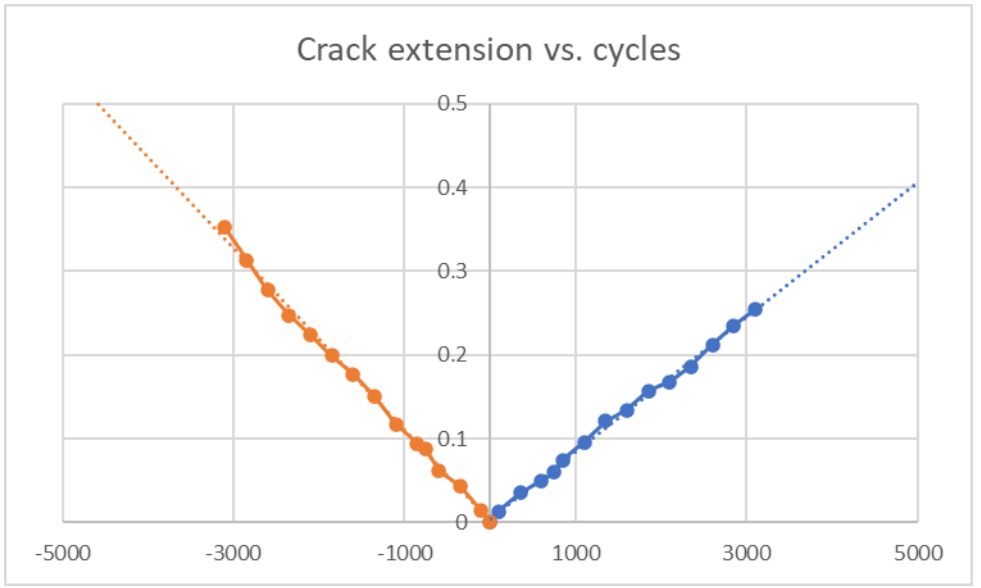
Chem Mill Phase 2: Crack Growth Data (3200 cycles)





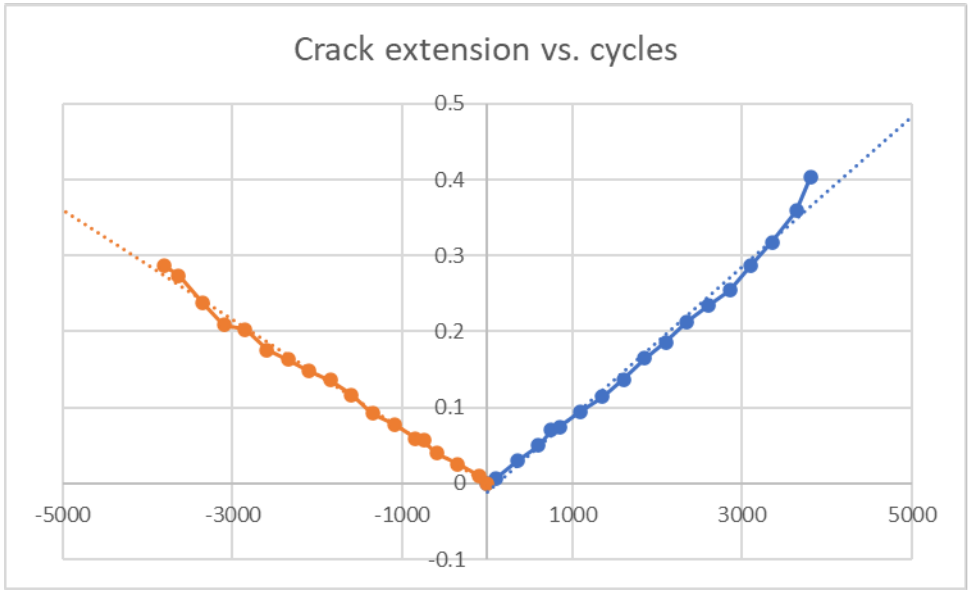


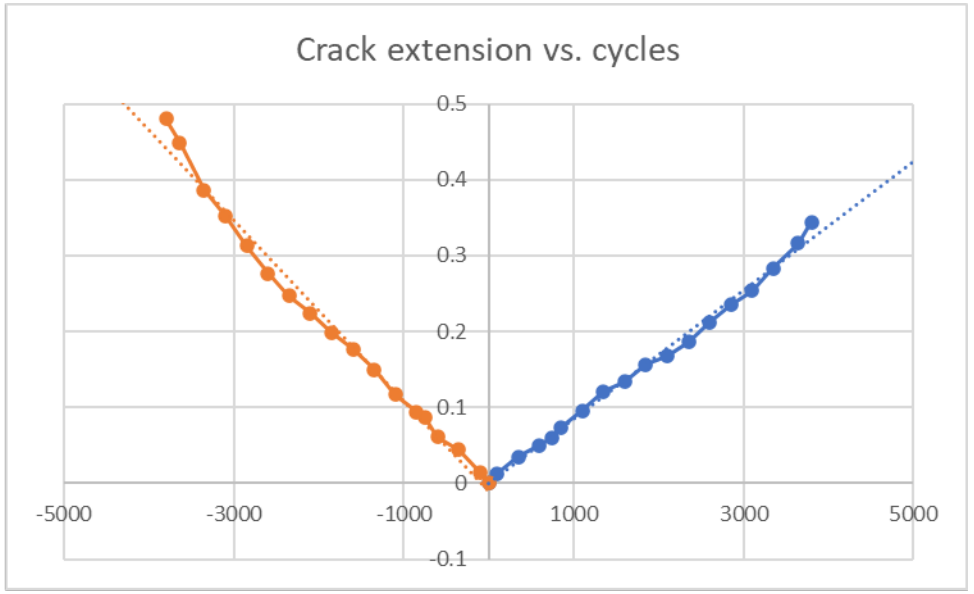


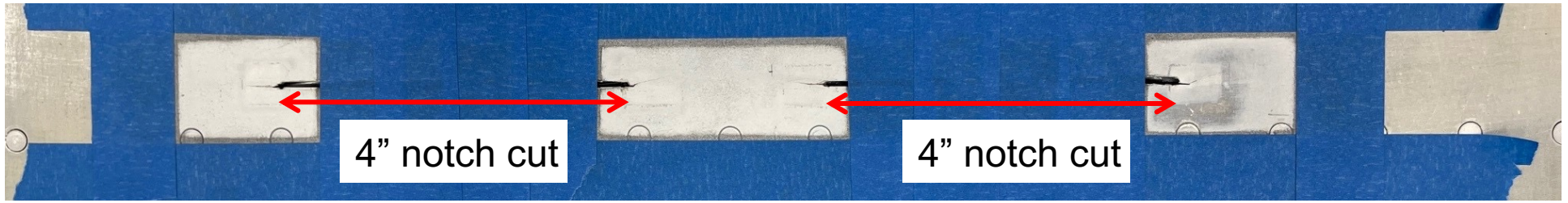


Chem Mill Phase 2: Crack Growth Data

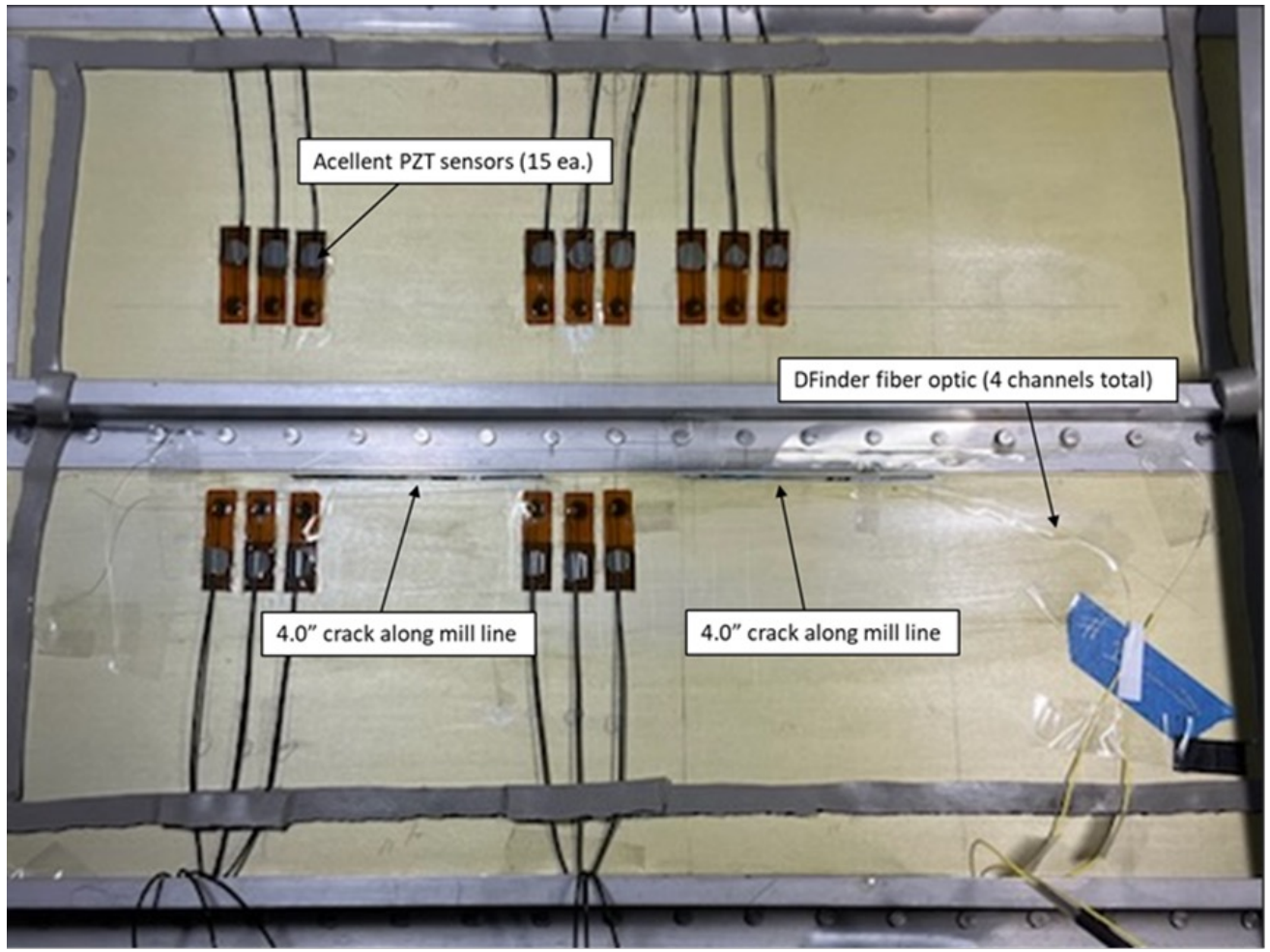
Test stopped at 3800 cycles







Chem Mill Phase 2 Testing – Next Steps



- Tests were also done in a "blind" fashion
- Recently received initial blind results from DFinder
- Completed in-house analysis with Acellent
- Next - send truth data to both companies for final comparison & analysis
- Report

Summary

- SHM at Chem Mill Line being looked at as a candidate SHM application for future Boeing certification efforts; “proof of concept” effort
- Within the simplified FASTER panel geometry, both PZT and CNT demonstrated ability to identify crack located at the mill line; more testing needed
- FAA research program focused on production of data
- Leverage collaborative R&D programs
- Data from FAA test programs reported to FAA Sponsors
  - Data from past FAA research program used in development of FAA Issue Paper for SHM use

Questions?

Danielle.Stephens@faa.gov

paul.e-ctr.Swindell@faa.gov

Federal Aviation Administration
Aviation Research Division
William J Hughes Technical Center
Atlantic City, NJ 08405