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Impact Damage Tolerance Guidelines for Stiffened Composite Panels

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Virtual Meeting

Participants

- **Principal Investigators & Researchers**
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  - Co-PI: Prof. Francesco Lanza di Scalea
  - Graduate Students
    - PhD: Chaiane Wiggers de Souza, Ben Katko, Chengyang Huang, Janelle Dela-Cueva, Ranting Cui*, Margherita Capriotti*, Eric Kim*
    - MS: none

** graduated since last review mtg (2019)*

- **FAA Technical Monitors**
  - Lynn Pham, Ahmet Oztekin

- **Other FAA Personnel Involved**
  - Larry Ilcewicz

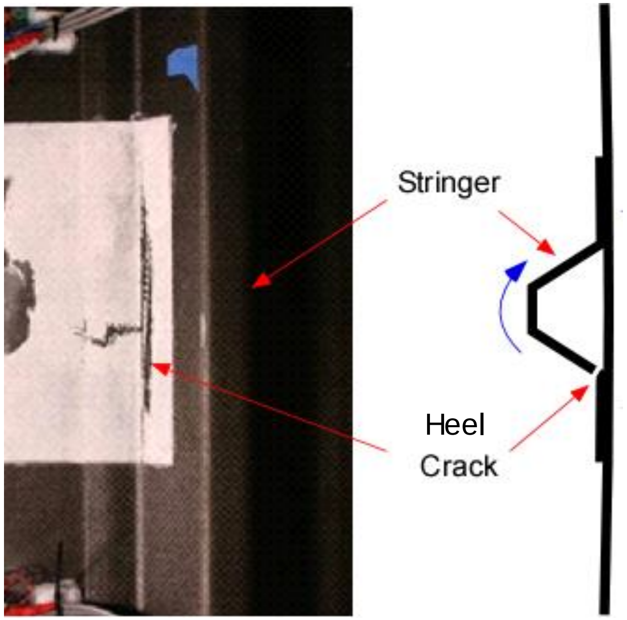
Motivation

- Impact to composite structures can cause internal damage
  - difficult to detect via visual inspection
- Ultrasonic guided wave (UGW) based inspection found to be sensitive to presence of internal damage
- External-only NDE needed as well as large-area fast inspection

Overall Objectives:

- Quantify detectable and non-detectable damage characteristics
- Relate Ultrasonic Guided Wave NDE measurements to damage state and **residual strength**

High Energy Wide Area Blunt Impact (HEWABI)



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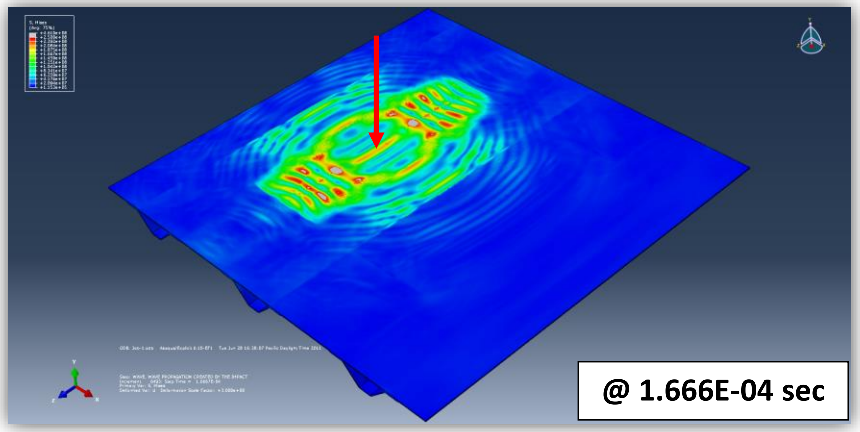
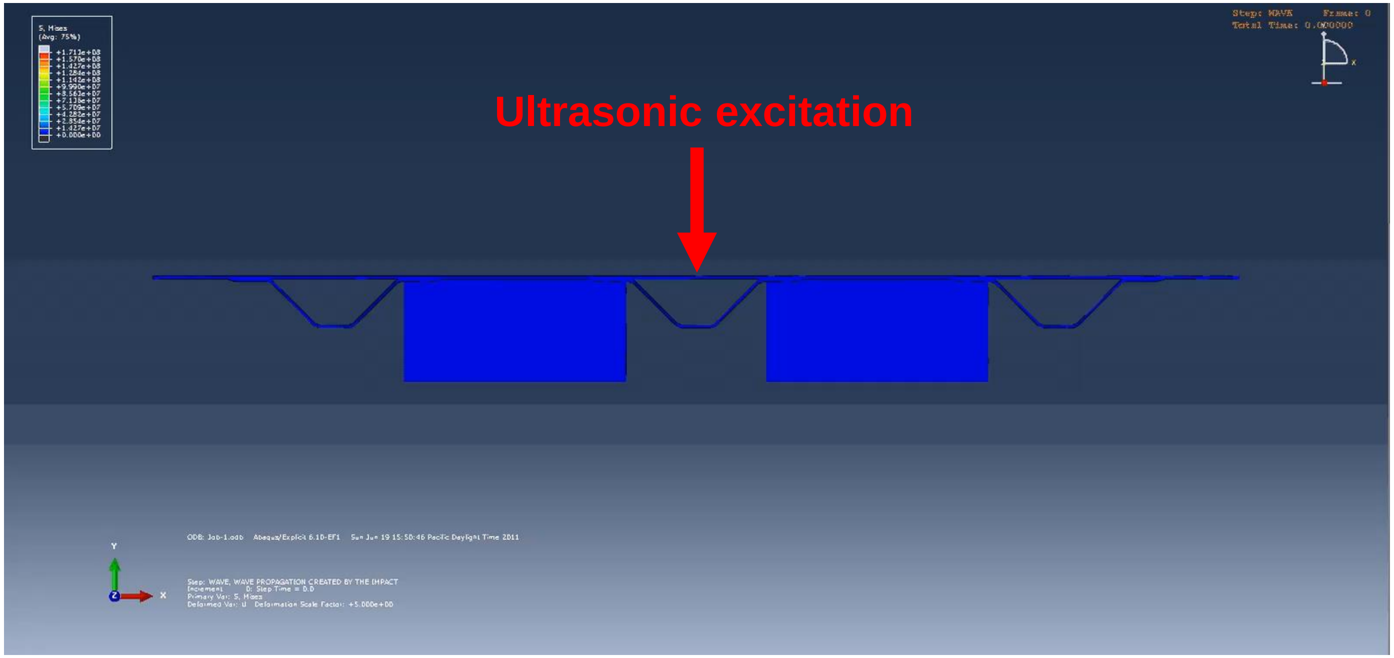
Ultrasonic Guided Waves: structure is a natural "waveguide"

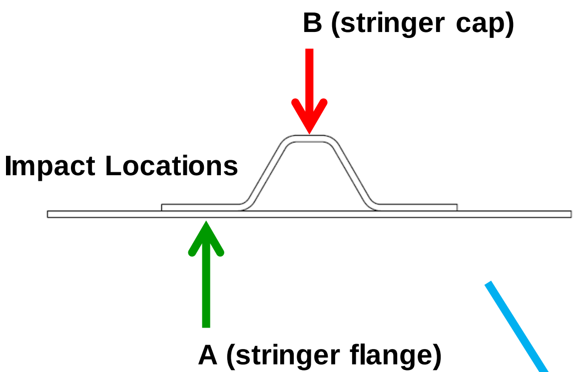


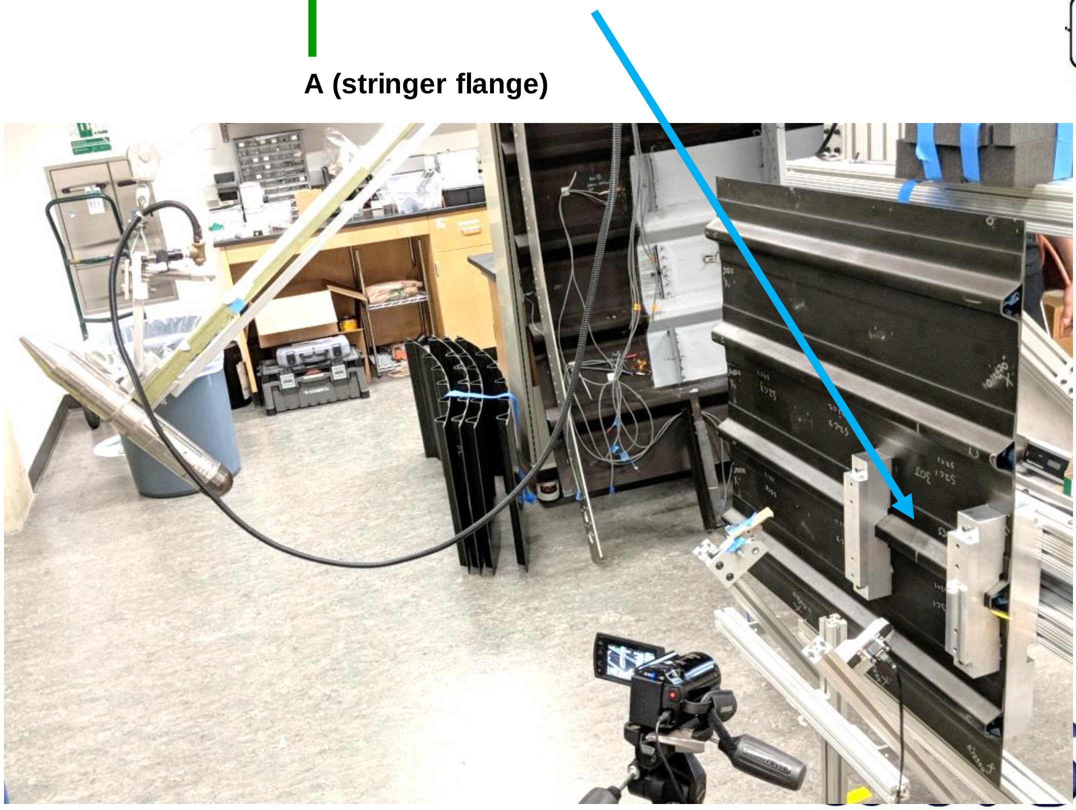


Previous Results Summary I: SIDO* Transfer Function Scanning Systems

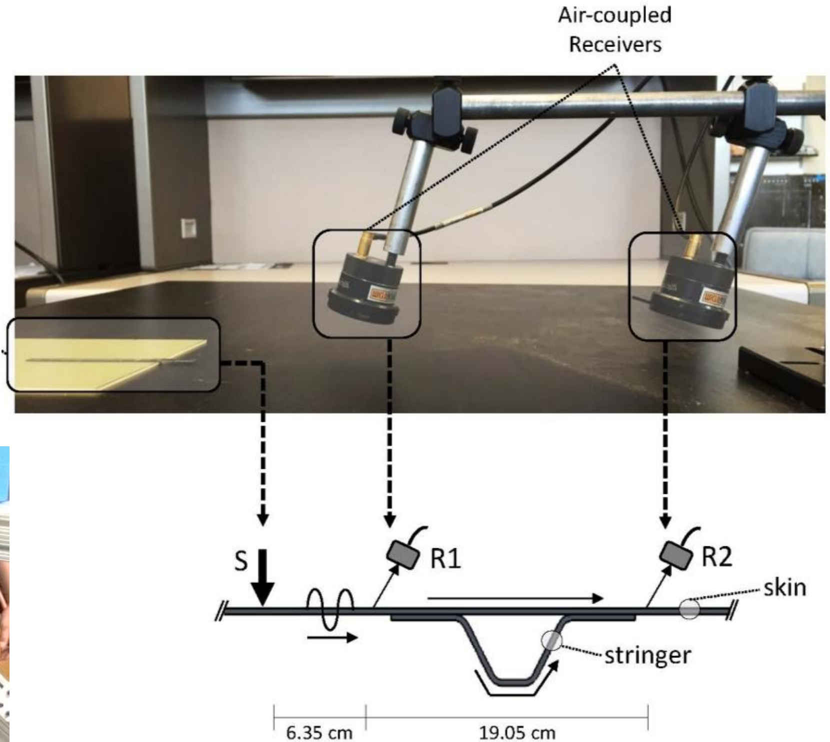
** Single Input Dual Output*

Impacts to Stringer-Stiffened Panel





Hybrid "Impact/Air-Coupled" Scanner

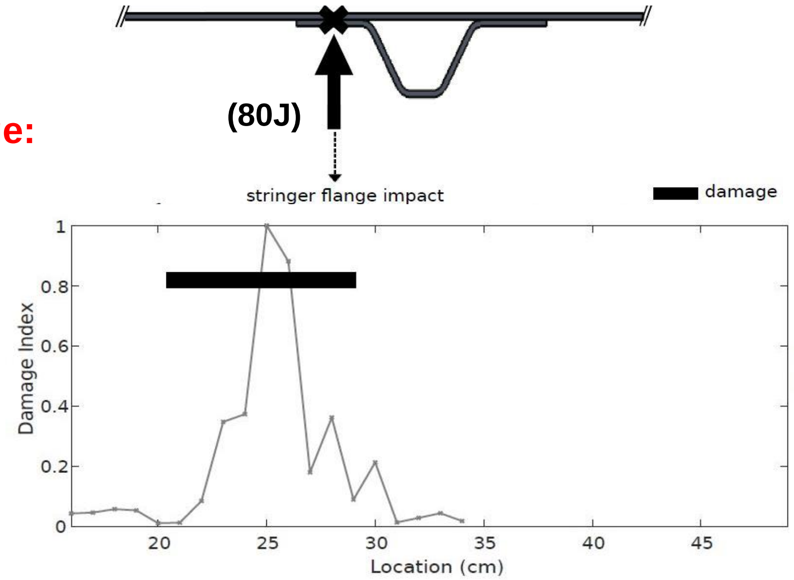


Mini-impactor + micro-machined capacitive transducers

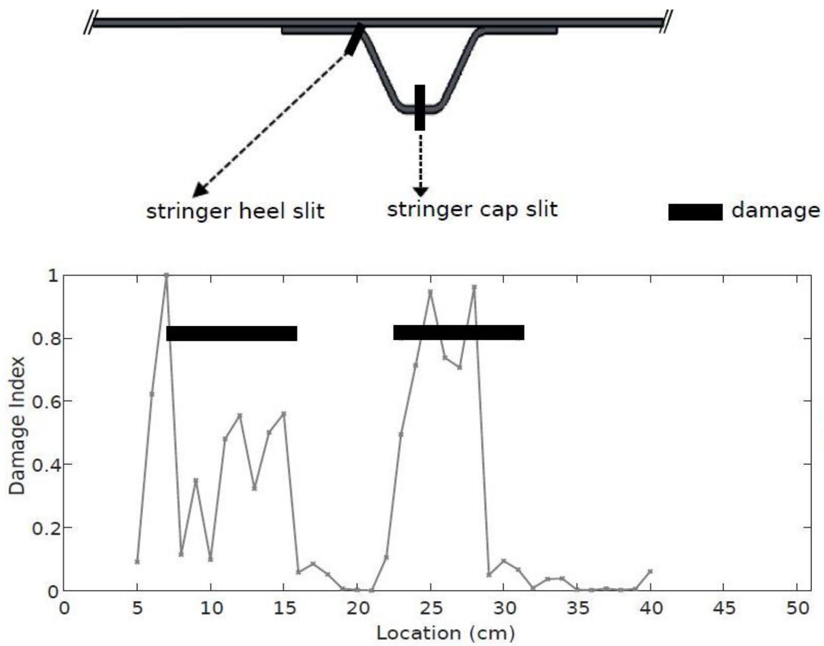
"low" and "broad" frequency band (40 – 270 kHz)

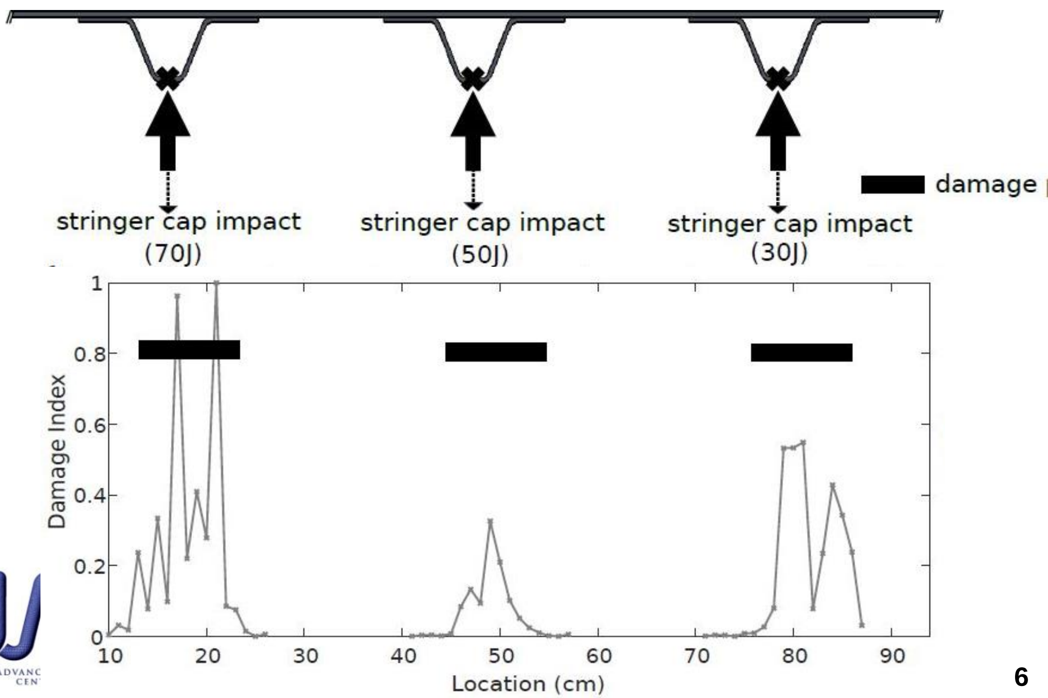
Previous Results Summary II: UGW Damage Detection

Actual Impact Damage:



Manufactured Damage – Saw Cuts





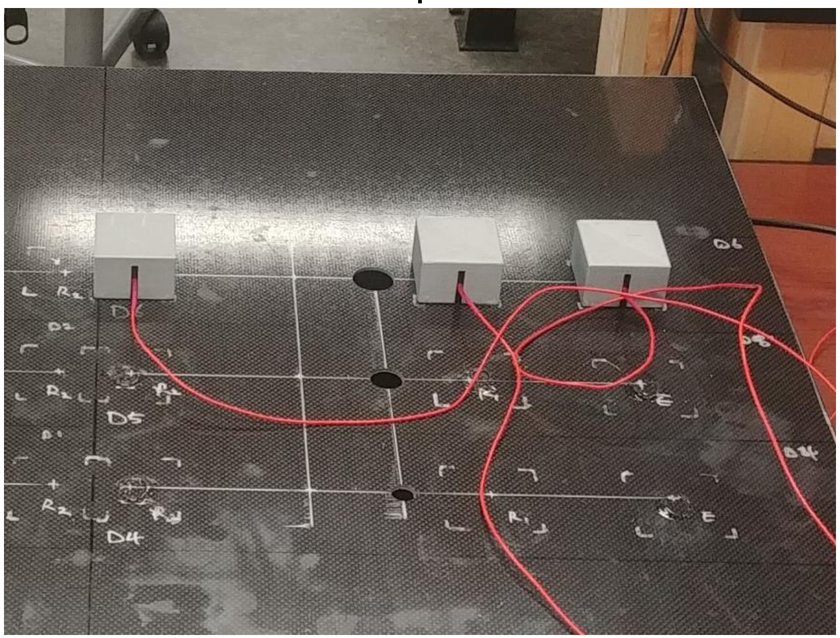
Hybrid impact/air-coupled scanner

(40 – 270 kHz)

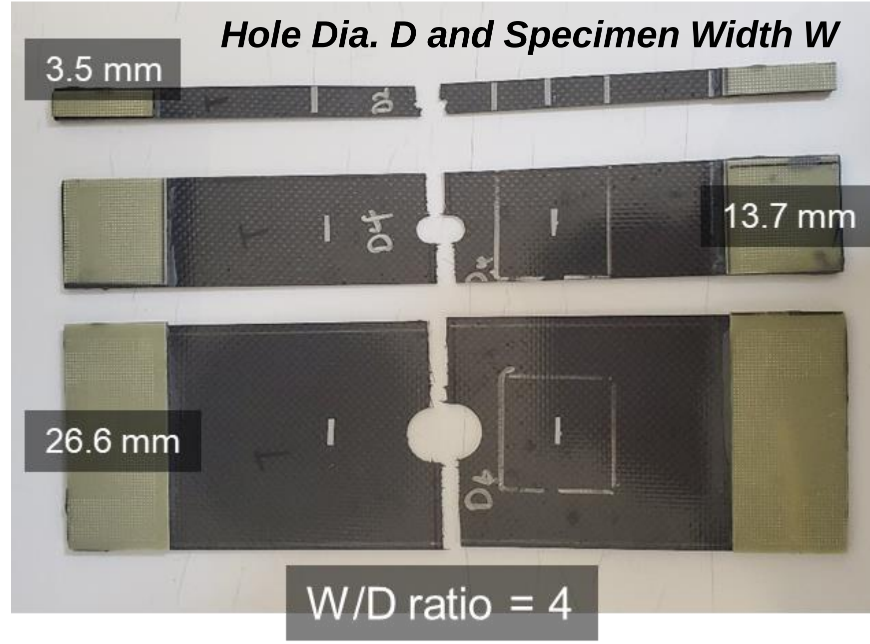
Previous Results Summary III: Residual Strength vs UGW

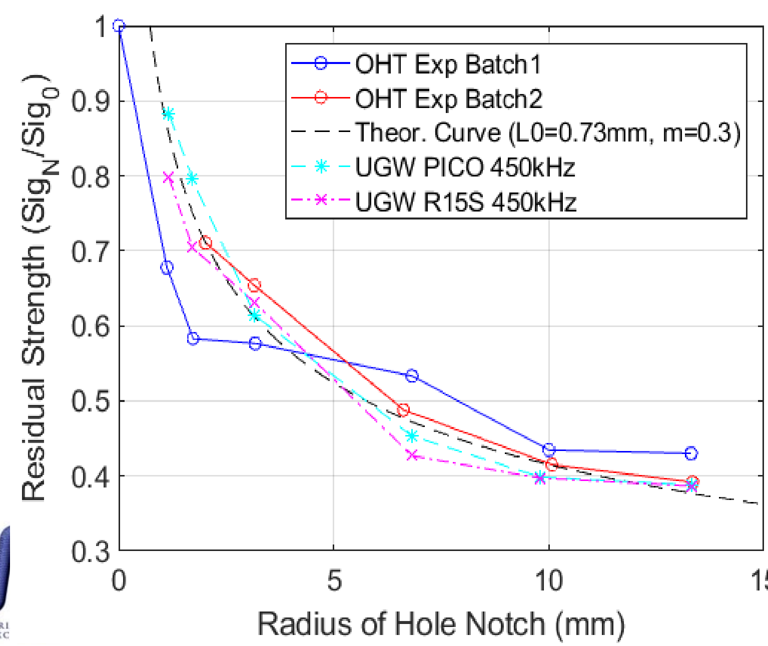
UGW vs OHT Experiments

Hexcel $[0]_{10}$ plain weave 282/SC780.
Holes from 2.5 mm to 25 mm dia, various frequencies



Comparison with UGW measurements show direct correlation between open hole tension strength reduction and signal attenuation.





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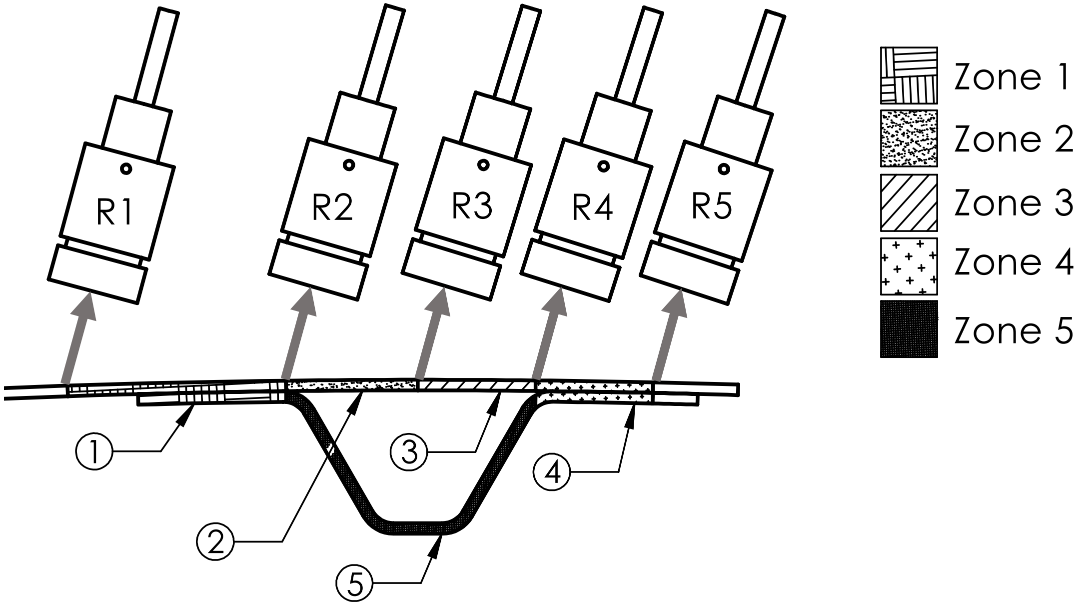
New Results

Damage Detection in Stringer-Stiffened Panels: 5-Sensor NDE Scanning System with Impact Excitation

- Goal 1: develop a non-contact guided-wave ultrasonic NDE system to detect internal damage in stringer-stiffened panels,
  - access limited to the external side (OML)
  - compensating for varying excitation
- Goal 2: detect damage in the scanning direction (along the stringer axis) and further locate damage in the cross-sectional direction

System scans in/out of page direction.



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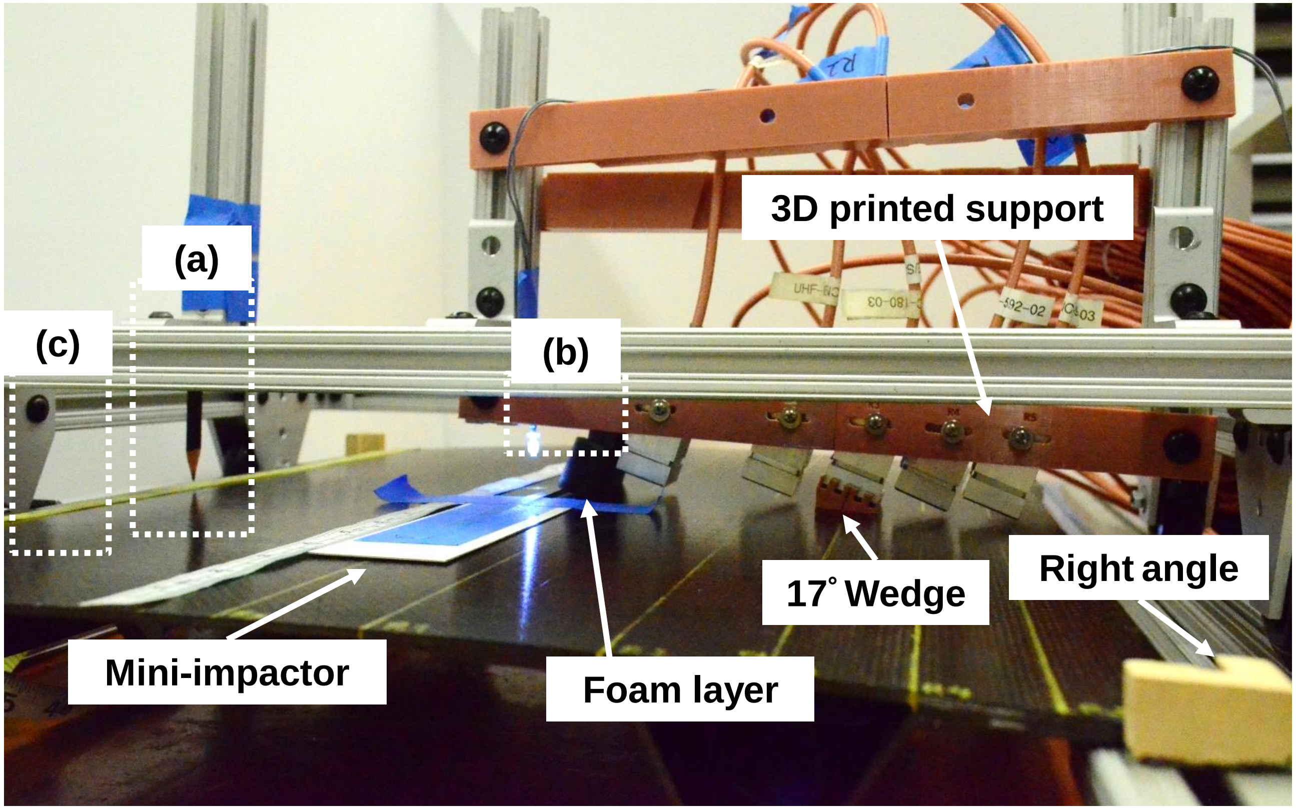
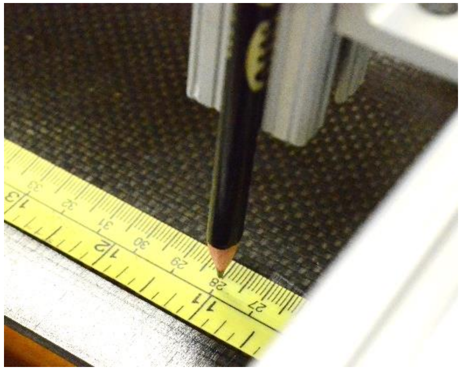
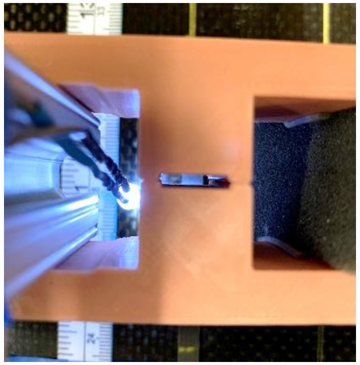
5-Sensor NDE Damage Detection Experimental Setup

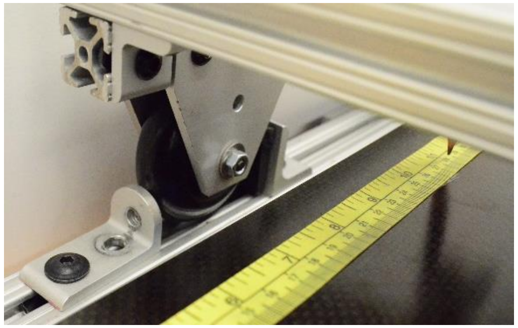




(a) Location needle



(b) Mini-impactor window & LED

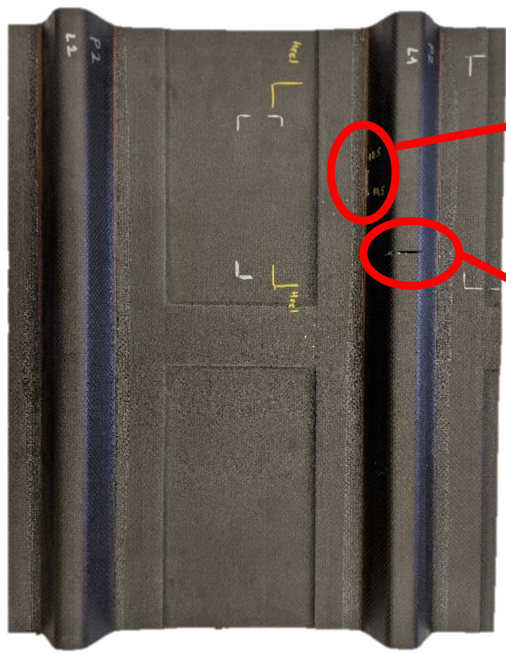


(c) Cart brakes

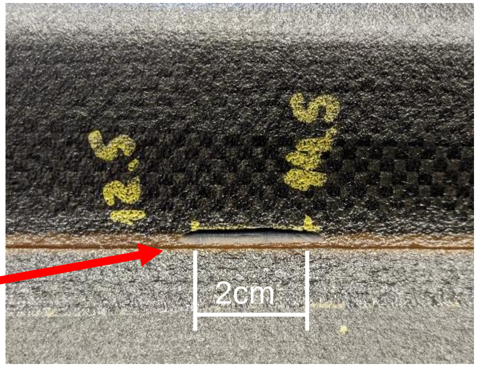
Specimens Description

- Curved 2-stringer carbon fiber-epoxy panel (unidirectional with woven outer plies)

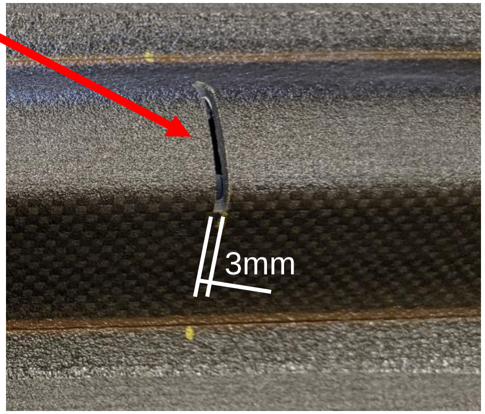
2-Stringer panel with added mass (2cm diameter steel nuts) simulating damage



2-Stringer panel with saw-cut notches



Stringer heel notch

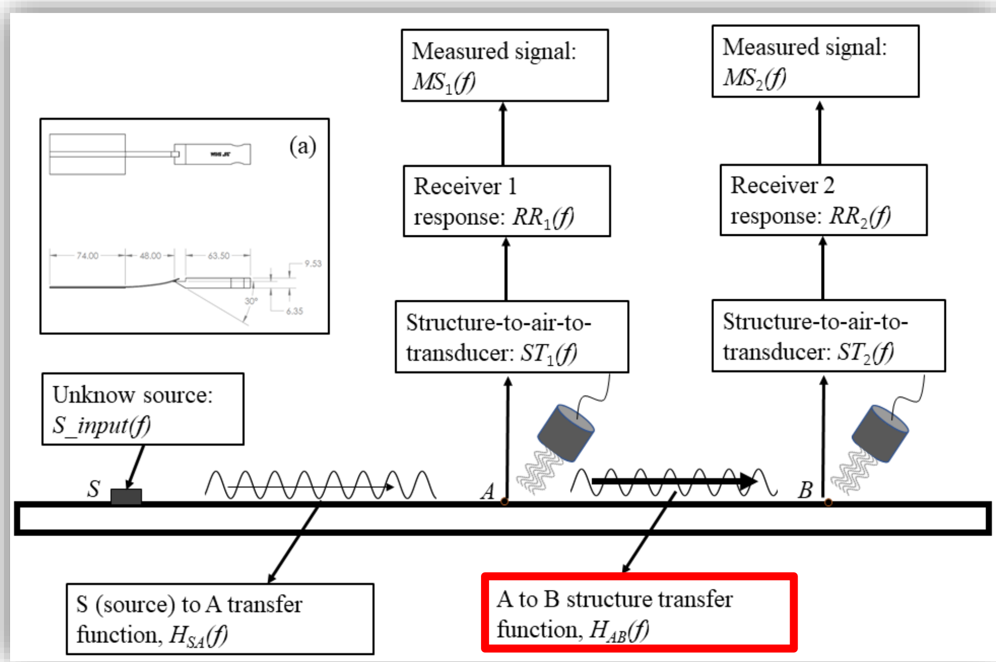


Stringer cap notch

UGW Damage Identification: Signal Processing Aspects/1

- Extract ultrasonic guided-wave (UGW) Transfer Function between combination of pairs of sensors (H_{AB}) by using a Normalized Cross-Correlation operation that compensates for any variations in impact excitation (“unknown source”).
- Track changes in time-domain Transfer Function to detect and locate damage.

$$MS_1(f) = S(f) \cdot H_{SA}(f) \cdot RR_1(f) + ST_1(f) \qquad MS_2(f) = S(f) \cdot H_{SA}(f) \cdot H_{AB}(f) \cdot RR_2(f) + ST_2(f)$$



Transfer Function in Frequency domain (normalized cross-power spectrum):

$$\frac{< CrossPower >}{< AutoPower >} = \frac{\cancel{|S(f) \cdot H_{SA}(f)|^2} \cdot H_{AB}(f)}{\cancel{|S(f) \cdot H_{SA}(f)|^2}} = H_{AB}(f)$$

Transfer Function in Time domain (inverse Fourier Transform):

$$\boxed{H_{AB}(t) = \int_{-\infty}^{\infty} H_{AB}(f)\, e^{i2\pi f t}\, df}$$

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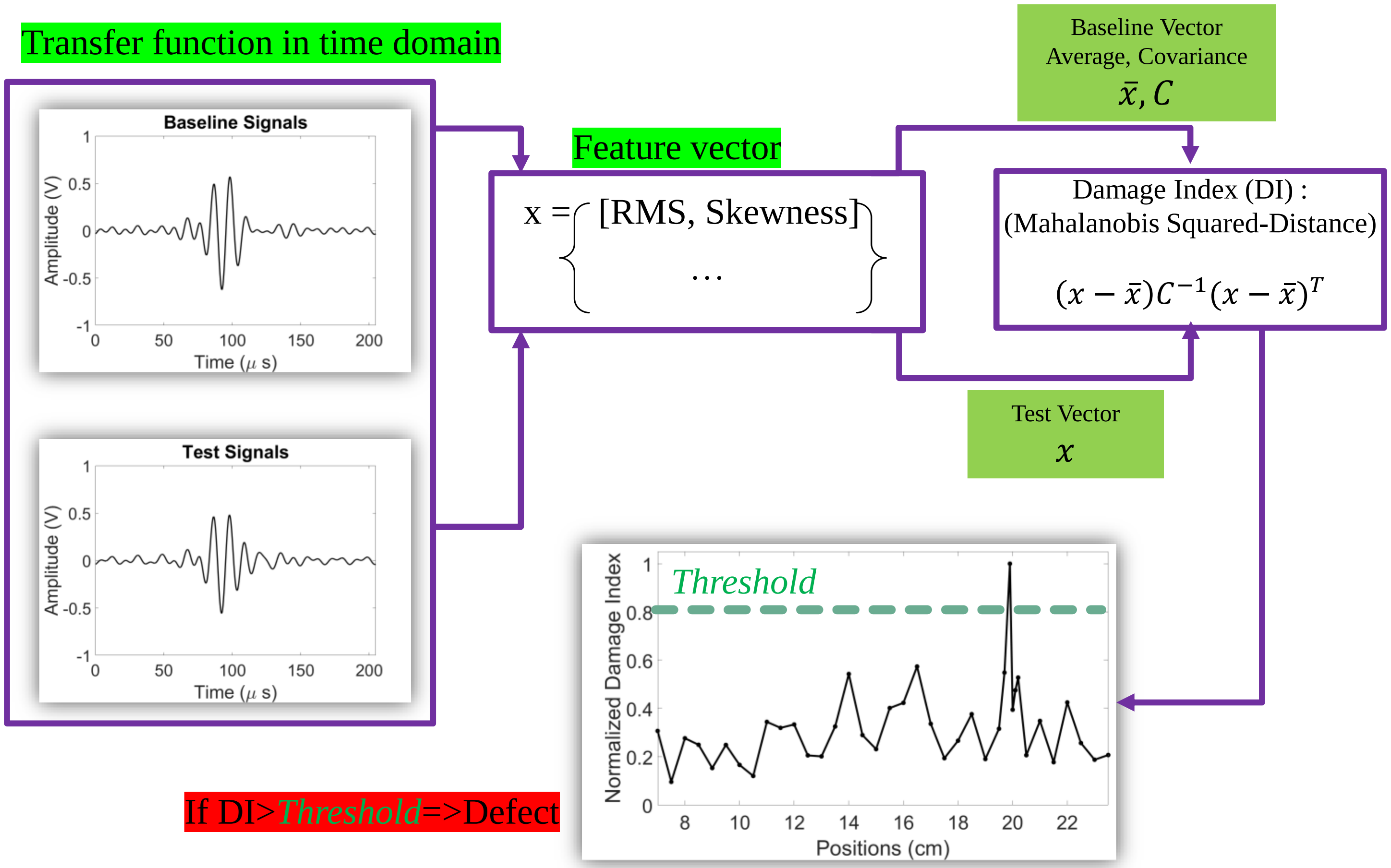
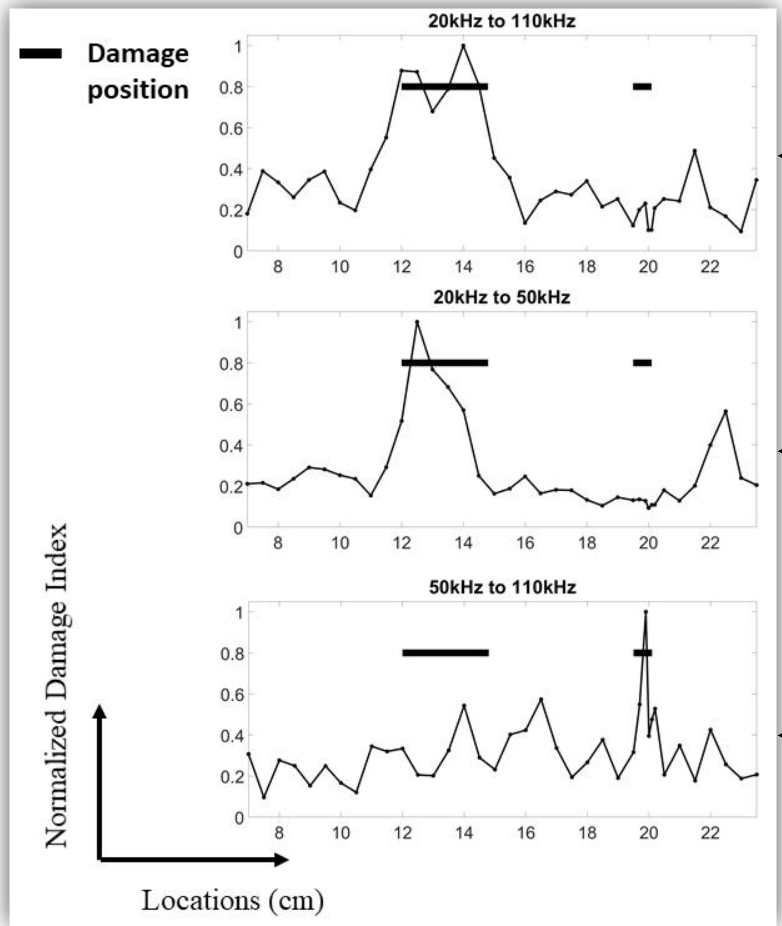
UGW Damage Identification: Signal Processing Aspects/2

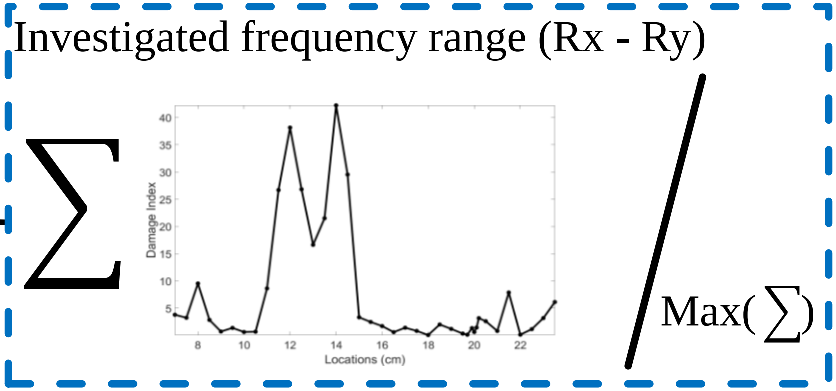
- Process time-domain Transfer Functions through statistical Outlier Analysis along scan to minimize False Positives and maximize True Damage Detections.

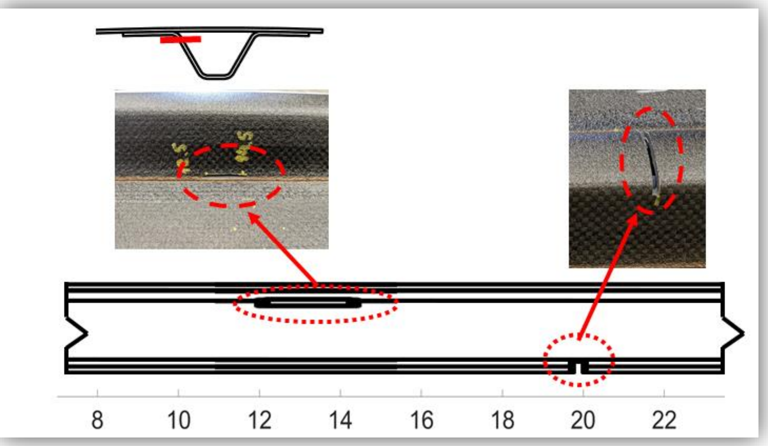


Result: Slit-Cut Damage; A Two-Step Scheme for Damage Localization/1

Step-1: localize damage along the scanning direction.



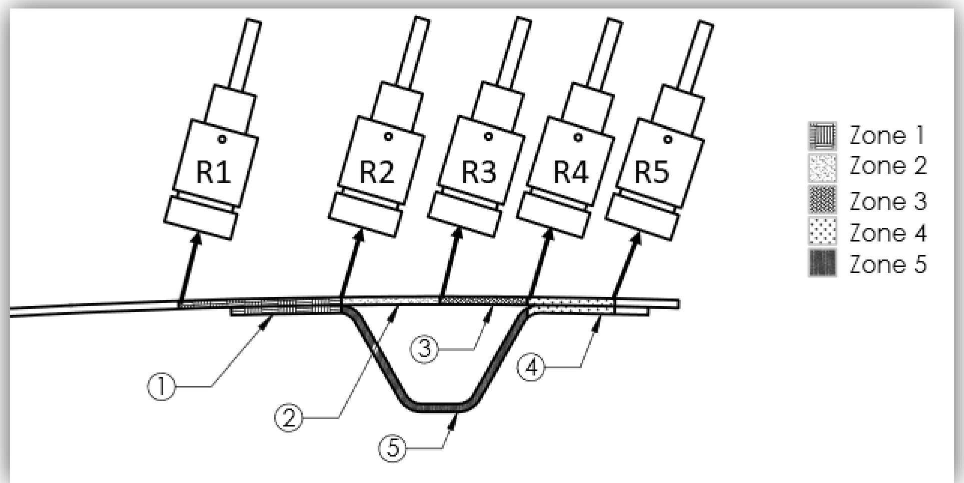




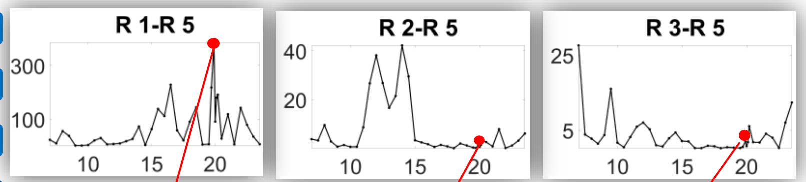
Result: Slit-Cut Damage; A Two-Step Scheme for Damage Localization/2

Step-2: localize damage in the cross-sectional direction.

Achieved via combination of receiver pairs.



Example: Zone-5 value (at location 20cm):



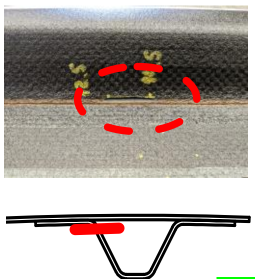
$R1\_R5_{20cm}*1+(R2\_R5_{20cm}+R3\_R5_{20cm})*0.8$

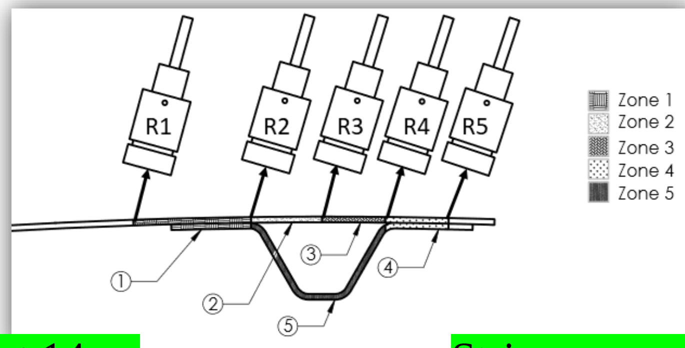
Zone number	Dominant	Secondary
1	R1—R2	R1—R3, R1—R4
2	R2—R3	R1—R3, R2—R4
3	R3—R4	R3—R5, R2—R4
4	R4—R5	R1—R5, R3—R5
5	R1—R5	R2—R5, R3—R5

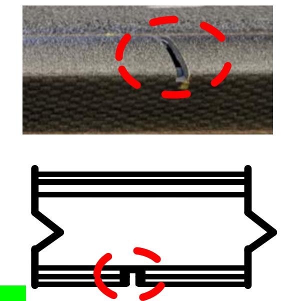
Location	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Damage location 14cm (20kHz ~ 110kHz)	0.02	0.55	0.35	0.76	1.00
Damage location 20cm (50kHz ~ 110kHz)	0.10	0.02	0.01	0.80	1.00

Result: Slit-Cut Damage; A Two-Step Scheme for Damage Localization/3

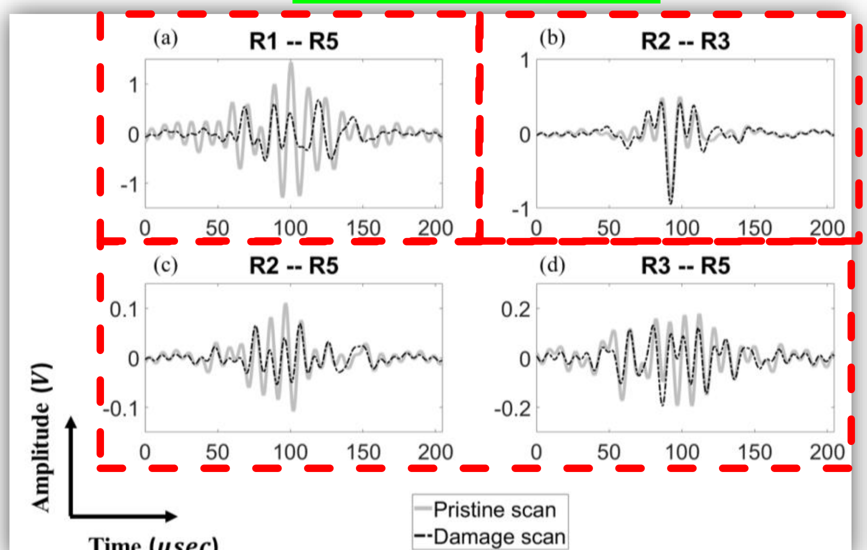
Step-2: localize damage in the cross-sectional direction.



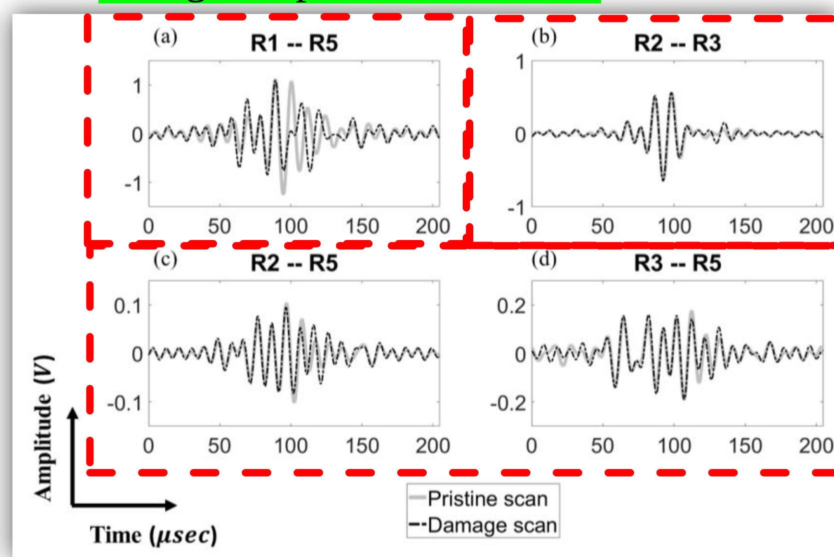




Heel slit cut at 14cm



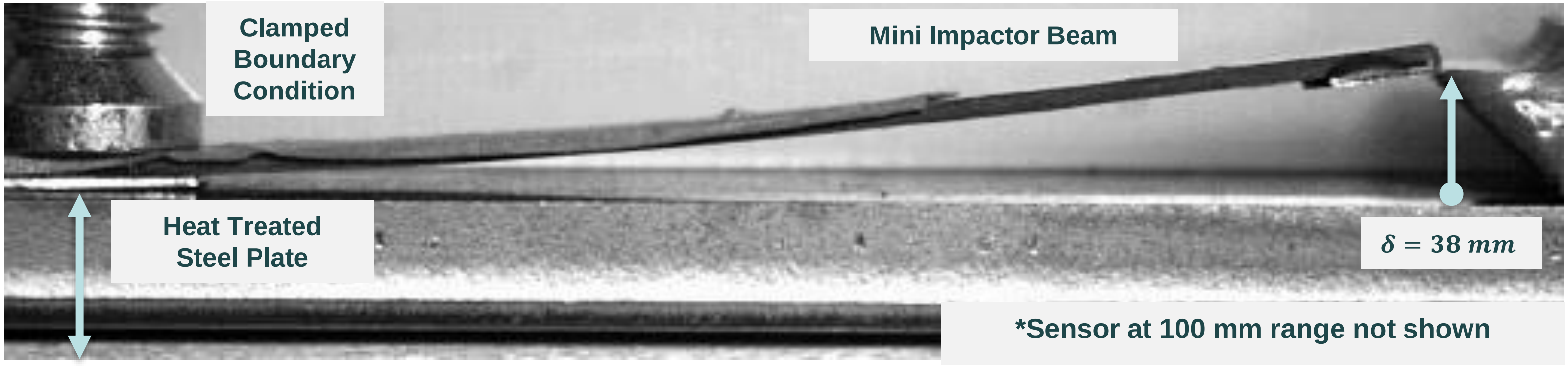
Stringer-cap slit cut at 20cm



Excitation: Mini-impactor Characterization and Parameterization

Background: intense UGWs excitation achieved via UCSD-created Mini-impactors; frequency content in 10^2 kHz range (> order of magnitude than traditional impact hammers)

Objective: understand performance characteristics of Mini-impactors on various plate materials, be able to select “best” Mini-impactor for given plate and desired frequency range

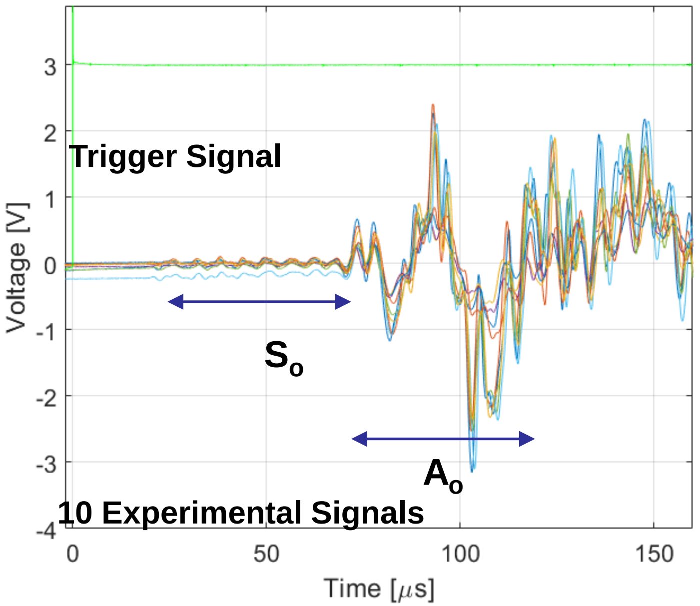


1) Select Mini Impactor and Plate Permutation → 2) Deflect Mini-impactor, Release → 3) Trigger DAQ via Switch Circuit → 4) Observe UGW via R15s Sensor → 5) Record Excited R15s signal with DAQ → 720 Raw Timeseries Experiments

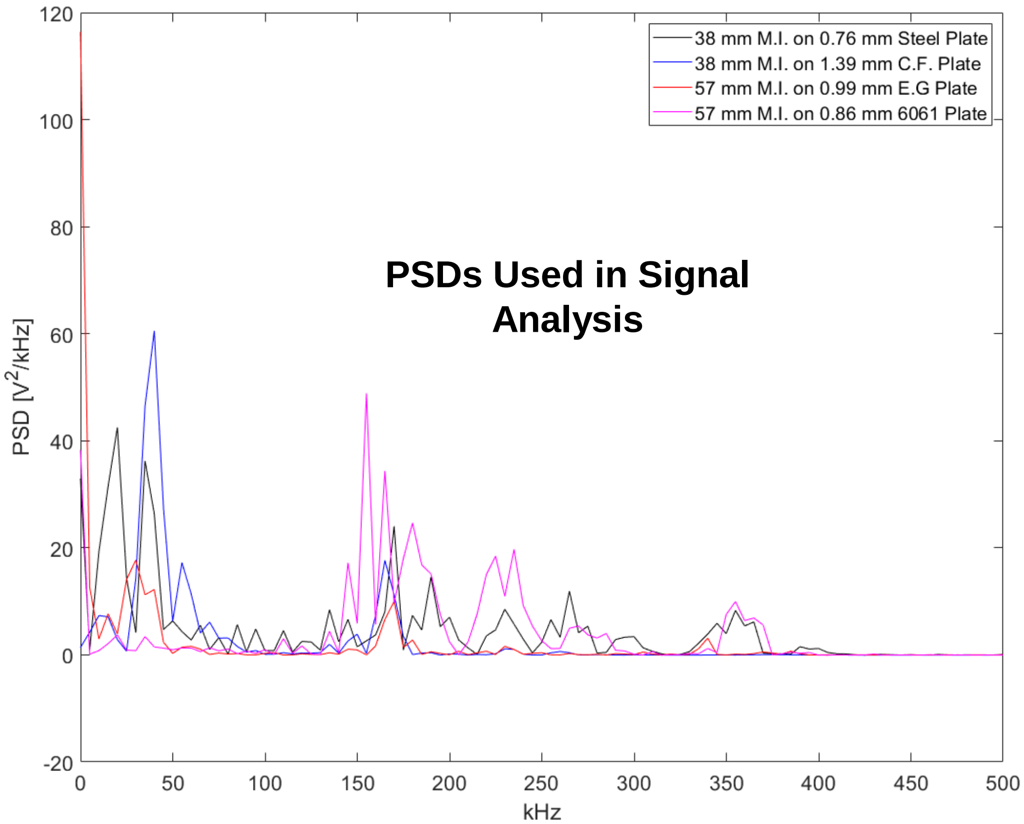
→ 720 Power Spectral Densities → Principal Component Analysis → Multivariate Analysis → Knowledge Discovery → Application Identification

Experimental Data and Signal Processing

Oscilloscope triggered via contact switch; raw voltage data from R15s piezoelectric sensor recorded



720 experiments conducted; time-history data converted to Power Spectral Density (PSD) plot showing frequency content



Testing Details:

- 1.5 mm thick CFRP plate impacted by the 6ply, 57 mm Mini-impactor. Repeated 10x.
- Impact triggers oscilloscope consistently, allowing unambiguous time alignment.

Data Analysis – A Data-Driven Approach (1)

- **Data Collection**
  - 720 experiments each sampled for period of 200μs at 80Mhz
  - $720\ [exp] * 16004\ \ [freq.bins] \approx 11E6\ data\ points$ (High dimensional space)

- **Principal Components (PC) Analysis**
  1. **Matrix Factorization**
     - Pre-Operations on PSD Data Matrix
       - Subtract PSD Data Matrix Mean
       - Calculate Covariance Data Matrix from PSD Data Matrix
     - Main Operation
       - Eigendecomposition of Covariance Data Matrix ****Akin to Vibrations Analysis Decoupling Step***
     - Post-Operations
       - Sort eigenvectors by the sorted eigenvalues (descending)
  2. **Knowledge Discovery (Multivariate Hotelling T^2 Metric)**

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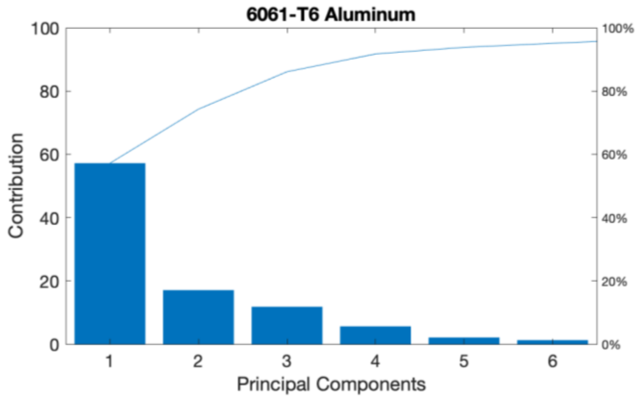
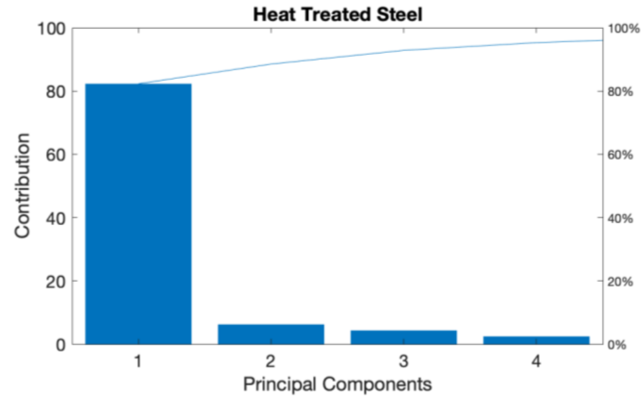
Data Analysis - A Data-Driven Approach (2)

Analyzed Subsets Of The Total Data. Divided By Plate Material Type

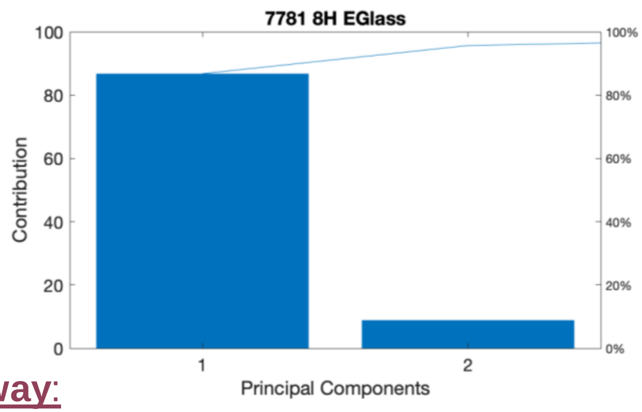
ISOTROPIC MATERIAL

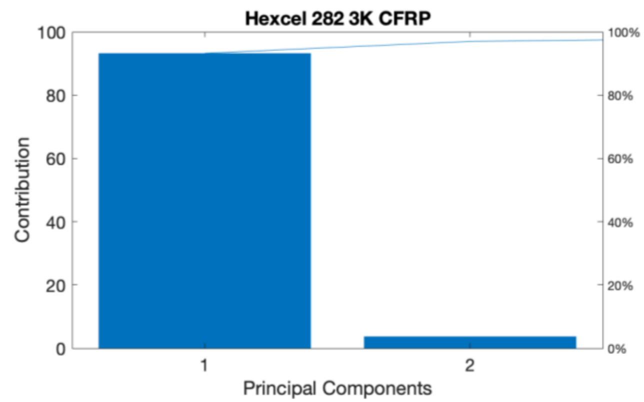




Isotropic Materials Require More Pcs, More Frequencies Excited Across Spectrum

ANISOTROPIC MATERIAL





Anisotropic Data Is Described With Only 2 Pcs, Less Frequencies Excited Across Spectrum

Main Take Away:

Eliminating unnecessary data that is contributing to the total signal can be achieved through this data matrix decoupling. Determining the number of principal components is achieved by truncating the PCs at a threshold value (e.g. 95%). It might be the case that the first 6 principal components achieve 95% contribution but only comprise of 3% of the original data. The remaining 97% of the data can be truncated

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Results: Mini Impactor Selector

For plate/shell structure of interest, best mini impactor providing UGW excitation:

Plate Material	Plate Thickness (mm)	Best Mini Impactor	Max Freq Content (kHz)
Carbon/Epoxy	4.86	6 Ply x 57 mm	300
3K Plain Weave	1.39	8 ply x 88 mm	270
VARTM Epoxy	0.99	4 Ply x 38 mm	270
Glass/Epoxy	5.46	6 ply x 57 mm	200
7781 8HS	1.45	6 ply x 57 mm	250
VARTM Epoxy	0.99	4 Ply x 38 mm	250
Aluminum	6.67	8 ply x 88 mm	210
6061-T6	1.65	8 ply x 76 mm	300
	0.86	4 Ply x 38 mm	370
Steel	7.17	6 ply x 57 mm	225
Heat Treated	1.48	8 ply x 76 mm	250
	0.76	4 Ply x 38 mm	400

UGW Estimation of OHT Residual Strength (1)

Objective

- Correlate UGW Measurements to Open Hole Tension Strength for More Complex Layups; Use Analysis of Wave Dispersion
  - Quantify Residual Strength vs Hole Dia. vs UGW Metrics
  - Measure UGW Dispersion Degradation Relative to Baseline State

Methodology

- Specimen Interrogation
  - Excite Specimen with Mini-impactor
  - Observe Stress Waves at Selected Distance with Broadband Acoustic Transducers (BATs)
  - Shift Sensors By Δx and Repeat Experiment
  - Calculate Lamb Wave Dispersion for All Cases and Compare
- Open Hole Tension
  - Specimens Cut After UGW Scanning Completed
  - Test to Failure; Full-Field Strain via Digital Image Correlation

UGW Estimation of OHT Residual Strength (2)

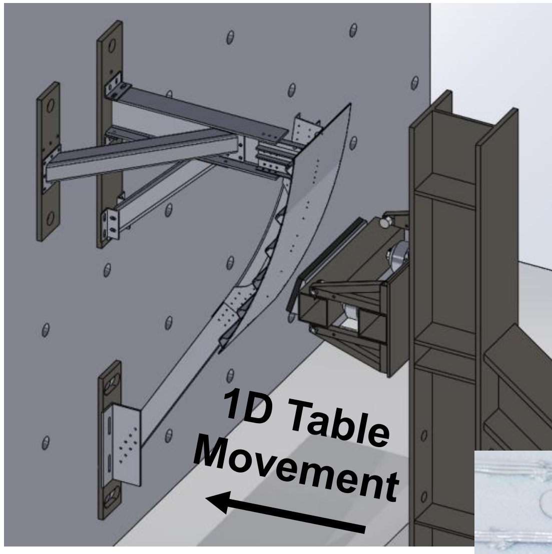
New Specimen Series – Quasi-Isotropic Type Layup (previously only $[0_{10}]$)

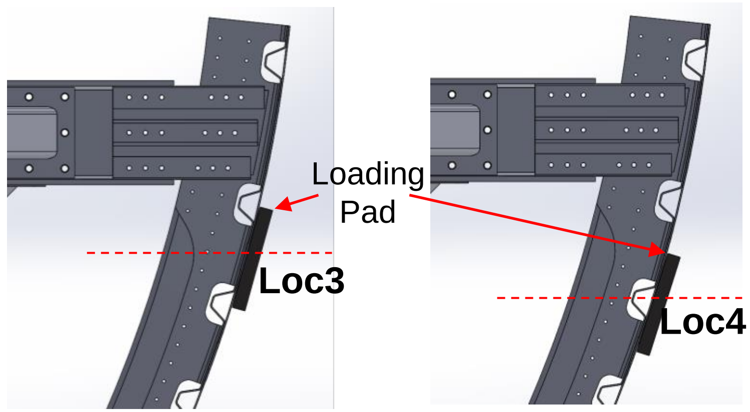
- Completed Manufacturing of two Hexcel PW 282 3K/ VARTM Epoxy Plates
  - Layup $[0/45/0/-45/0]_s$
- Fabricating Linear Sensor Stage
  - Hole Diameters (inch) – [0.0469 0.0625 0.0925 0.125 0.25 0.50 1.00]
  - Constant Specimen Width to Diameter Ratio W/D = 4

Future Work

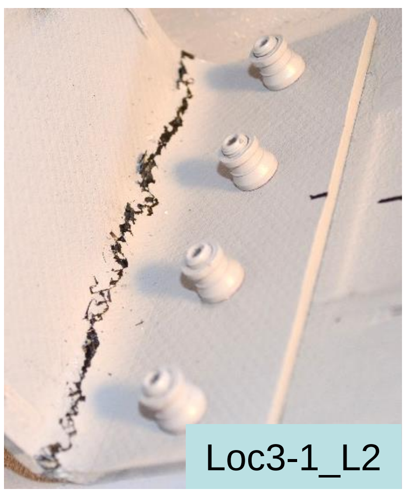
- Planned Experimentation
  - Baseline UGW measurement (pristine/undamaged panel)
  - Drill holes
  - Damaged state UGW through holes
  - Cut into OHT specimens with W/D = 4
  - Test to failure
- Extended to Impact Damage
  - Repeat above but with impact damage instead of drilled holes

HEWABI Results: Test Setup and Failure Modes

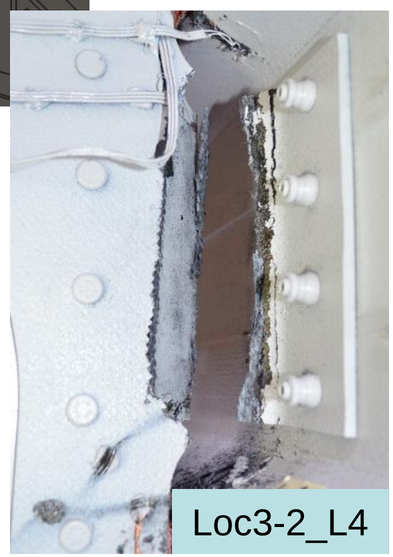




Extensive shear tie cracks



Crack on shear tie corner



Second crack on shear tie

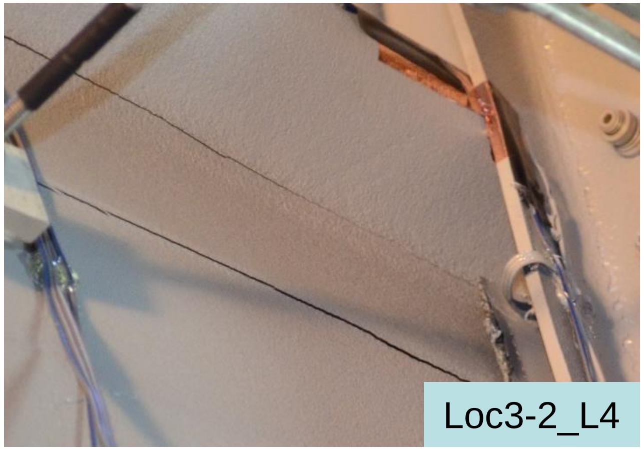
Passenger floor beam crack

HEWABI Project Concluded 2020

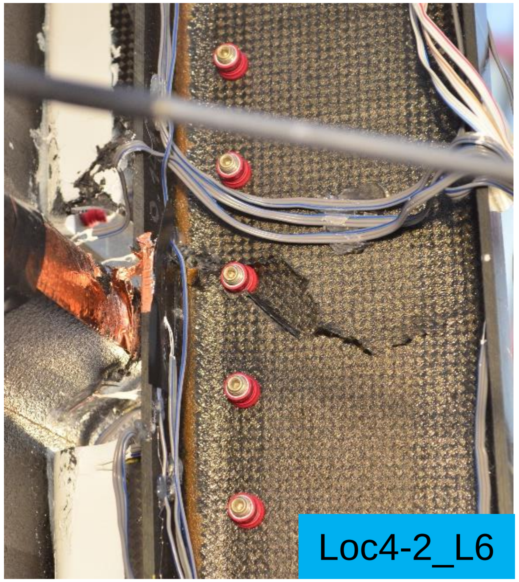
HEWABI Results: Failure Modes

HEWABI Project Concluded 2020

Stringer cut by shear tie



Stringer flange disbond & Stringer heel crack



C-frame crack across Hi-Lok

Shear tie crack originating from mouse hole and following C-frame crack

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Conclusions

- Designed a mobile scanning system using five air-coupled ultrasonic sensors and impact excitation.
- Extracted the Transfer Function of the structure between two sensors as output-only system (compensating for variations in “unknown” excitation).
- Proposed a two-step scheme for damage detection and location:
  - Step-1: Detect damage along the scanning direction
  - Step-2: Localize the damage along the cross-section
- Mini-Impactor characterization identifies best impactor configuration for excitation of ultrasonic guided waves
- OHT residual strength correlates strongly with UGW signal attenuation
  - Extension to quasi-isotropic type layups

Benefits to Aviation

- Robust UGW scanning system to detect damage realistically caused by GSE
  - accessing only aircraft external side
- Identification of damage on stringer-stiffened panels along the cross-section
- Mini Impactor provides simple method for creating high-intensity ultrasonic excitation in 100s kHz range
- Residual tension strength strongly correlated with attenuation of UGW measurements – provides ability to non-destructively assess strength loss

Future Work

- Improve damage detection capabilities for small damage, or narrow damage relative to the wave propagation direction
- Automate mini-impactor excitation mechanism for faster scanning
- Extend damage detection/location to more internal components (shear tie and C-frame)
- UGW and OHT strength experimentation on quasi-isotropic type specimens
- Estimation of residual strength reduction of stringer-stiffened panels vs NDE (UGW) measurements