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Non-Destructive Evaluation Methods for Detecting Major Damage in Internal Composite Structural Components

Francesco Lanza di Scalea

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Non-Destructive Evaluation Methods for Detecting Major Damage in Internal Composite Structural Components

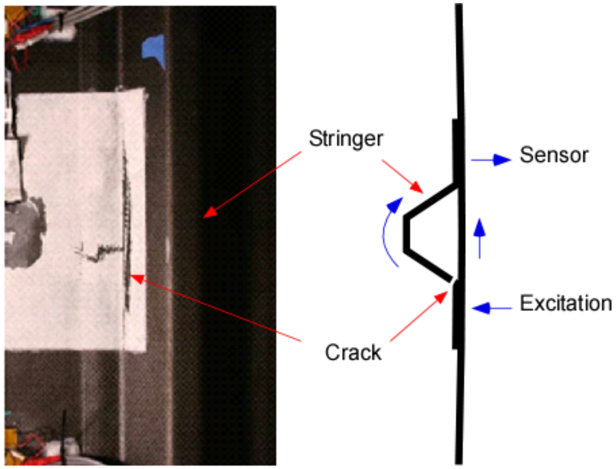
- **Principal Investigators & Researchers**
  - Co-PIs: Professors Hyonny Kim and Francesco Lanza di Scalea
  - Graduate Students
    - PhD: Eric Hyungsuk Kim, Margherita Capriotti, Thompson Nguyen
    - MS: n/a
    - Post-doc (in kind): Stefano Mariani
- **FAA Program Monitor**
  - David Westlund
- **Other FAA Personnel Involved**
  - Rusty Jones
  - Larry Ilcewicz
- **Industry Participation**
  - Boeing, United Airlines, Delta Airlines

Motivation

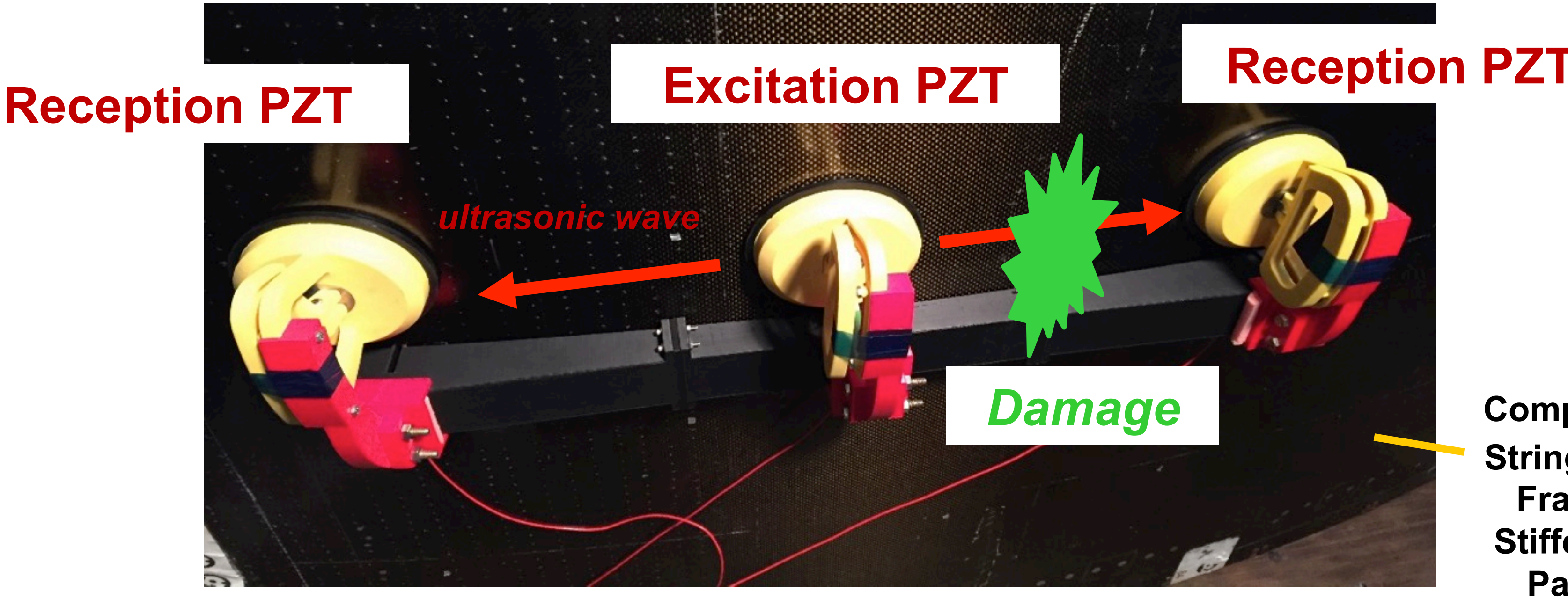
- damage from Ground Service Equipment (GSE) can be difficult to visually detect
  - blunt impact damage problem
- key interest: presence of **major damage to internal structure** (frame, shear tie, stringer)
  - cracks usually not detectable by typical one-sided NDE from external skin
  - need quick NDE tool to decide if further inspection/action needed

Objectives

- establish detection method for finding major damage to internal structure
- detection performed only from exterior skin-side
- longer-term: relate NDE measurements with damage location, mode, and severity



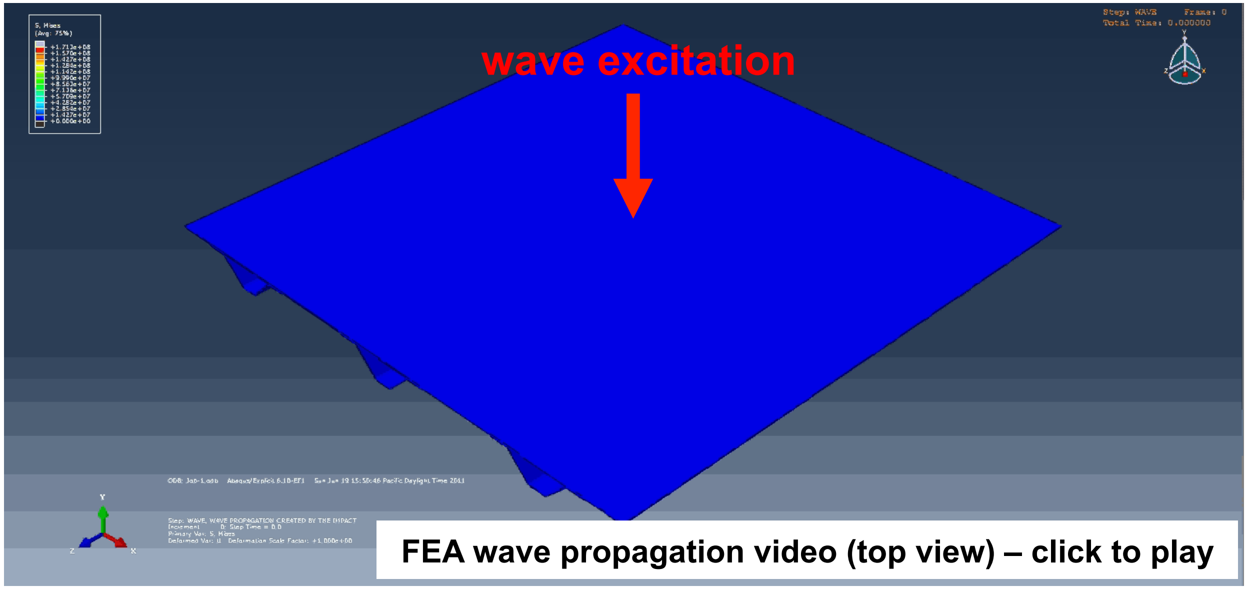
Approach: “Differential” Damage Detection Scheme

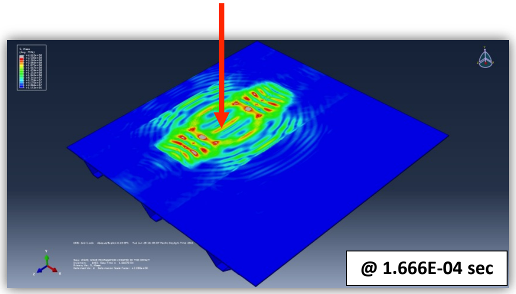


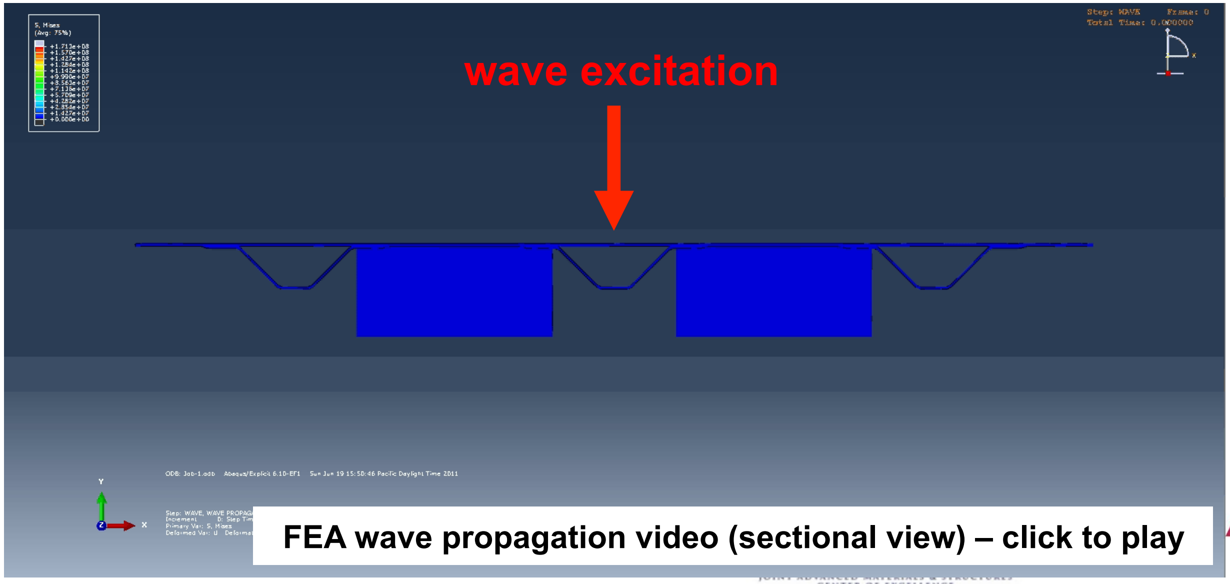
Composite Stringer & Frame Stiffened Panel

- Detects damage as an “unbalance” between the two wave receptions
- Robust against variations in excitation strength (e.g. coupling, input V)
- Lends itself to statistical processing (Outlier Analysis) to maximize true detections and minimize false positives (see later for this)

Panel is a natural "waveguide"







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Previous work (June 2014 - June 2015)

- Survey of damage to previously-impacted panels
- Guided wave tests on damaged panels
- Development of ultrasonic testing procedure and methodology: excitation, reception, dispersion curves…
- Development of FEA wave propagation simulations

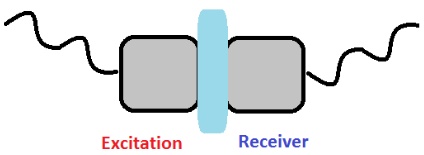
Current Work (July 2015 - present)

- Piezoelectric transducers characterization
- Detection of internal damage in two previously-impacted panels
- Statistical analysis and determination of Receiver Operating Characteristic (ROC) curves

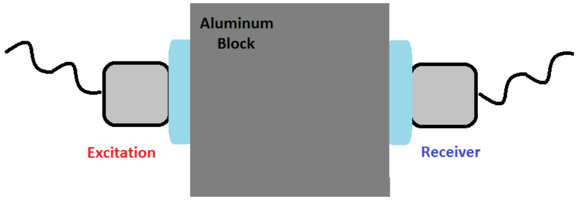
PZT Transducers Characterization

- Need to deconvolve the transducer response from the ultrasonic measurements to get the net panel response

- **R15 transducers: face to face**

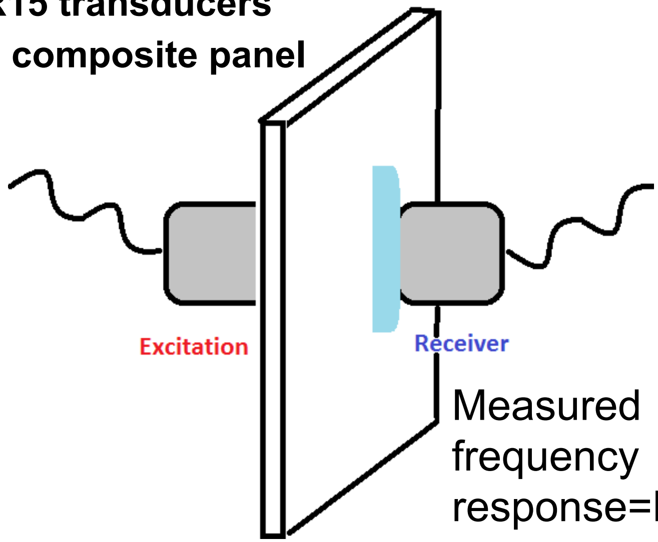


- **R15 transducers: on Aluminum block**



Transducer frequency response=T(ω)

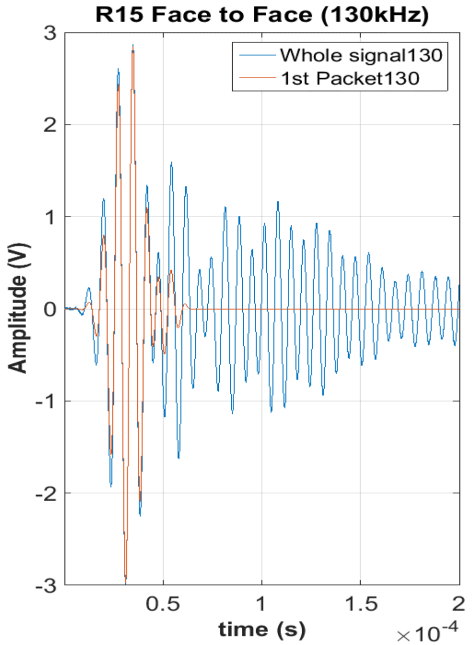
R15 transducers on composite panel

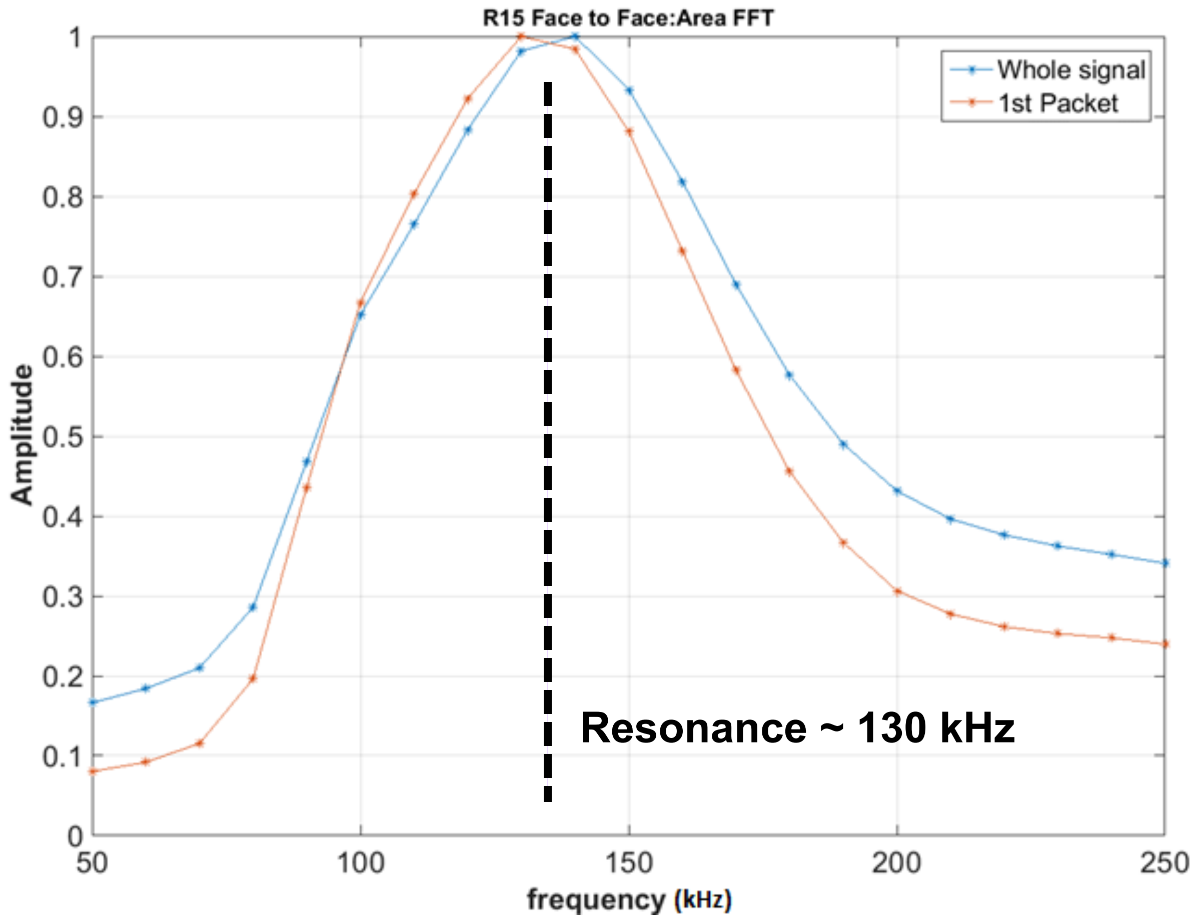


Measured frequency response=M(ω)

Frequency Transfer Function of Panel: $FRF(\omega) = M(\omega)/T(\omega)$ (deconvolution)

R15 transducers frequency response: face to face





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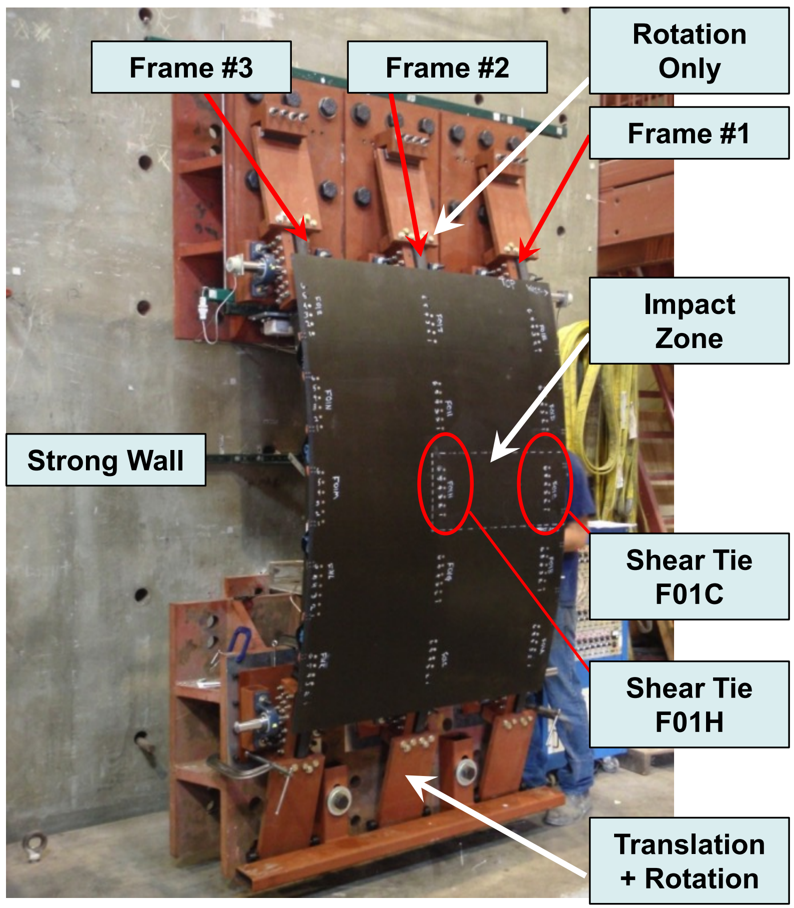
Test Panels

High Energy Wide Area Blunt Impact on Composite Aircraft Structures (DeFrancisci, 2013)

Used Existing Damaged Panels

- previously-tested specimens from FAA project “Impact Damage Formation on Composite Aircraft Structures”
- FrameXX panel series



1D Dynamic Shake Table. Impactor head moves into specimen – simulating GSE contact.

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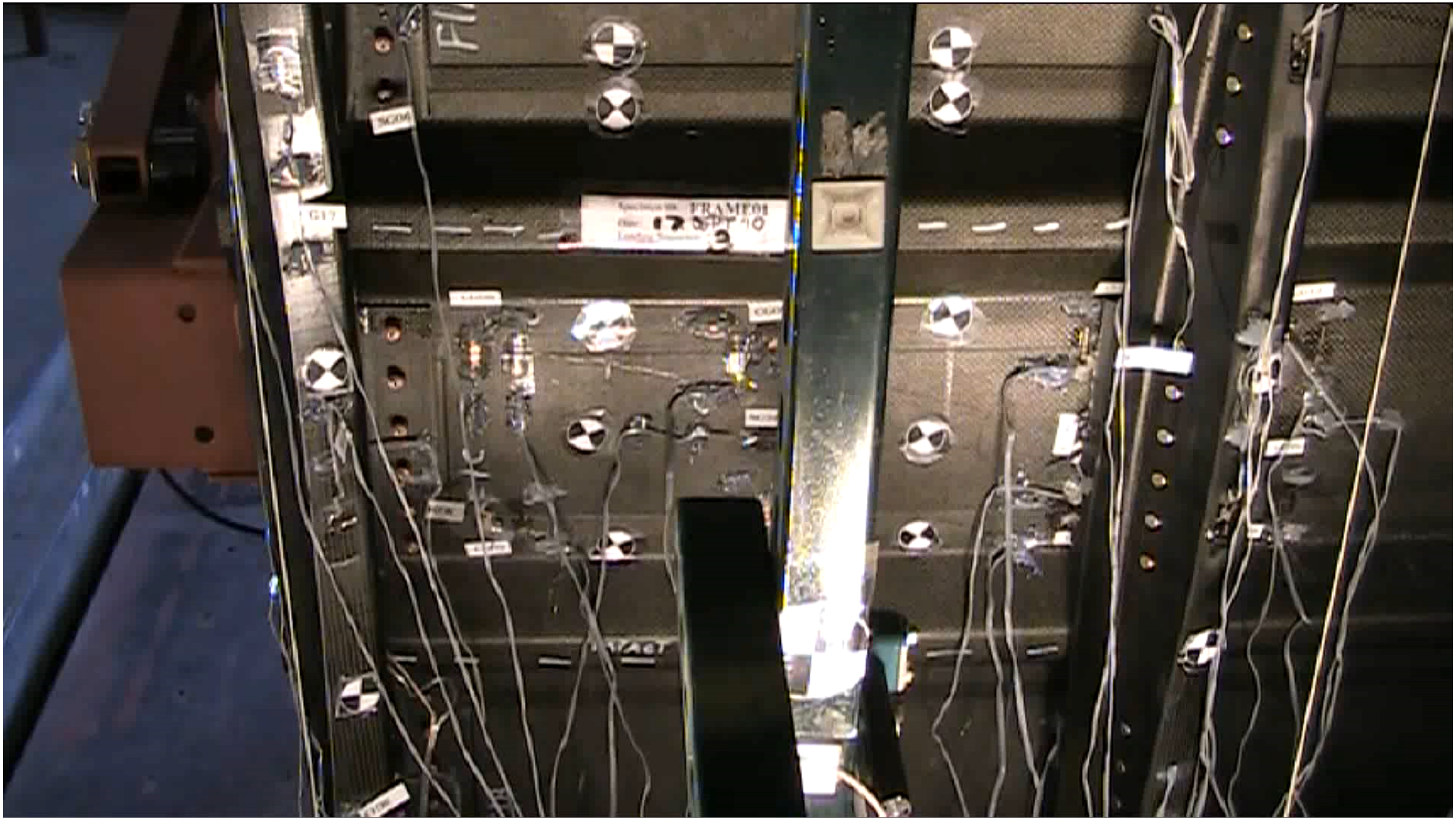
Blunt Impact Test



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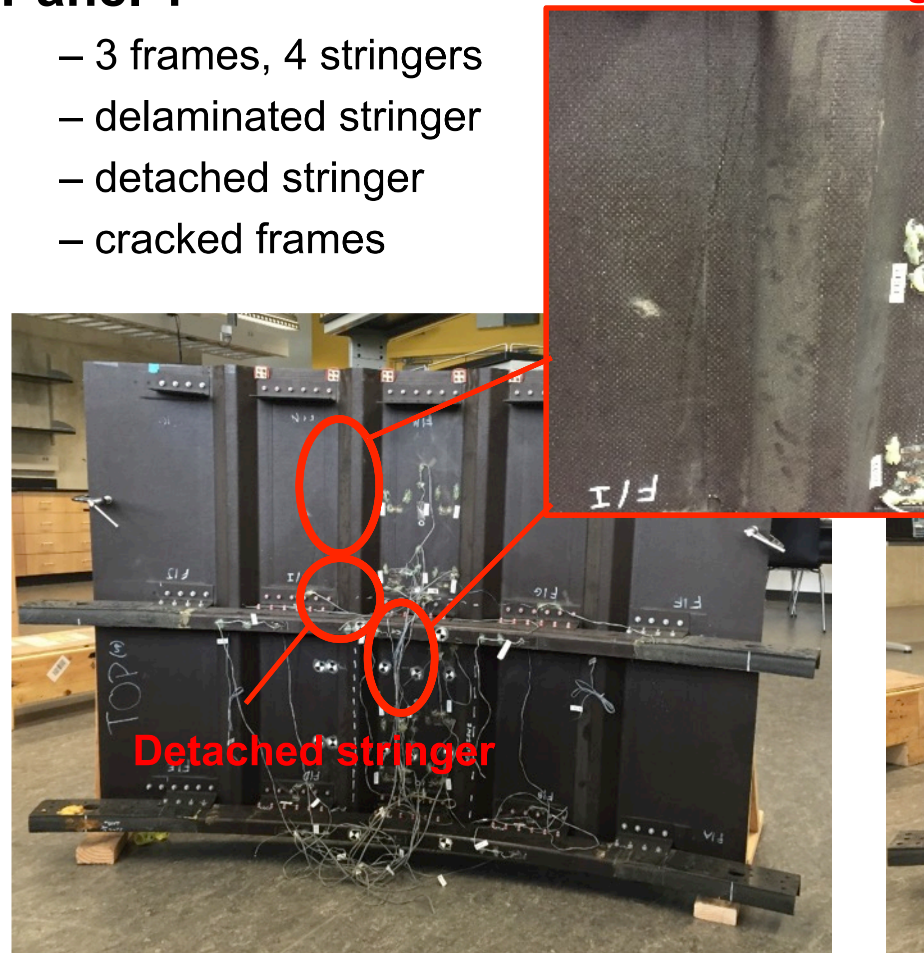
Damage Survey: Test Panels 01 and 02

Panel 1

- 3 frames, 4 stringers
- delaminated stringer
- detached stringer
- cracked frames

Delaminated stringer



Panel 2

- 3 frames, 5 stringers
- cracked stringer
- cracked skin
- cracked frames

Cracked stringer

Cracked skin

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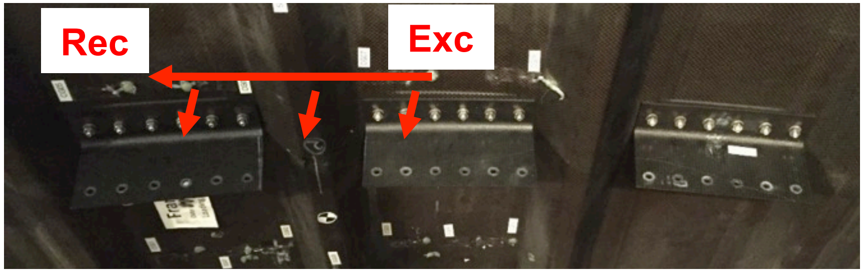
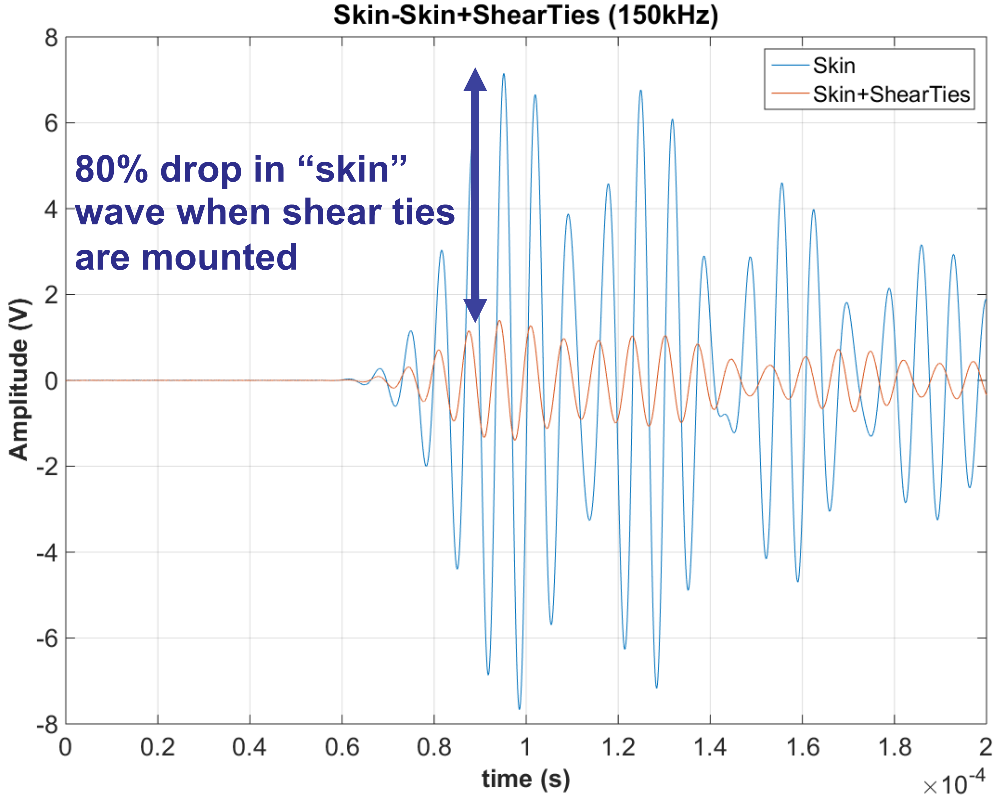
Selected Component Testing: no C-frames



- Frequency sweep range: 130-180 kHz
- Conclusion: shear ties absorb much of the wave energy travelling through the skin (good to detect internal damage from the skin side).



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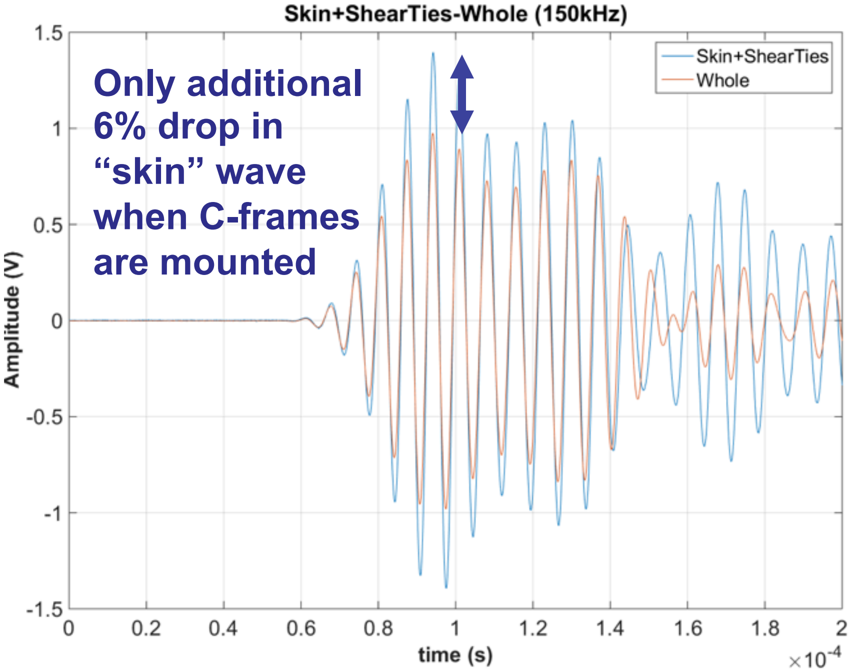
Selected Component Testing: fully assembled panel

- Frequency scan range: 130-180 kHz
- Conclusion: C-frame absorbs little of the propagating wave energy (could test lower frequencies to penetrate C-frames from the skin side)



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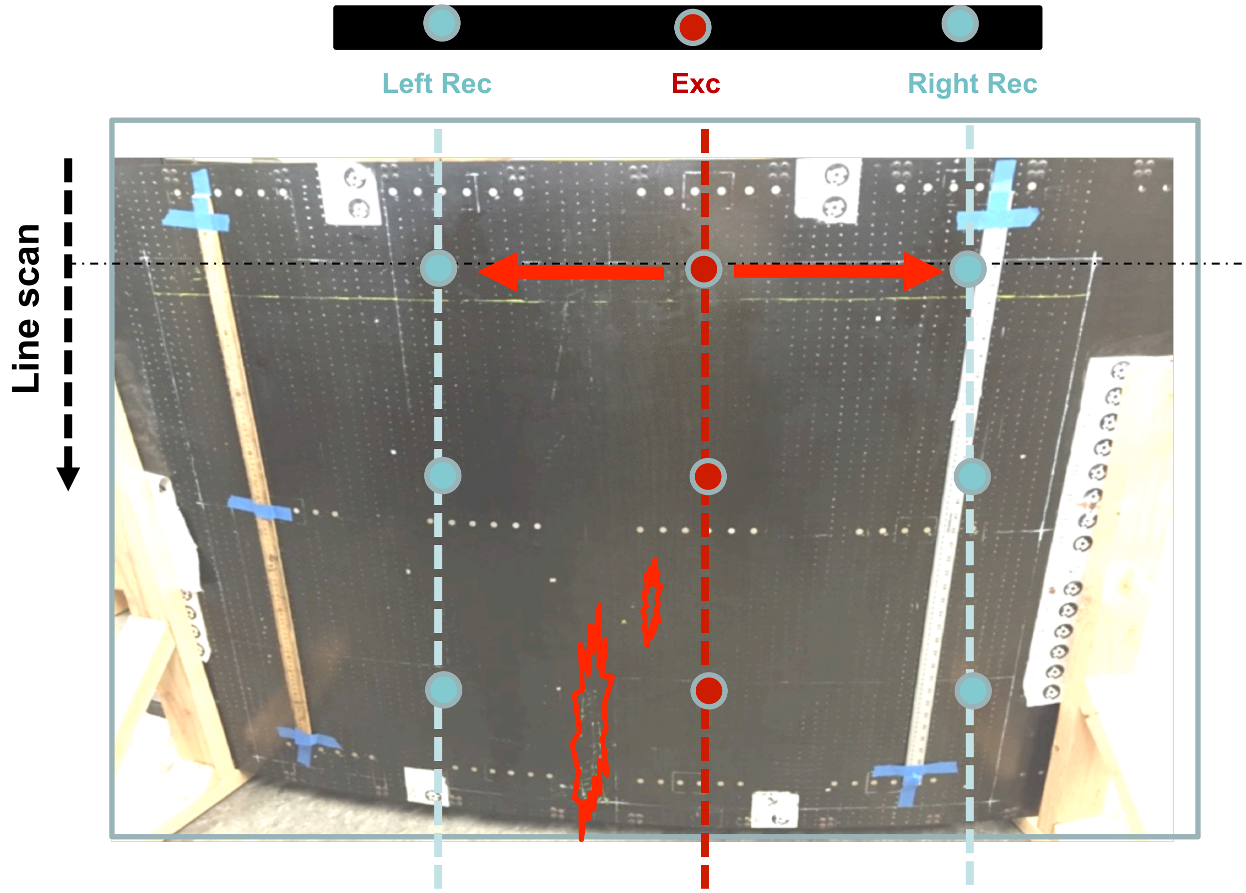
Statistical Outlier Analysis

Purpose: maximize True Detections of damage and minimize False Positives

Line scan approach with differential probe



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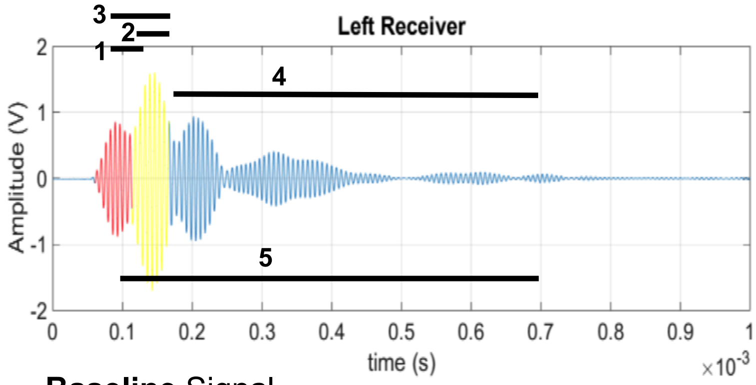
Statistical Outlier Analysis

Statistical processing algorithm:



Baseline Signal
(six possible time gates)

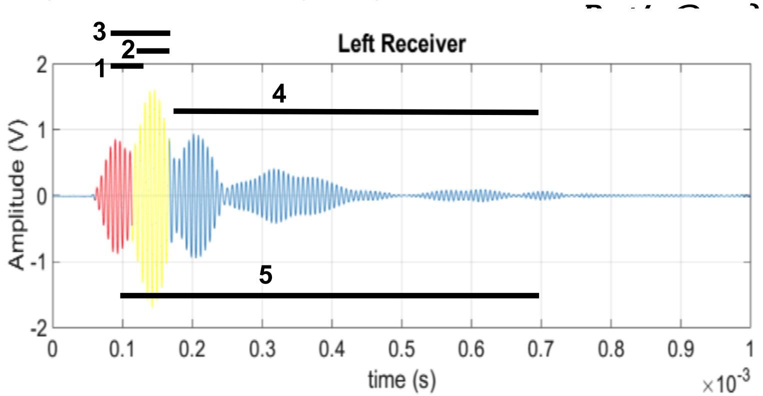
Feature Vector
("balance" metric)

x={■Rms
Ratio@Rms
Norm@■DI
Max@Ppk

Baseline Vector
Average, Covariance

x , C

Test Signal
(six possible time gates)



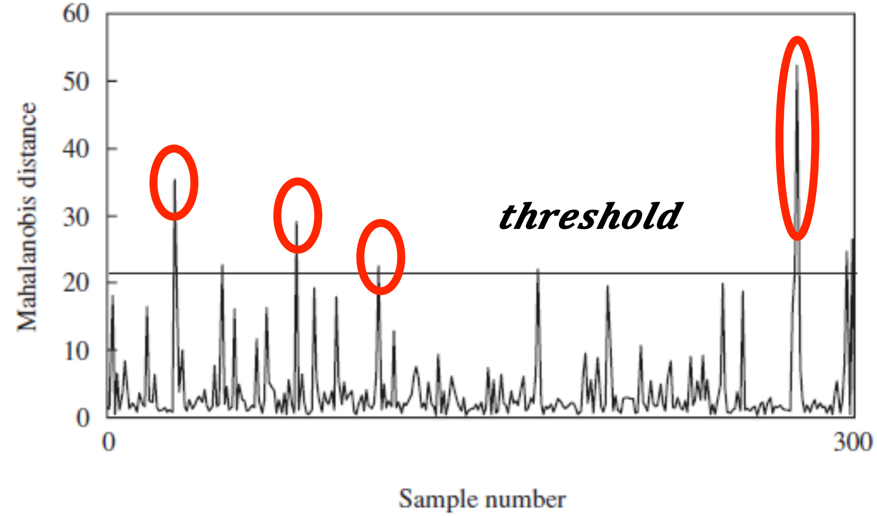
Test Vector

$x↓$

Damage Index (DI) :

(Mahalanobis Squared Distance**)**

$(x-x)*C^{-1}*(x-x)^{T}$

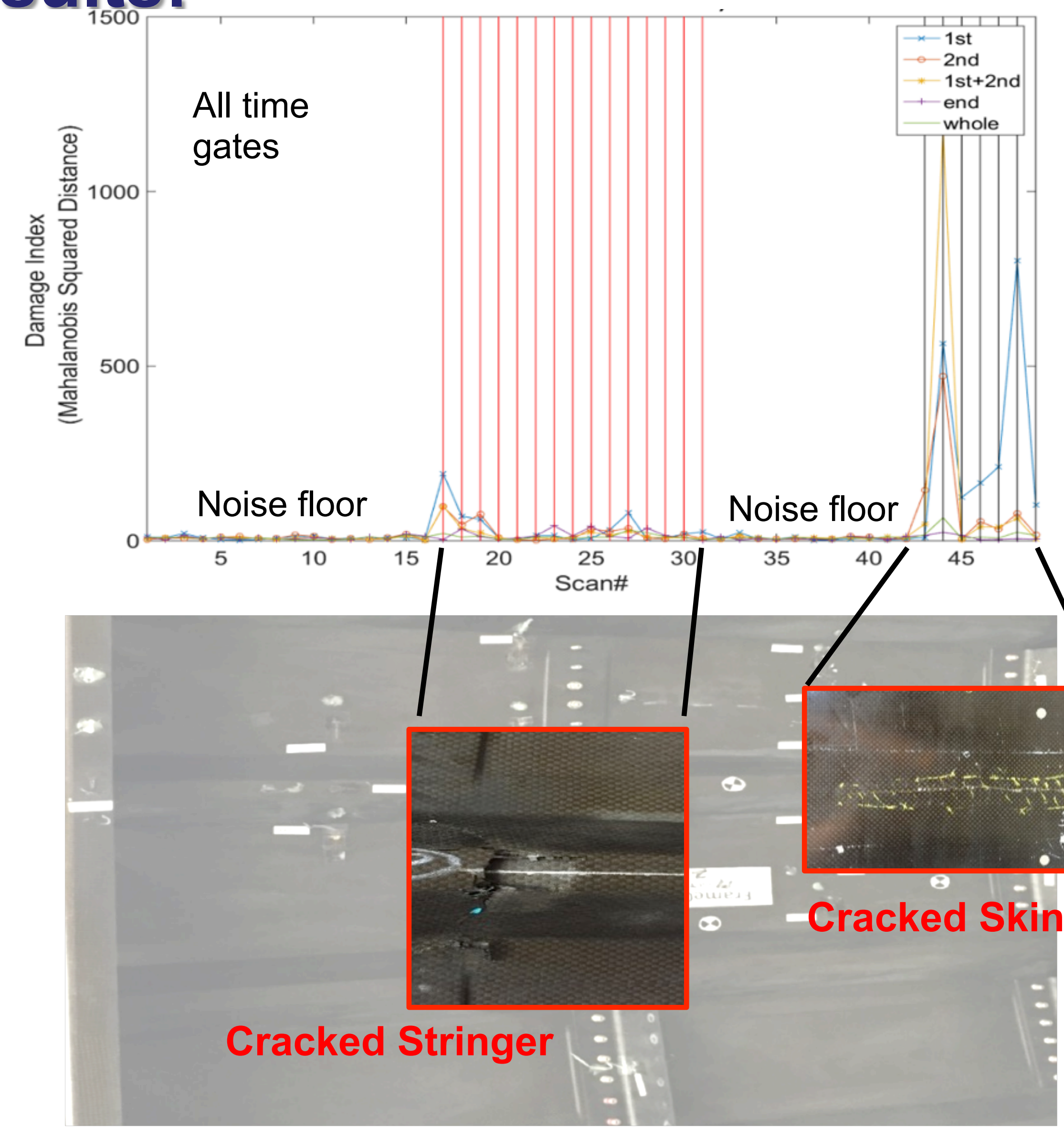


If DI>threshold ⟹ **DEFECT**

Outlier Analysis Results: Panel 2

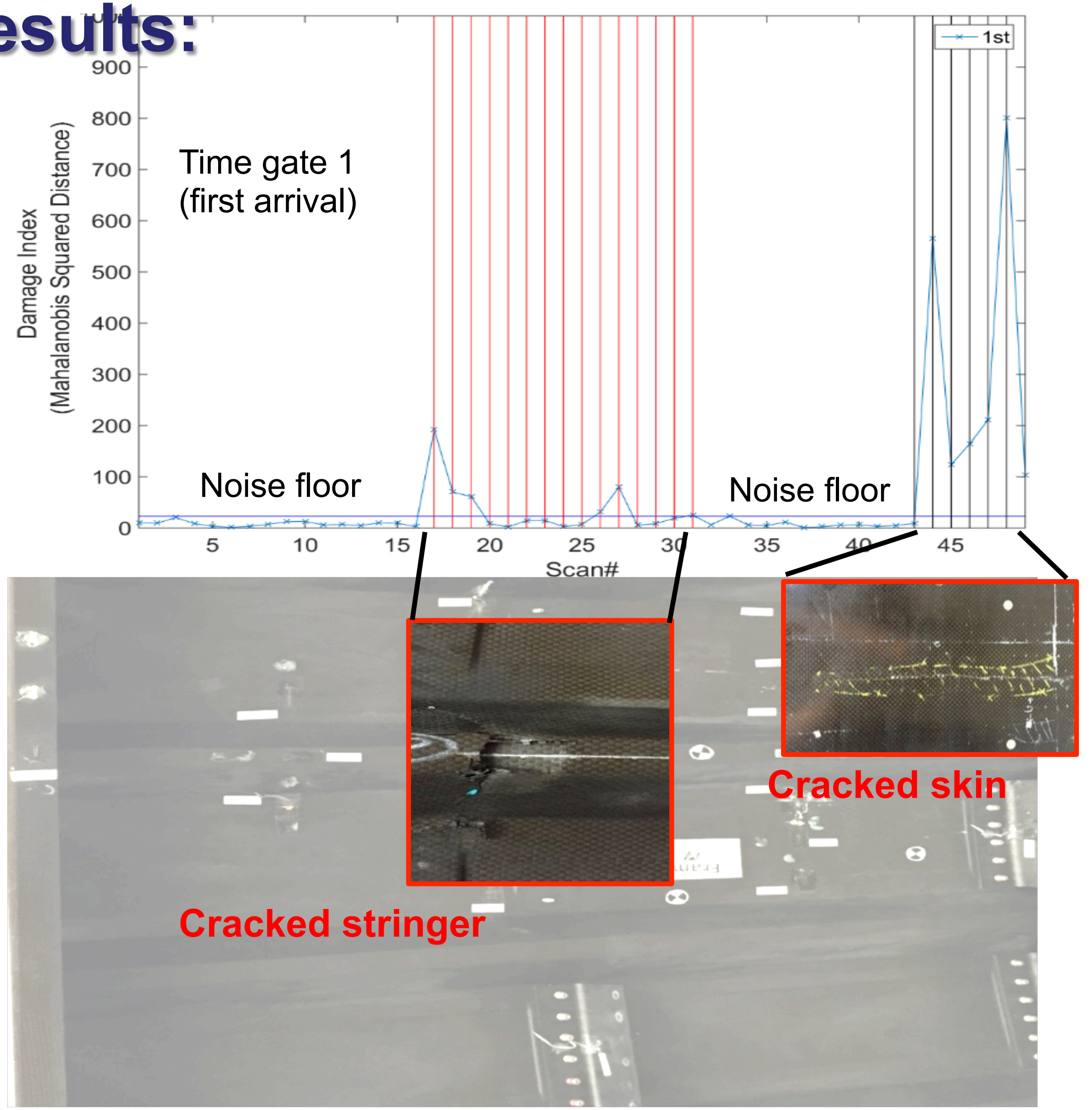
Panel 2 test details:

- Total scan lines: 49
- Scan lines at damage sites: 15 (cracked stringer), 7 (cracked skin)
- Scan step: 2 cm (nominal), 0.5 cm for cracked stringer



Conclusion: both defects clearly detected by large Damage Index values. Very low “noise” floor.

Outlier Analysis Results: Panel 2



Conclusion: both defects clearly detected by large Damage Index values. Very low “noise” floor.

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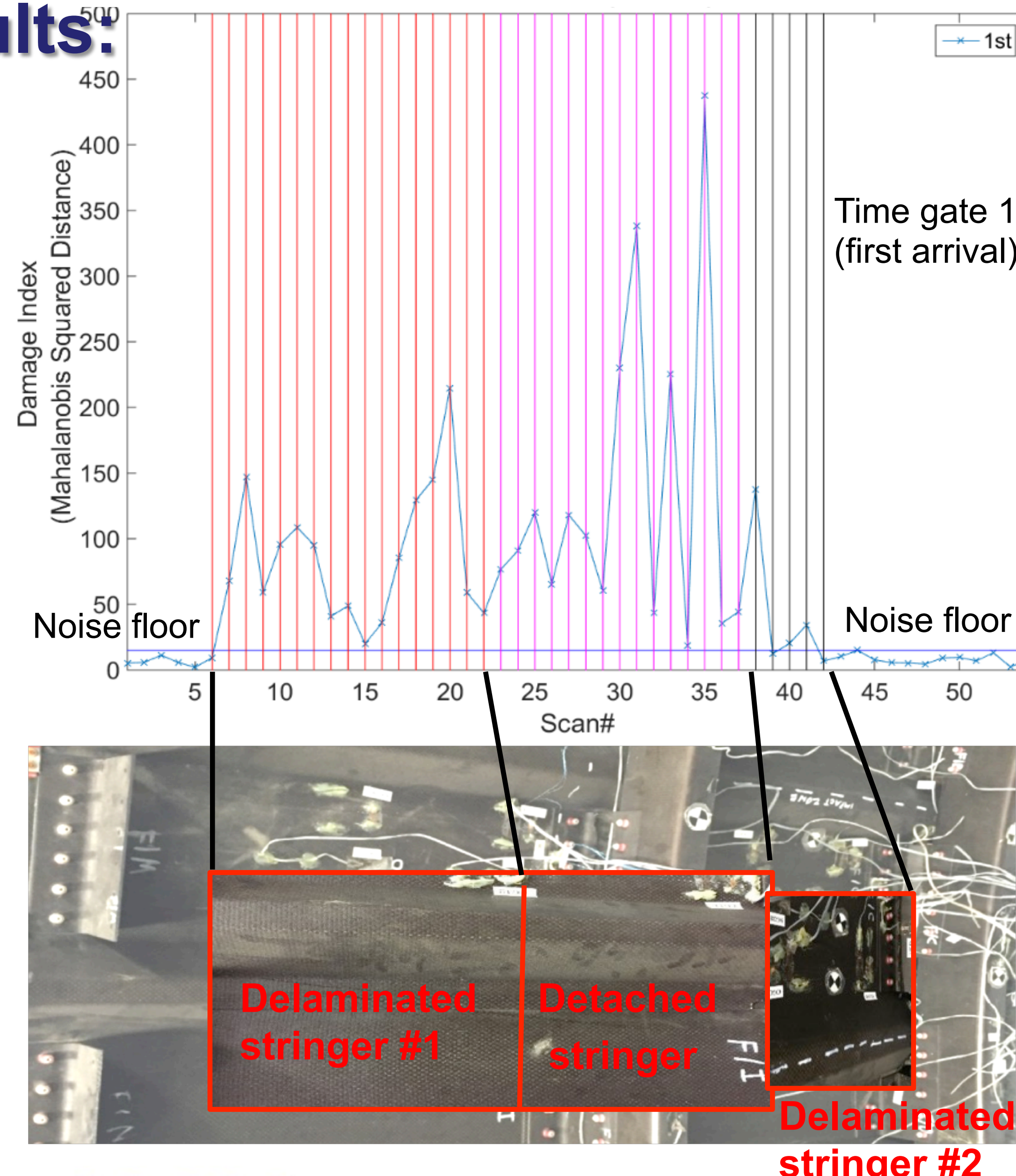
Outlier Analysis Results: Panel 1

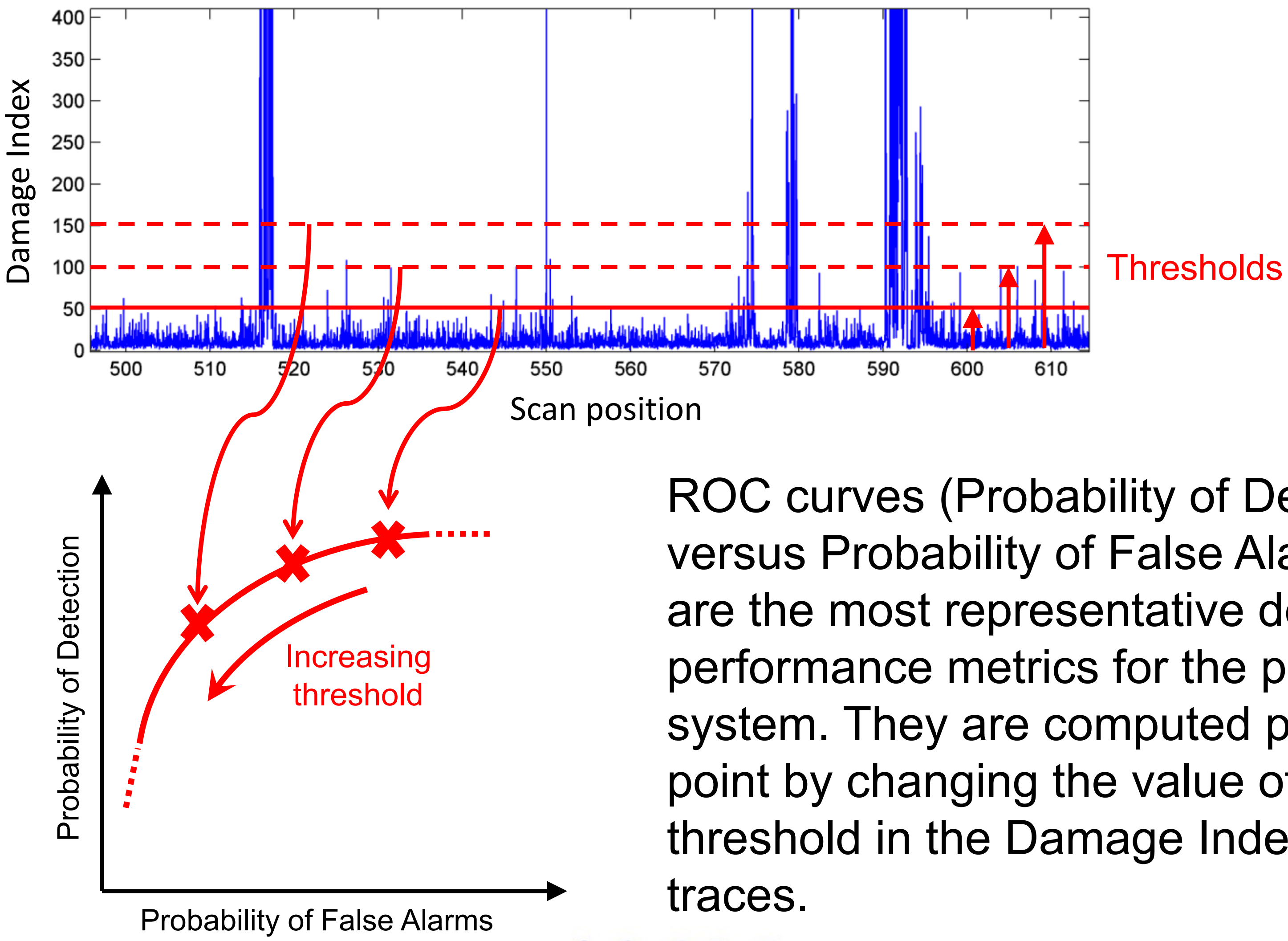
Panel 1 test details:

- Total scan lines: 54
- Scan lines at damage sites: 17 (delaminated stringer #1), 15 (detached stringer), 5 (delaminated stringer #2)
- Scan step: 2 cm (nominal), 0.5 cm for delaminated stringers, 1 cm for detached stringer



Conclusion: all three defects clearly detected by large Damage Index values. Very low “noise” floor.

Receiver Operating Characteristic (ROC) Curves Computation



ROC curves (Probability of Detection versus Probability of False Alarms) are the most representative detection performance metrics for the proposed system. They are computed point-by-point by changing the value of the threshold in the Damage Index traces.

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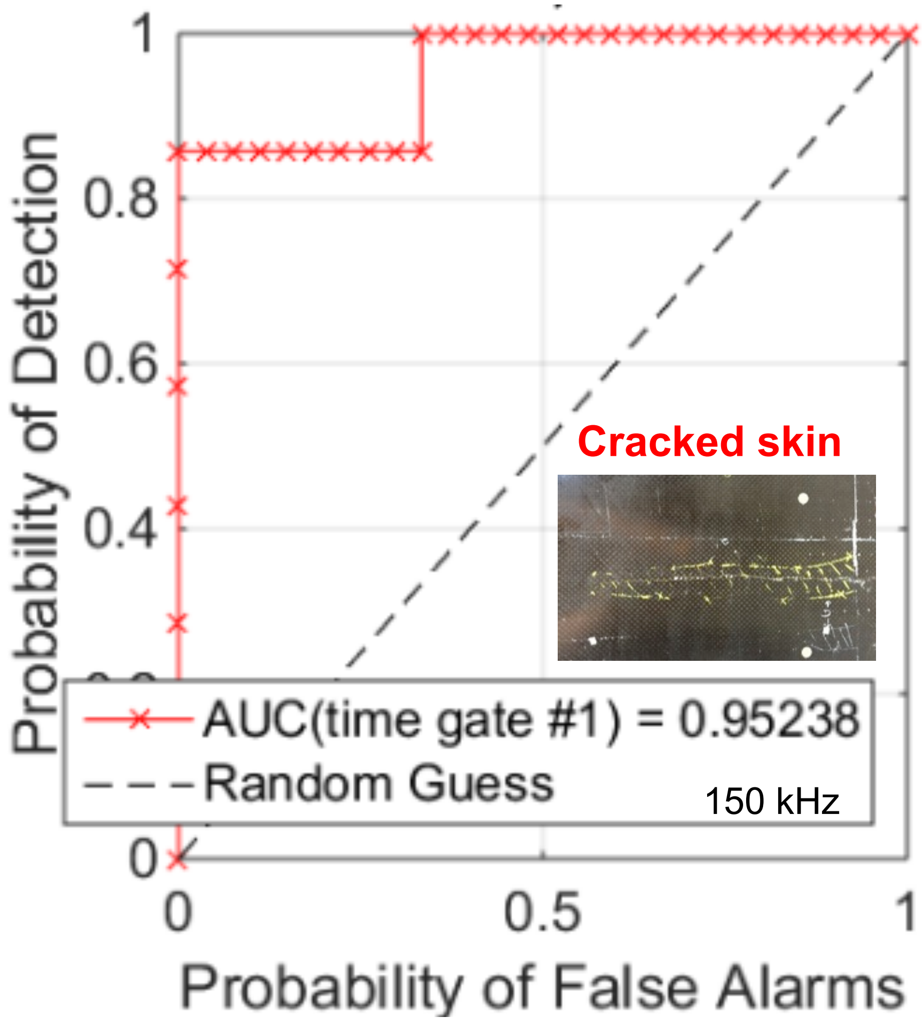
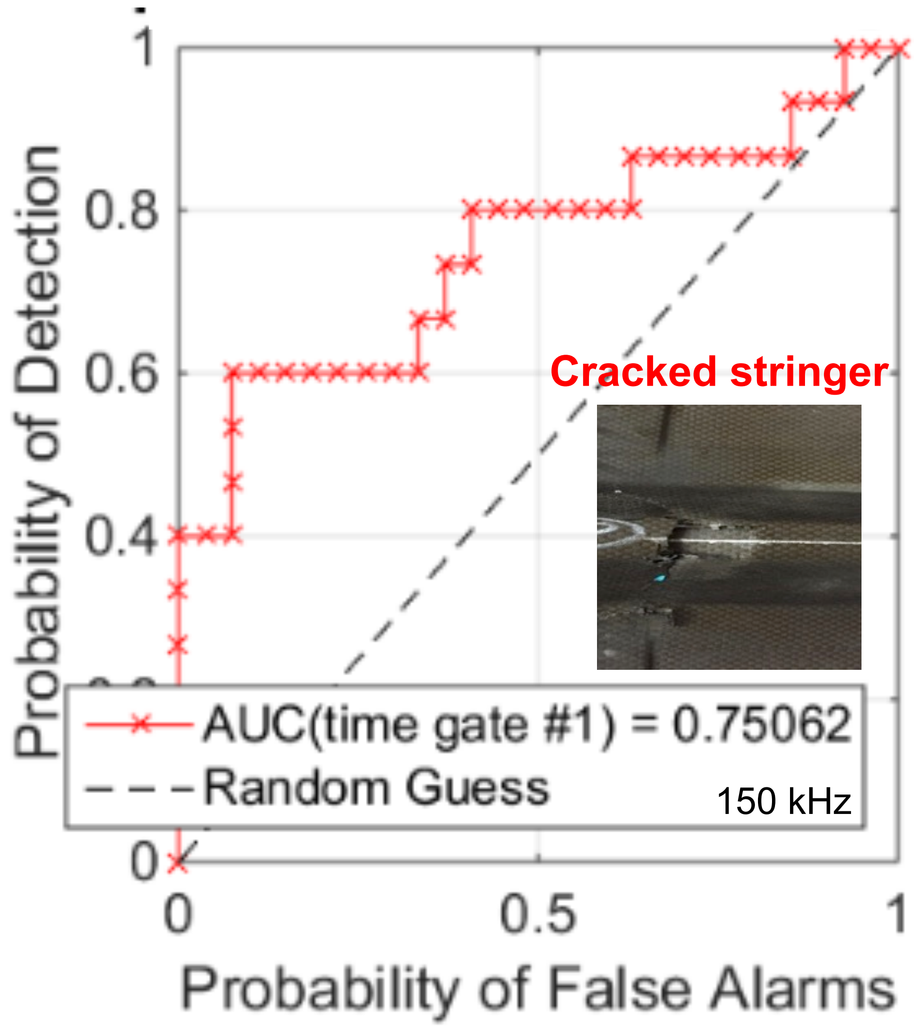
ROC Curve Results: Panel 2

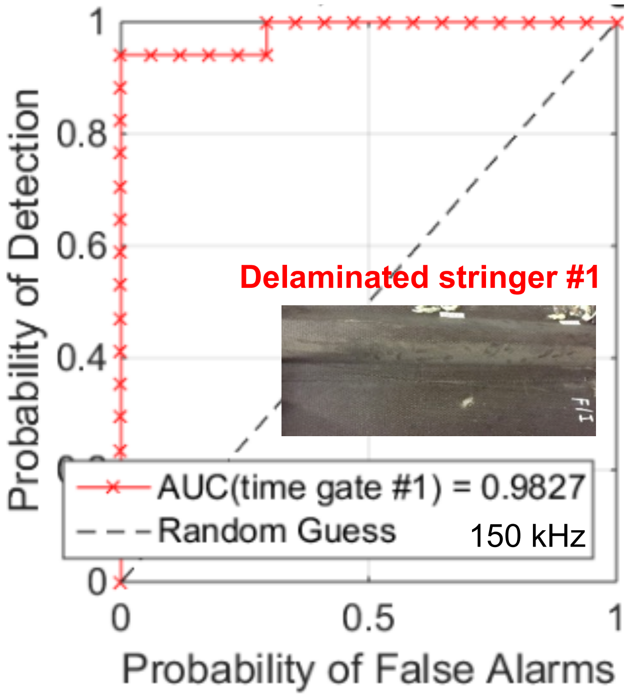


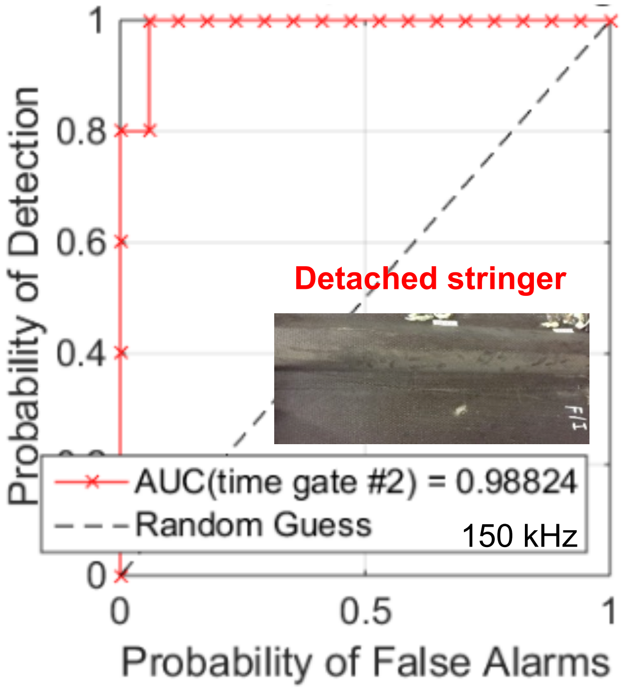


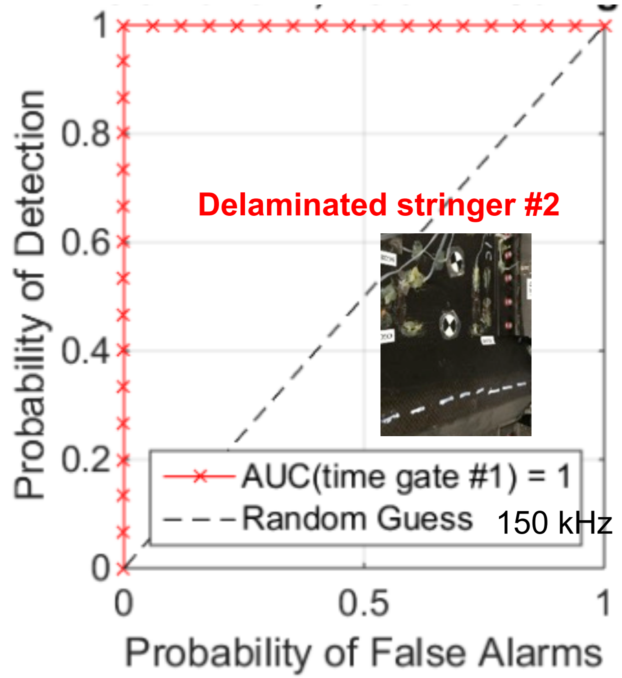
Excellent detection : 85% POD with 0% PFA, or 100% POD with 30% PFA

OK detection : 60% POD with 10% PFA, or 80% POD with 45% PFA

ROC Curve Results: Panel 1







Excellent detection :
95% POD with 0% PFA

Excellent detection :
80% POD with 0% PFA, or
100% POD with 10% PFA

PERFECT detection :
100% POD with 0% PFA

Conclusions

- A first-generation NDE methodology and prototype were developed to detect major damage in aerospace panels probed from the skin side

- The waveguide geometry of the panel was first studied by experiments and Finite Element Analyses

- The proposed NDE prototype relies on a differential ultrasonic detection scheme that detects damage as an “unbalance” between the two receptions, followed by a statistical analysis aimed at maximizing Probability of Detection (POD) and minimizing Probability of False Alarms (PFA)

- The prototype was tested on previously-impacted panels, and its performance was assessed by the computation of ROC curves.

- The ROC results indicated excellent detection performance, with very few false alarms, for Cracked Skins, Delaminated Stringers, and Detached Stringers, with more modest performance for Cracked Stringers.

Benefits to Aviation

- A method for detecting damage to internal structures is needed since typical ultrasonic one-sided inspection can't detect these damage modes.
- Relatively quick and non-invasive detection method can be applied following event involving contact with GSE.
- Inspection method can prospectively provide enhanced detection capability:
  - possibly can be supplement to visual inspection (cracks difficult to see on black carbon/epoxy)
  - could be incorporated into scheduled inspection procedures

Looking Forward

- The probing ultrasonic frequencies utilized in the first-generation prototype (largely determined by PZT transducers used) were likely too high to penetrate into the C-frames, i.e. damage in frames would be currently difficult to detect. Lower frequencies (i.e. different transducers) should be considered to detect damage in frames.

- A larger variety of damage types should be tested for a more comprehensive assessment of the NDE prototype through the computation of additional ROC curves.

- Additional tests could also be used to identify a statistical correlation of the ultrasonic measurements with the location, mode and severity of damage.

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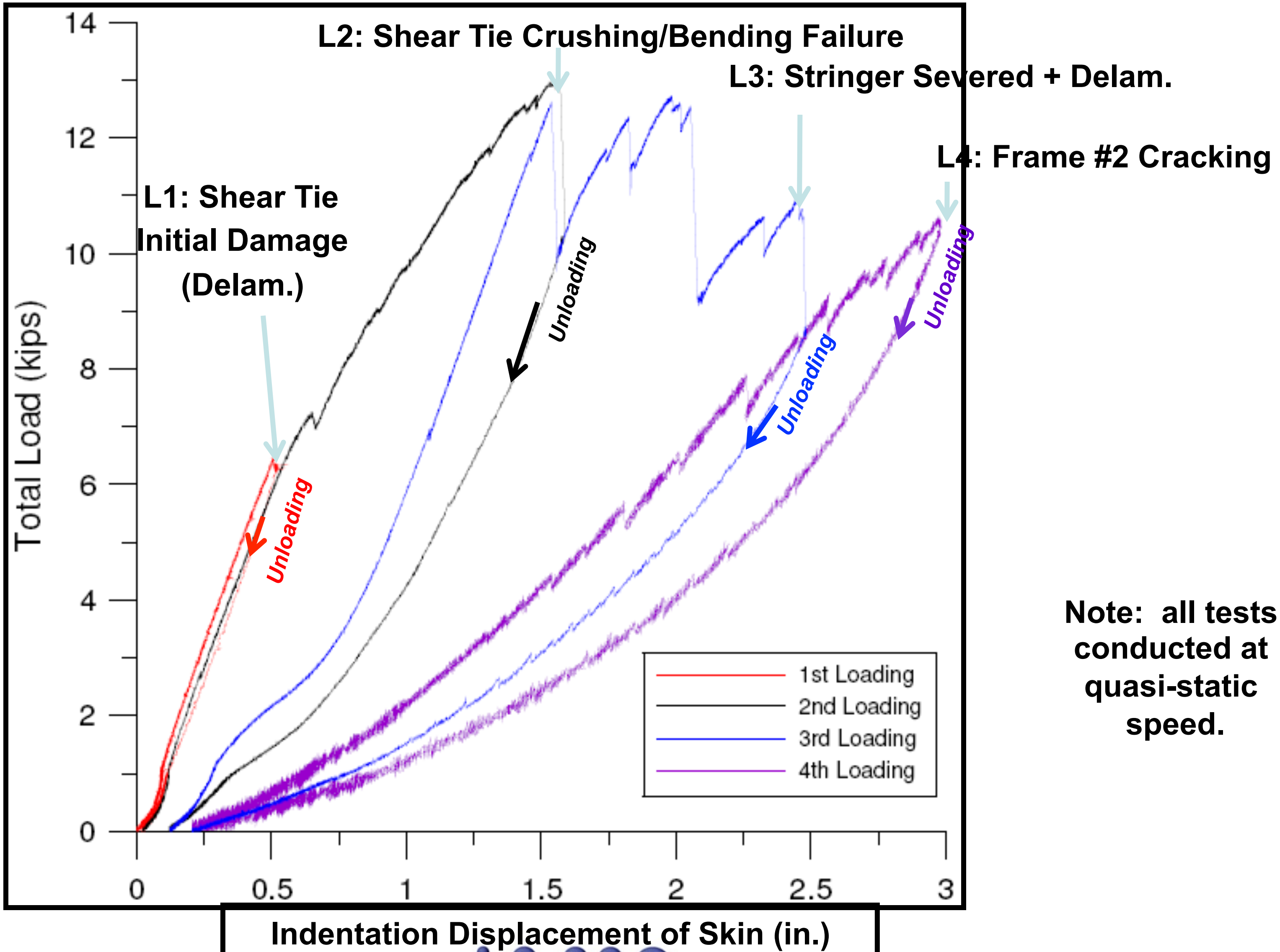
Specimen Frame01 Load vs. Indentation

High Energy Wide Area Blunt Impact on Composite Aircraft Structures (DeFrancisci, 2013)



Note: all tests conducted at quasi-static speed.

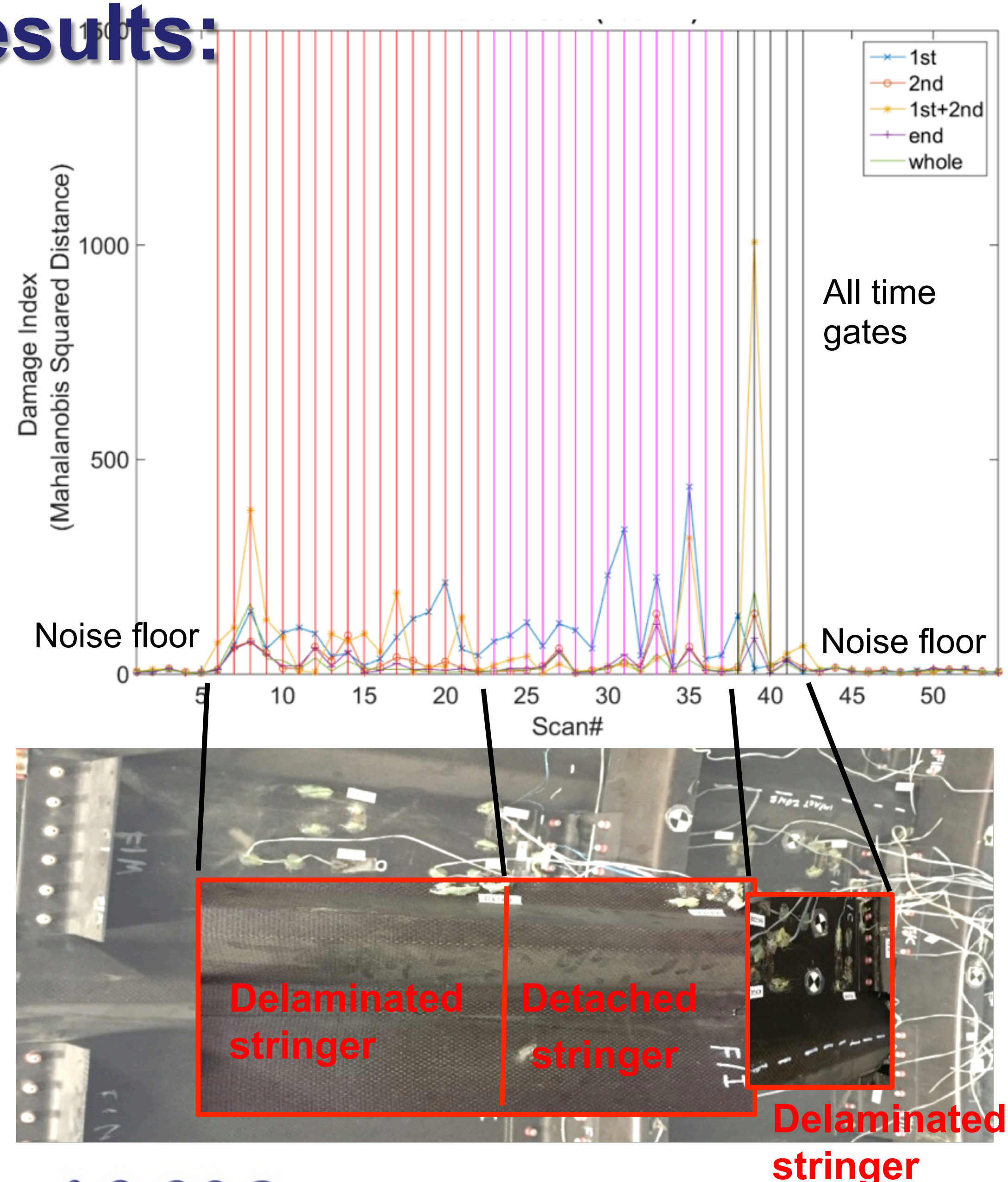
Outlier Analysis Features

- Rms Ratio: RMS_1/RMS_2
- Rms Normalized: $|RMS_1 - RMS_2|/\sqrt{RMS_1 * RMS_2}$
- Max (DI Max): $Max(Max|1|/Max|2|, Max|2|/Max|1|)$
- Area Ratio: $Area_1/Area_2$
- Peak to Peak Ratio: $|Ppk_1 - Ppk_2|/\sqrt{Ppk_1 * Ppk_2}$
- Max (PPk Ratio): $Max(Max|Ppk_1|/Max|Ppk_2|, Max|Ppk_2|/Max|Ppk_1|)$

- Area FFT Ratio: $|AreaFFT_1 - AreaFFT_2|/\sqrt{AreaFFT_1 * AreaFFT_2}$
- Rms Difference: $RMS(2-1)$

Outlier Analysis Results: Panel 1

Conclusion: all three defects clearly detected by large Damage Index values. Very low “noise” floor.



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