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Impact Damage Tolerance Guidelines for Stiffened Composite Panels

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Participants

- **Principal Investigators & Researchers**
  - PI: Prof. Hyonny Kim
  - Co-PI: Prof. Francesco Lanza di Scalea
  - Graduate Students
    - PhD:

Name	BS Info	PhD Start	Expected Finish
Janelle Dela-Cueva	2021 UCSD Structural Eng.	Aug 2021	June 2025
Ben Katko	2018 Mechanical Engineering, New Mexico Institute of Mining and Technology	Sept. 2018	Graduated - April 2023
Chengyang Huang	2019 Shanghai Jiao Tong Univ. Mechanical Engineering	September 2020	TBD 2024

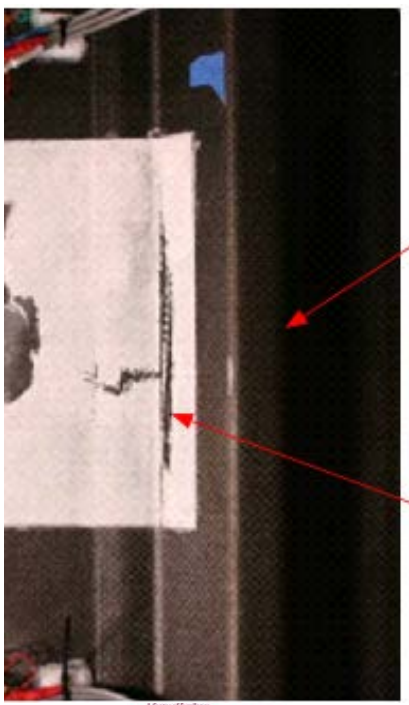
    - MS: none
- **FAA Technical Monitors**
  - Lynn Pham, Ahmet Oztekin
- **Other FAA Personnel Involved**
  - Larry Ilcewicz

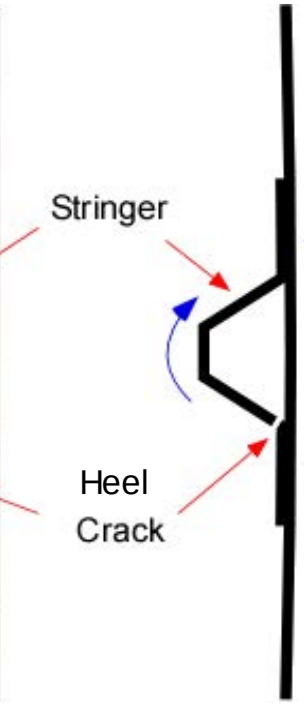
Motivation

- Impact to composite structures can cause internal damage
  - difficult to detect via visual inspection
  - external-only NDE needed
  - large-area fast inspection
- Ultrasonic guided wave (UGW) based non-destructive evaluation (NDE)
  - travels over long distances (1 m)
  - sensitive to presence of internal damage

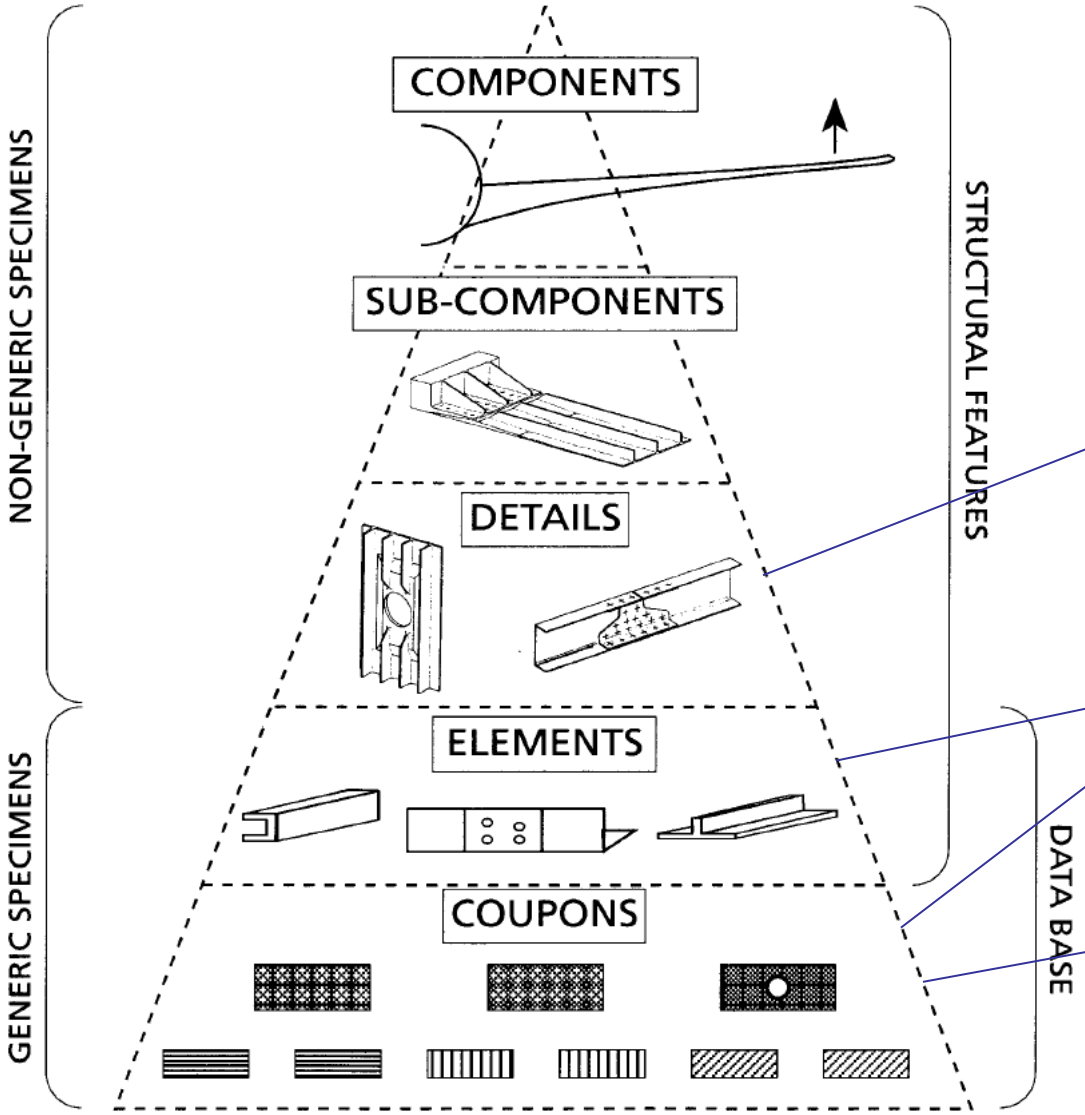
Overall Objectives:

- Quantify UGW detectable and non-detectable damage
- Relate UGW NDE measurements to **damage state** and **residual strength**





Overarching View of Project



Initial Assessments:
Large Stiffened Panels w/Damage.
→ Detection - Yes/No

Deeper Focus:
2-Stringer Panels, Notched Tension
→ Damage Modes

Current Focus:
Flat Panels With Single-Mode Damage
→ Residual Strength Determined From NDE

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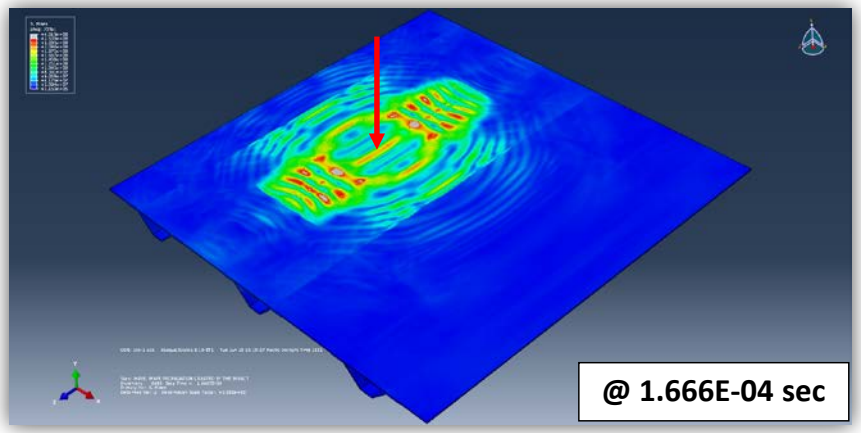
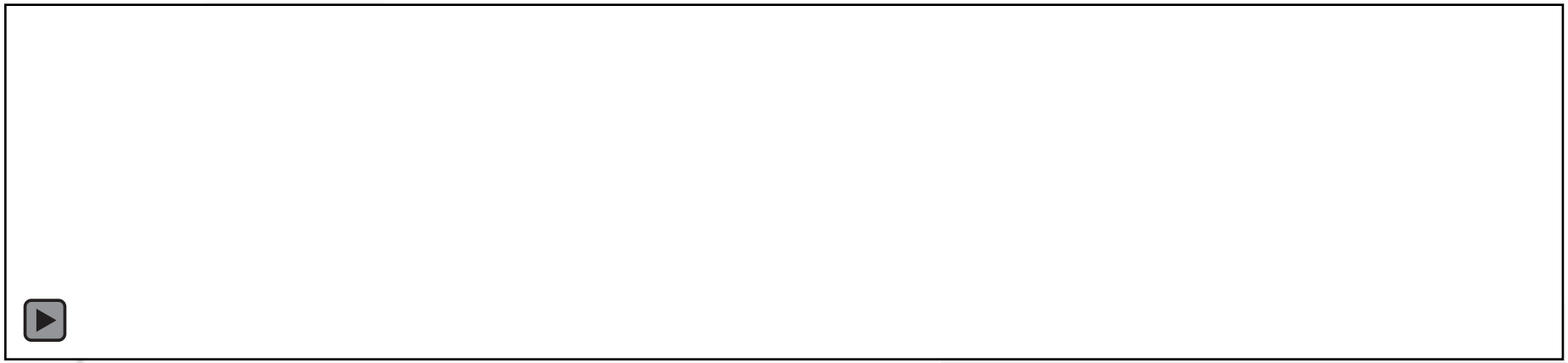
Ultrasonic Guided Waves: Structure is a Natural "Waveguide"



Intense Excitation: Mini-impactor

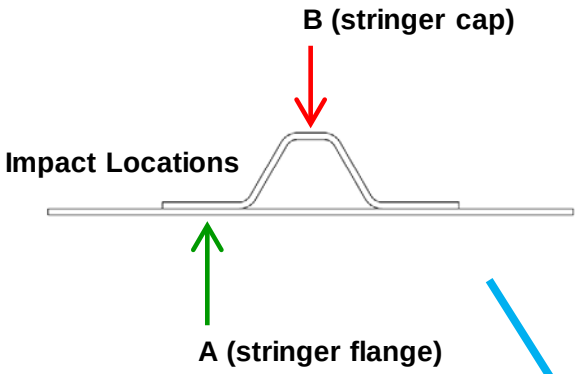
- Intense UGWs excitation achieved via UCSD-created Mini-impactors
  - frequency content up to 400 kHz
  - order of magnitude greater frequency than traditional impulse hammers (~20 kHz)
- Intense excitation especially needed for air-coupled transducers



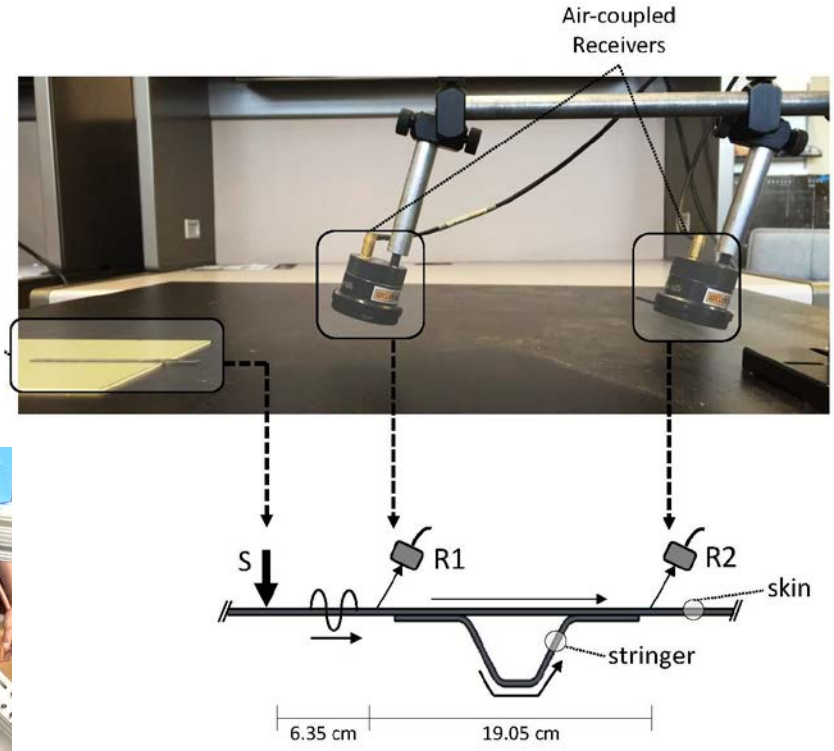
Large Panel Level Investigations with SIDO*

** Single Input Dual Output*

Impacts to Stringer-Stiffened Panel



Hybrid "Impact/Air-Coupled" Scanner

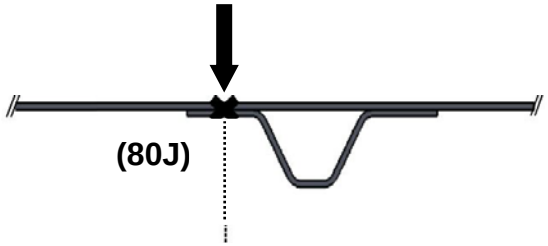


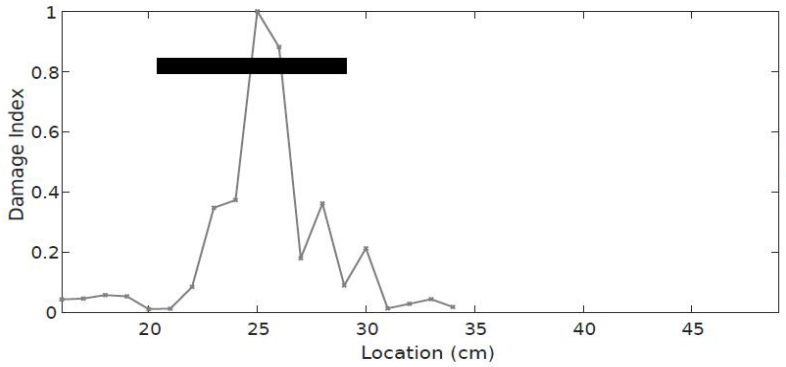
Mini-impactor + micro-machined capacitive transducers

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

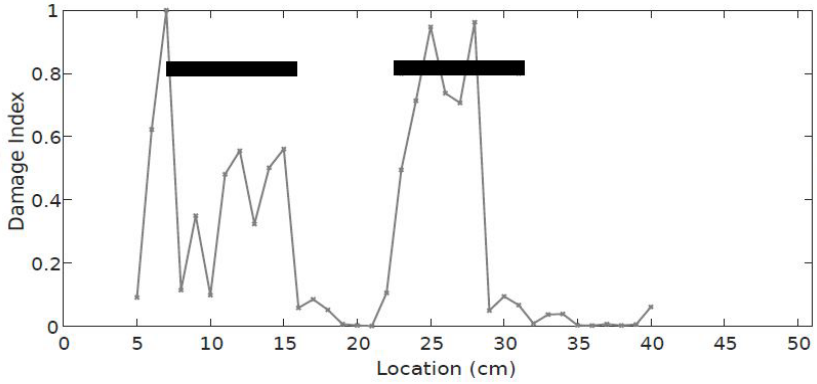
UGW Damage Detection

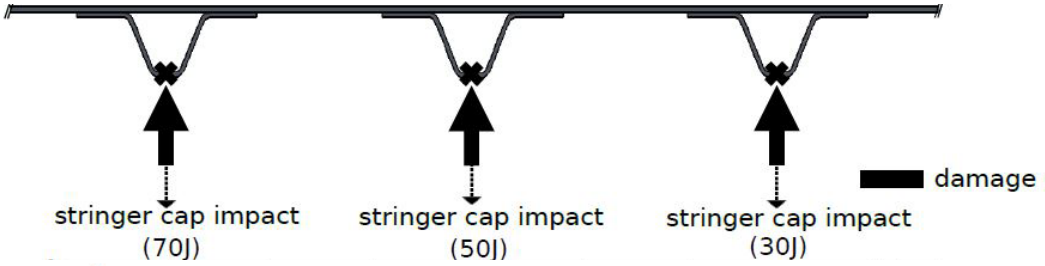
Actual Impact Damage:

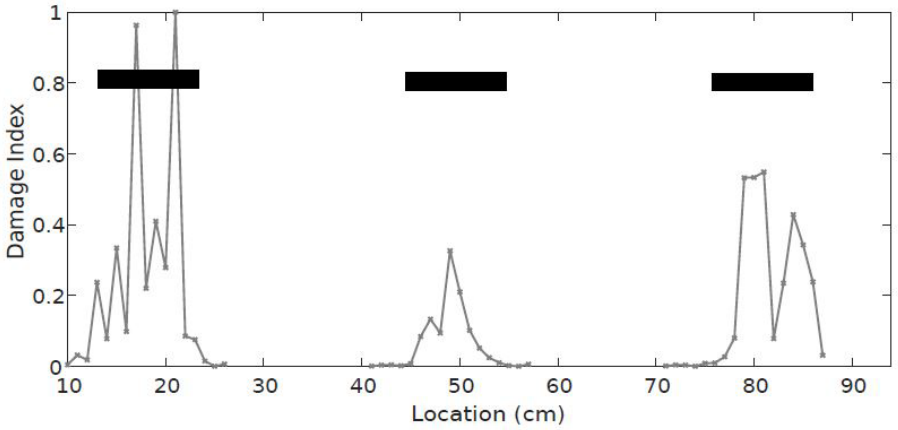




Manufactured Damage – Saw Cuts







Hybrid impact/air-coupled scanner

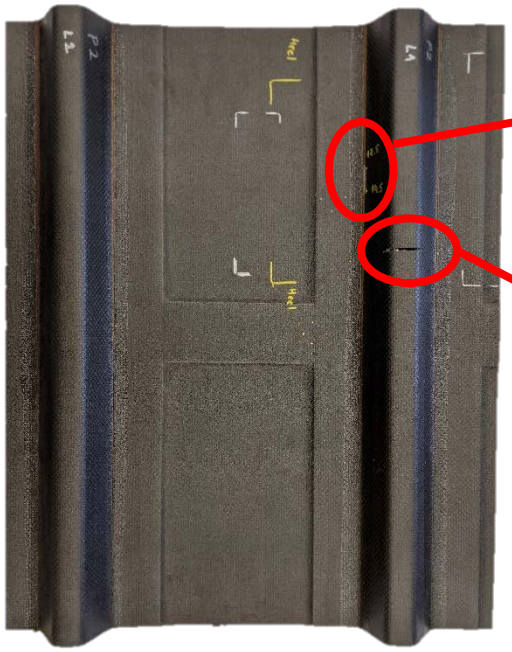
(40 – 270 kHz)

Successful Damage Detection – Yes/No
Large Area Covered by Moving Line-Scan

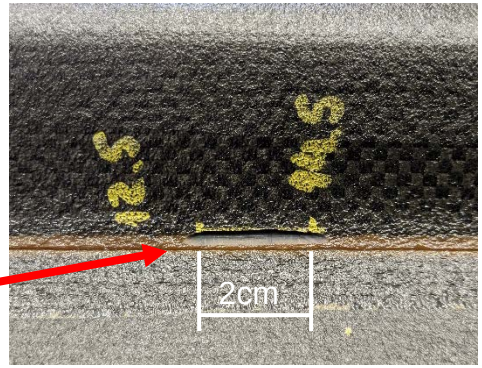
2-Stringer Panels Specimens Description

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

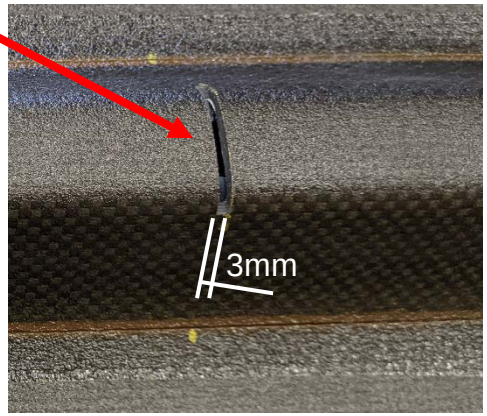
2-Stringer panel with added mass (2cm diameter steel nuts) simulating damage



2-Stringer panel with saw-cut notches



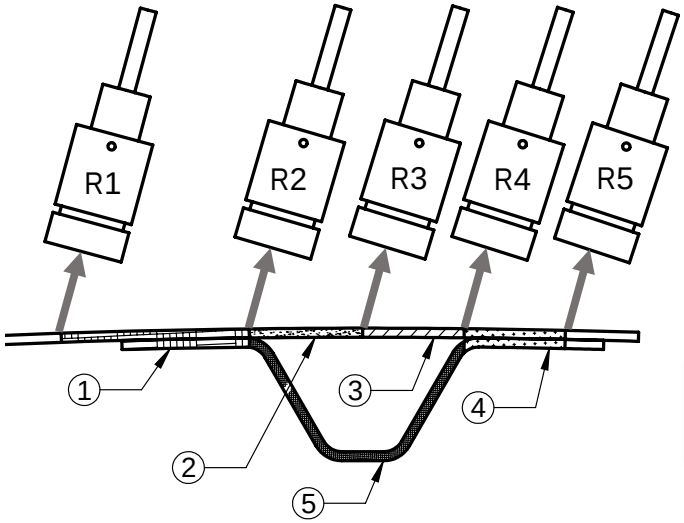
Stringer heel notch

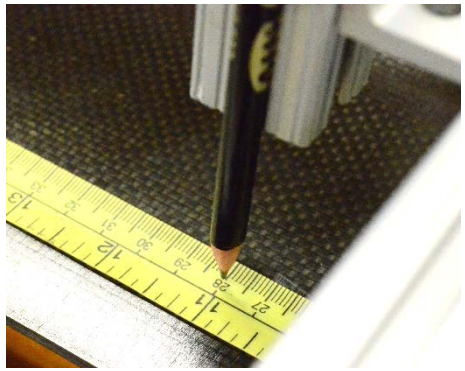


Stringer cap notch

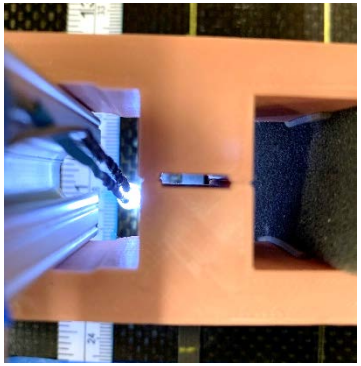
5-Sensor UGW Experimental Setup

System scans in/out of page direction.

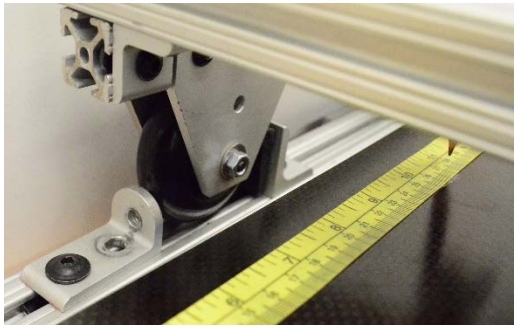




(a) Location needle

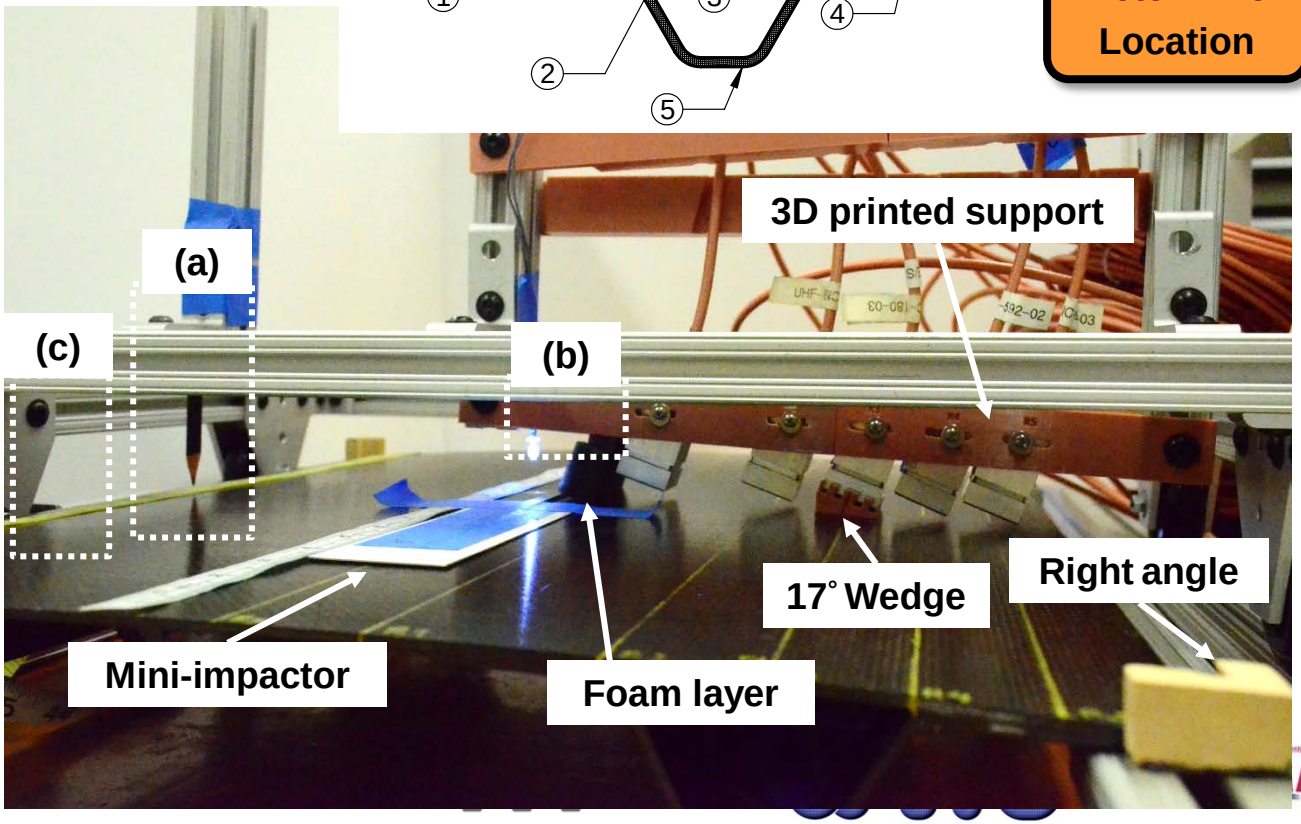


(b) Mini-impactor window & LED



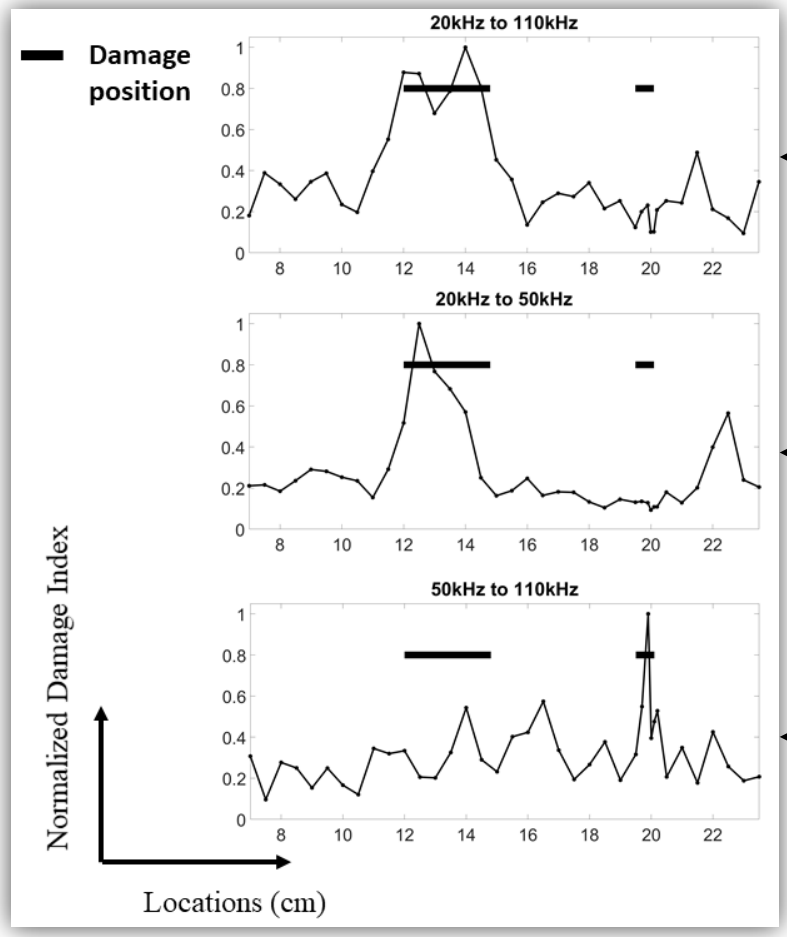
(c) Cart brakes

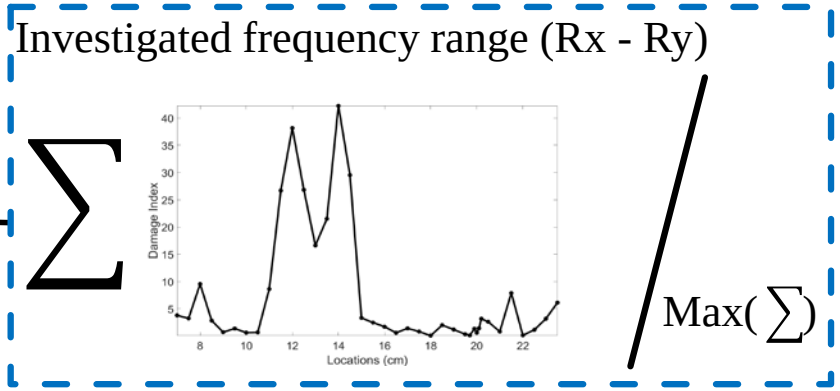
Determine Location

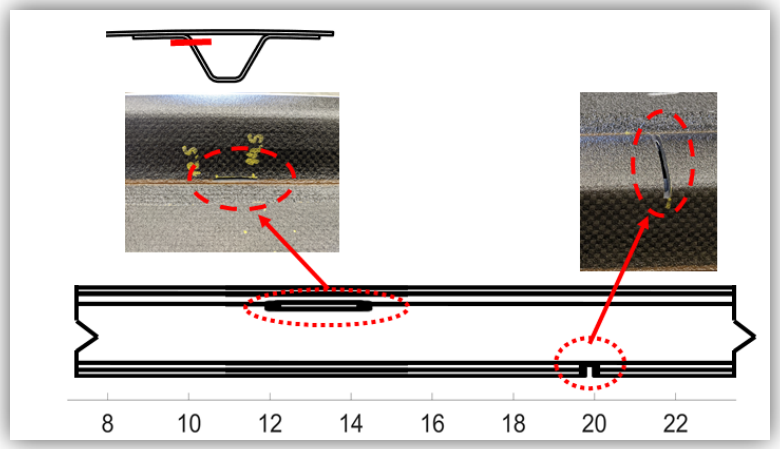


Result: Slit-Cut Damage; A Two-Step Scheme for Damage Localization/1

Step-1: localize damage along the scanning direction.

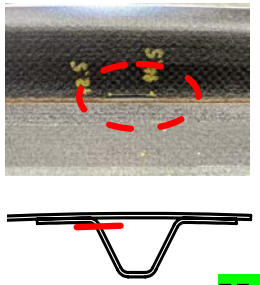


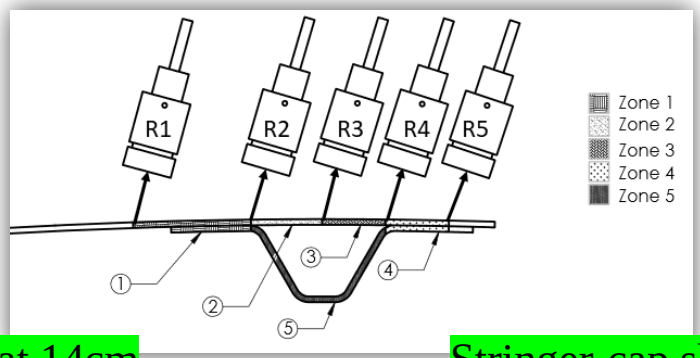


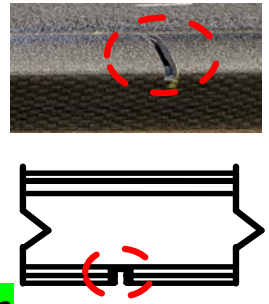


Result: Slit-Cut Damage; A Two-Step Scheme for Damage Localization/3

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

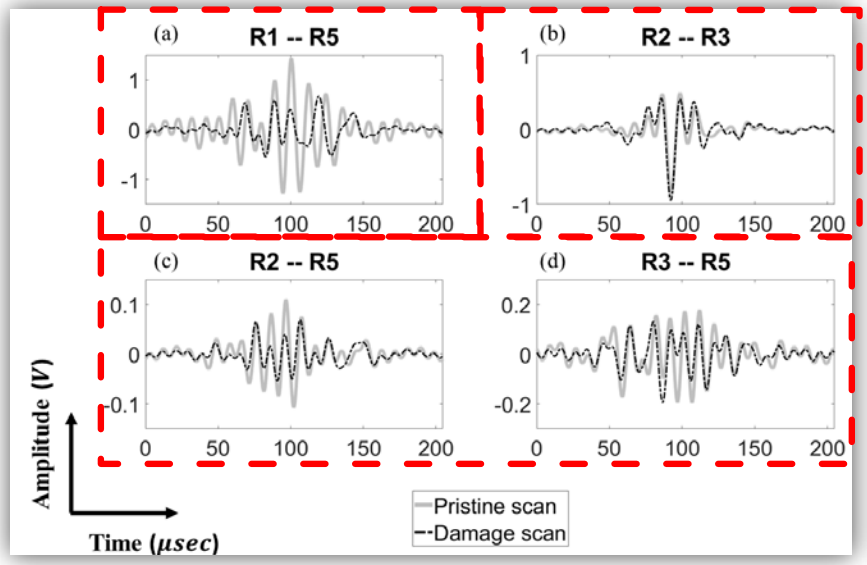


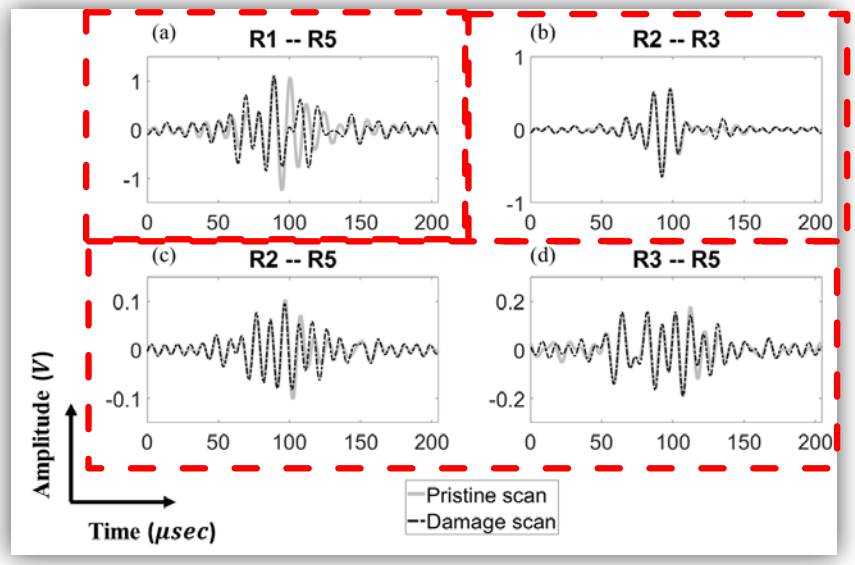




Heel slit cut at 14cm

Stringer-cap slit cut at 20cm





Damage Localization Differentiation

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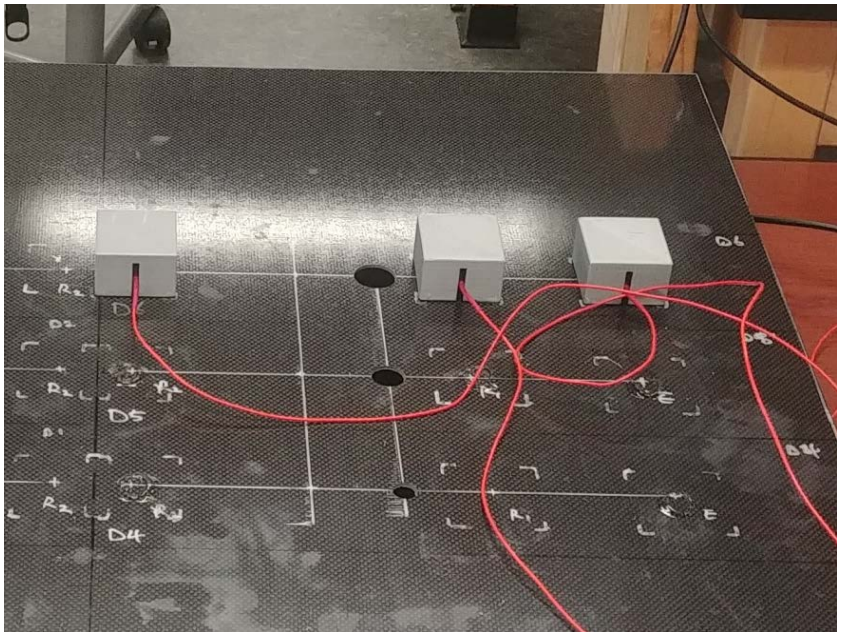
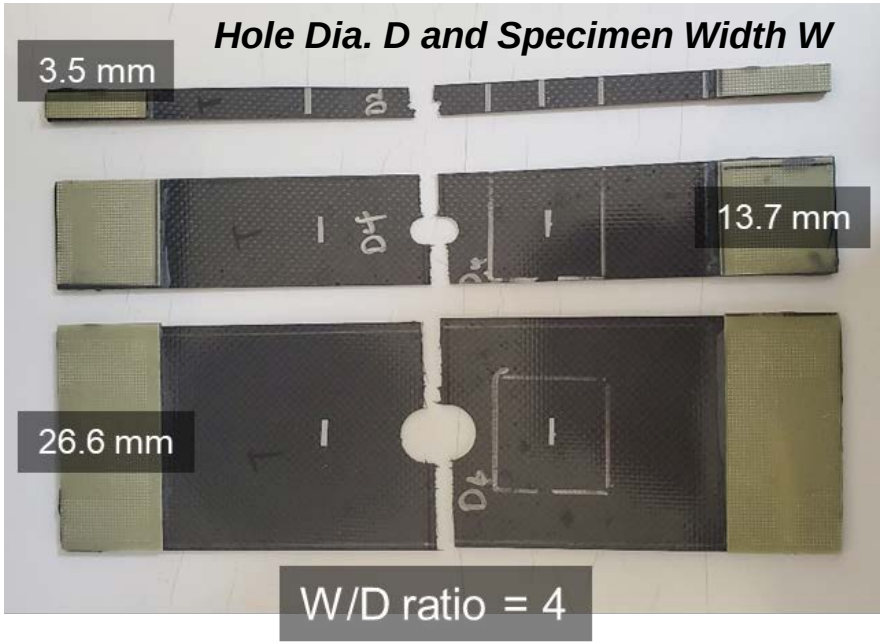
Open Hole Residual Strength Estimation From UGW

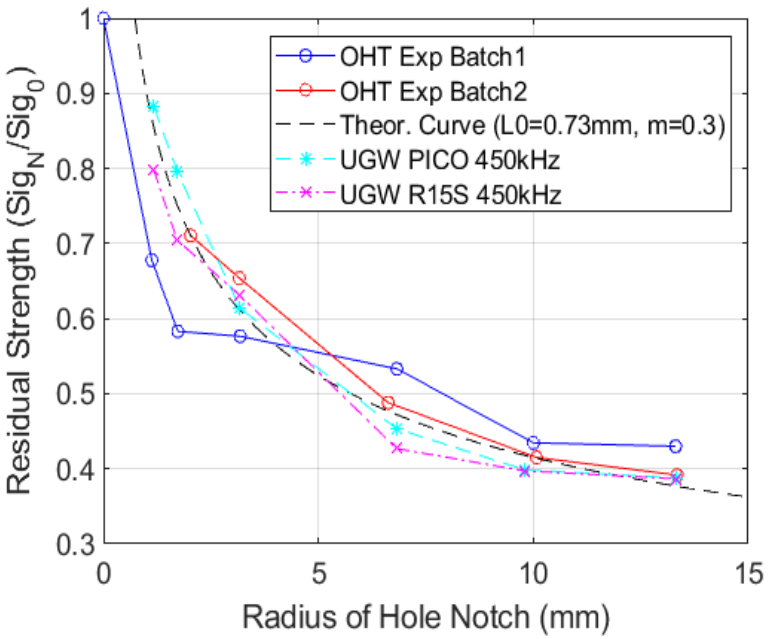
UGW vs OHT Experiments

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





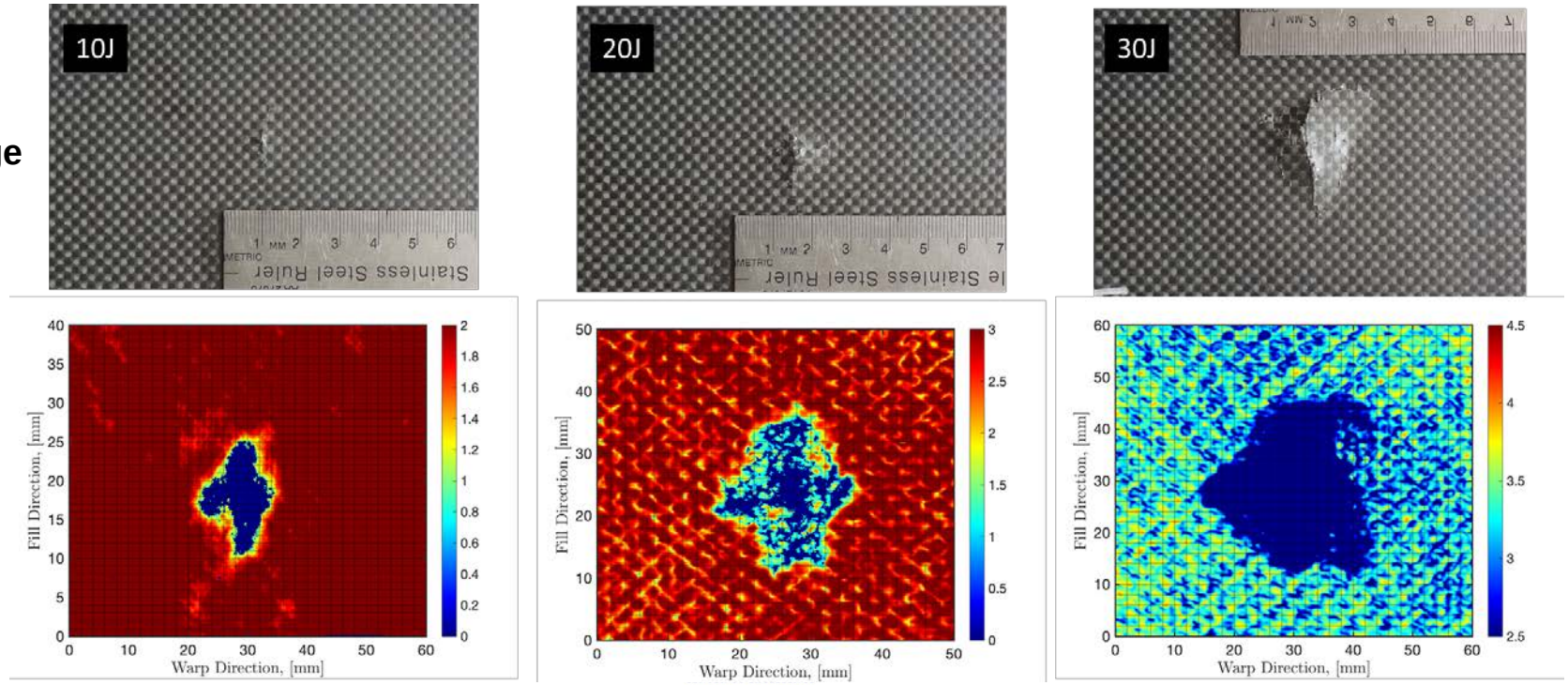
Comparison with UGW measurements show direct correlation between open hole tension strength reduction and signal attenuation.



Impact Damage Residual Strength Estimation from UGW

- Estimate impact-damaged panel residual strength using UGW NDE phase velocity dispersion measurements
- Collect spatiotemporal UGW data with and without damage
- Use singular value decomposition (WAVSVD) algorithm to extract phase velocity information
  - dispersion curve change in damage zone
  - max wavelength of UGWs in damaged zone
- Use Average Stress notched strength criterion to relate UGW to residual strength for impact

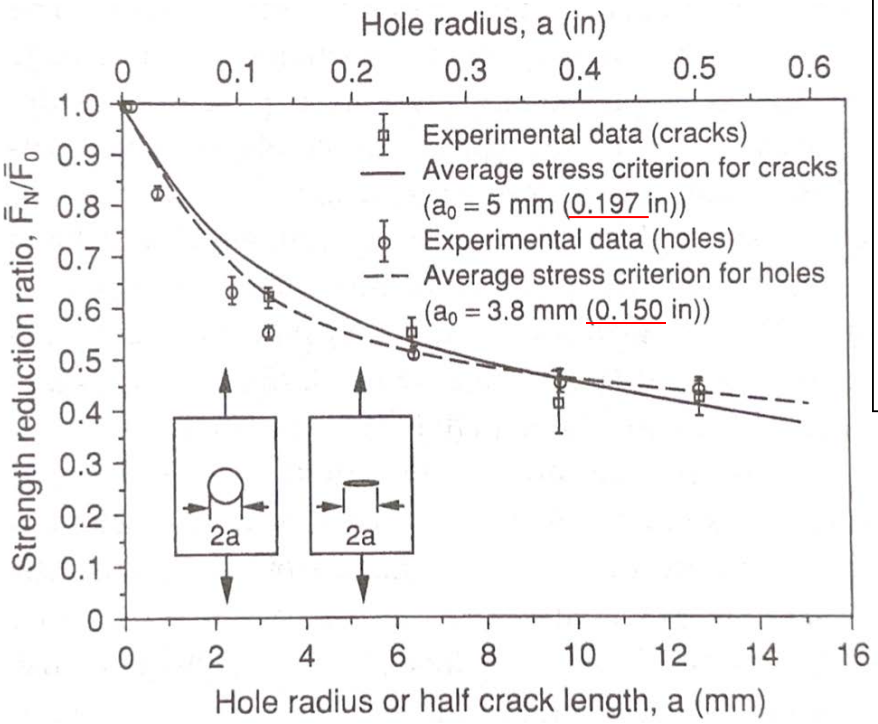
Impact Damage

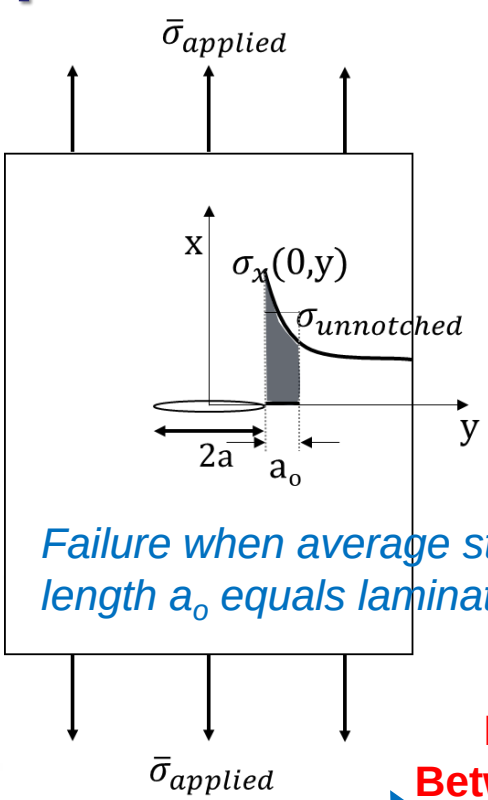


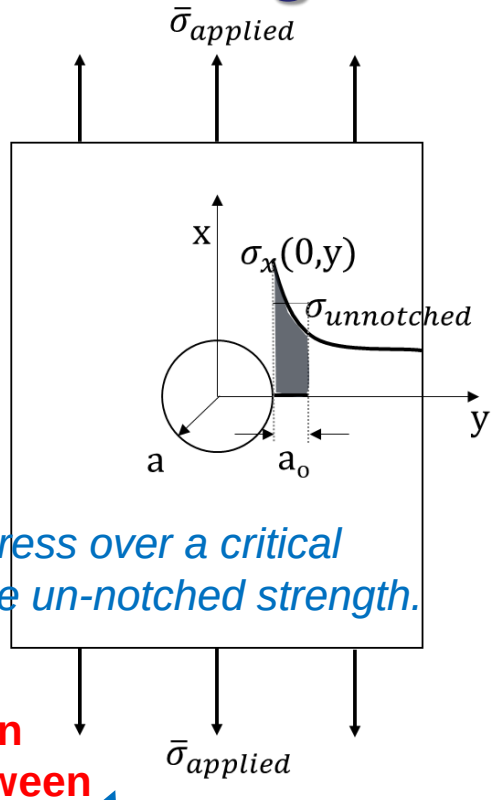
Average Stress Semi-Empirical Notched Strength

Average Stress Failure Criterion:

$$\frac{1}{a_o}\int_{a}^{a+a_o} \sigma_x(0,y) = \sigma_{unnotched}$$







Failure when average stress over a critical length a_o equals laminate un-notched strength.

In Between ?

Cracks and holes are related via Average Stress Criterion: different value of characteristic length a_o depending on stress concentration intensity.

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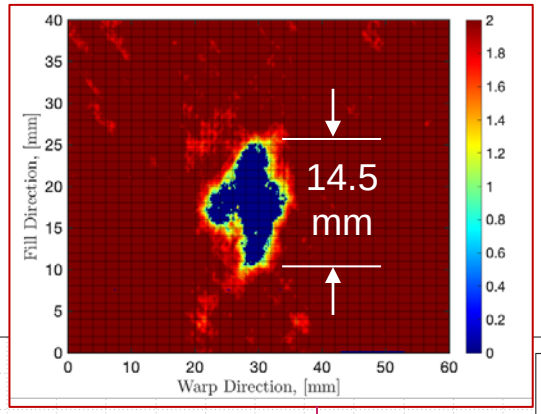
Open Hole and Impact Damage Residual Strength

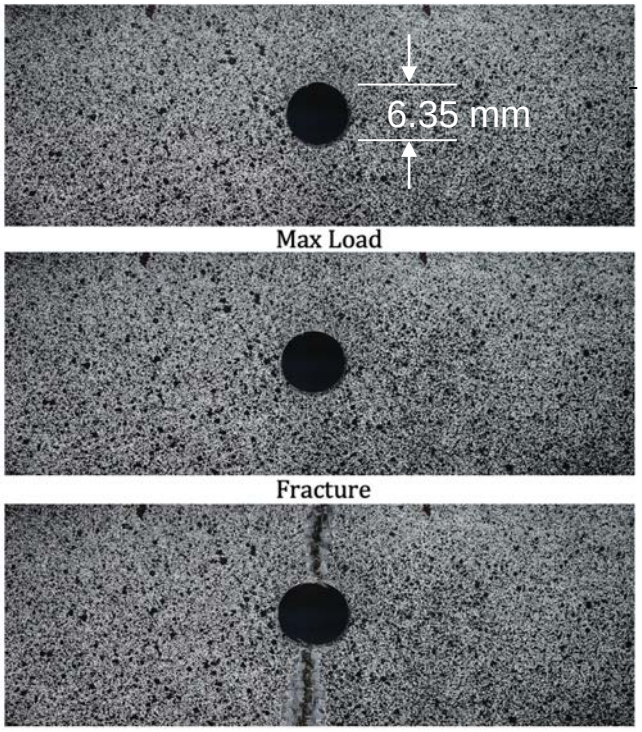
Residual Strength for $[0/45/0/-45/0]_s$ PW Carbon/Epoxy Laminates

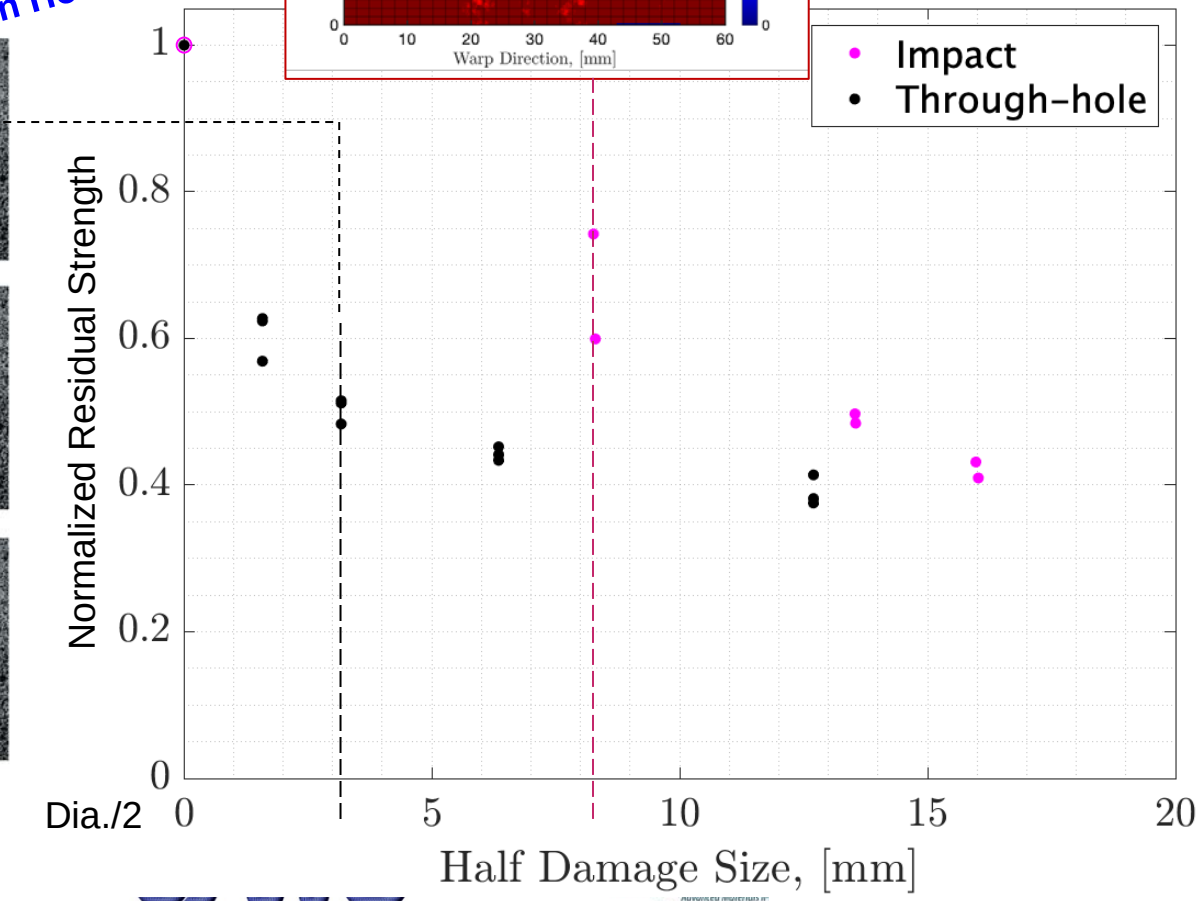
1. Open Through-Hole
2. Impact Damage



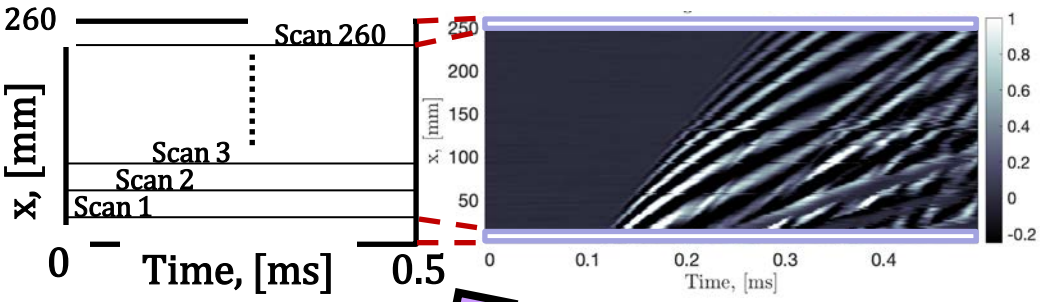
Ultrasonic C-Scan (or A-Scan) Gives Damage Size a

Tension Loading in Horizontal Dir.

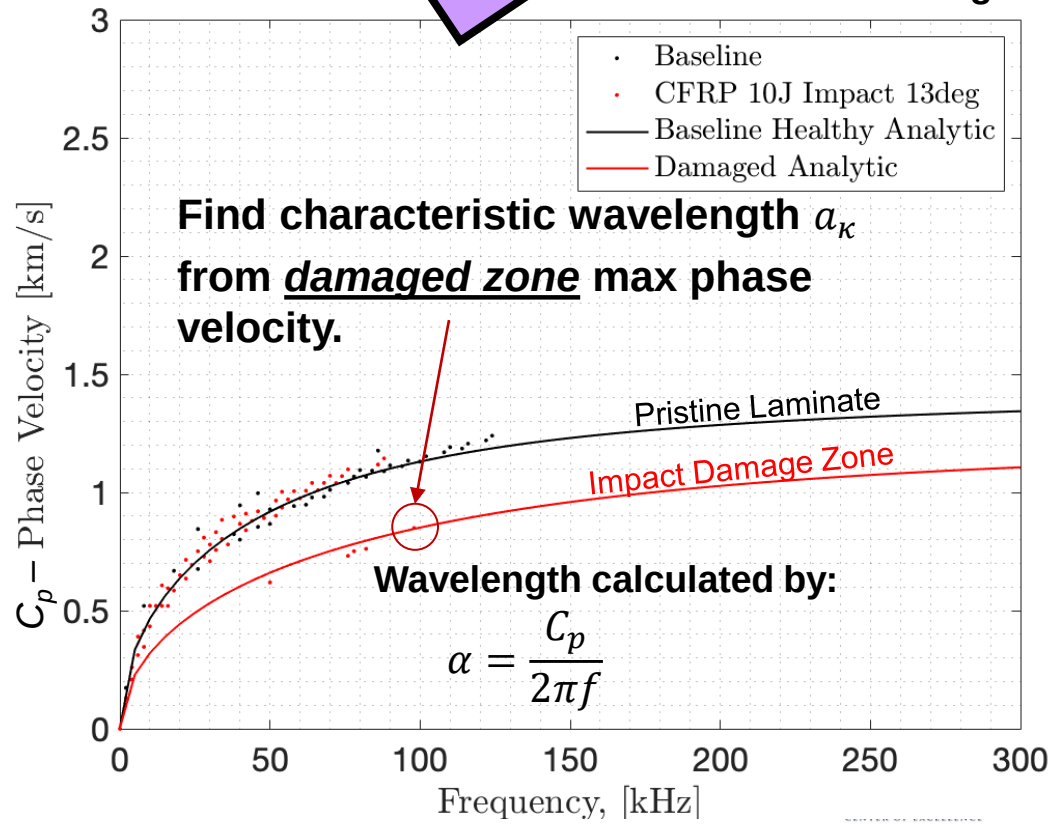


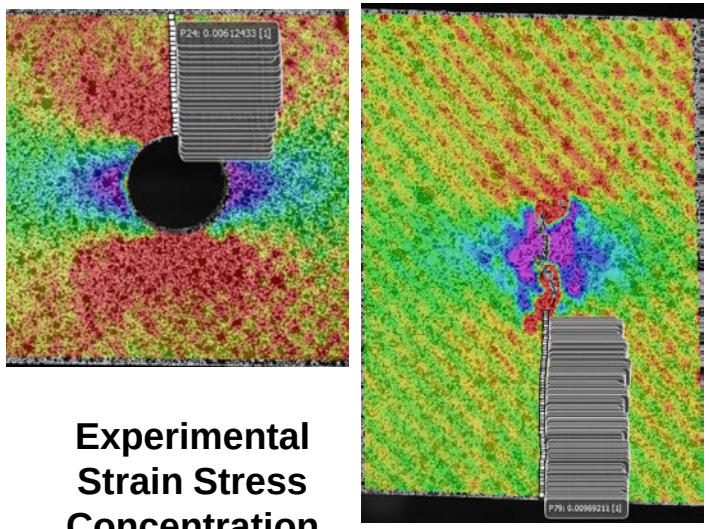


UGW Characteristic Wavelength and Experim. SCF

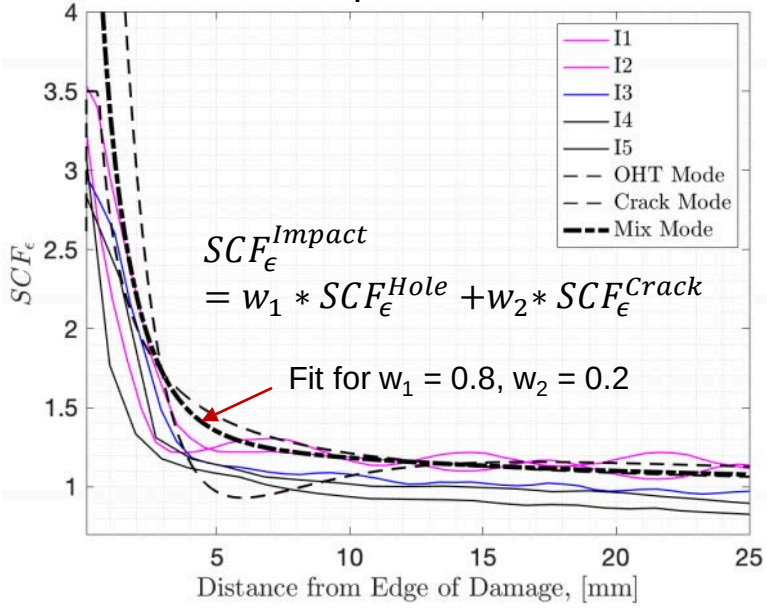


Construct Dispersion Curve via WAVSVD Processing





Experimental Strain Stress Concentration Distribution → K_I



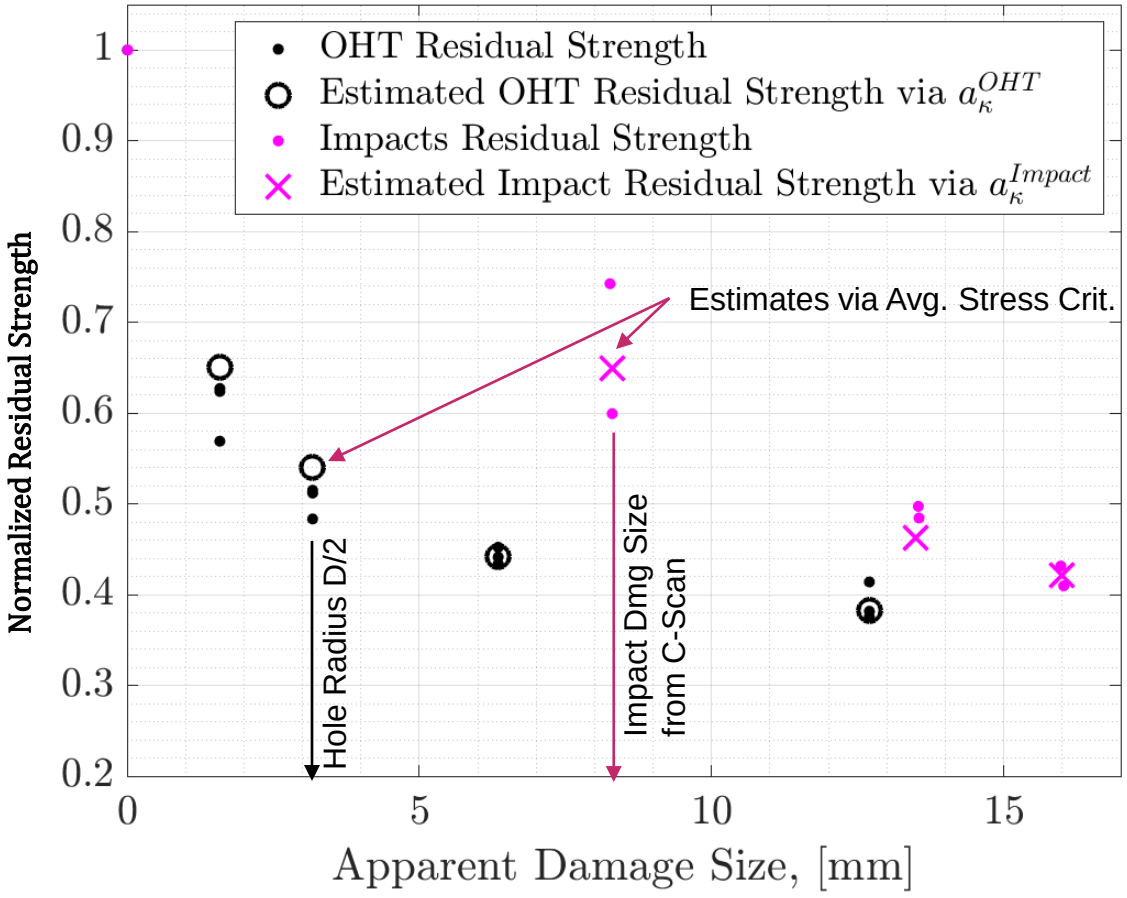
NDE-Correlated Residual Strength Estimate

Residual Strength Estimate of Impact-Damaged Panels:

Characteristic wavelength a_k from UGW dispersion curves substituted into the Average Stress Fracture equation

$$\frac{K_I}{\sqrt{\pi(a + a_\kappa)}} = \sigma_{Notched}$$

UGW measured physical metric (a_k) used to estimate test-measured residual strength vs damage size.



NDE-based residual strength estimation: characteristic wavelength a_k is a suggested characteristic length parameter to use in the average stress criterion (replaces a_o).

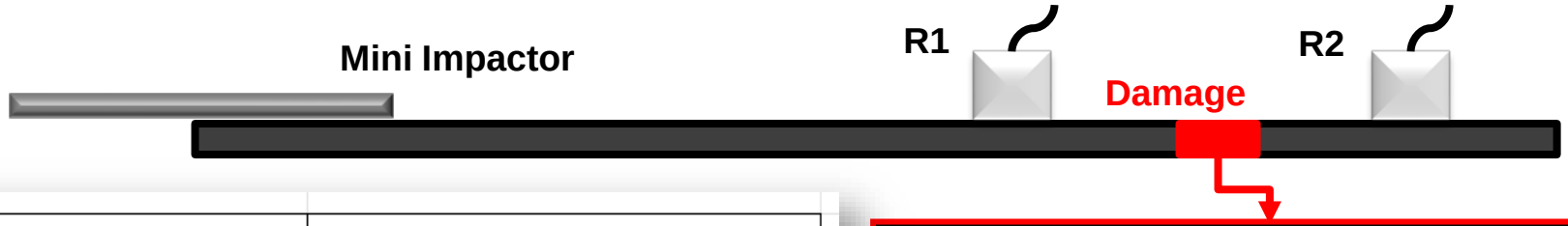
Extracting Damage Mode in Composite Panels Through Measured Wave Characteristics

Objectives

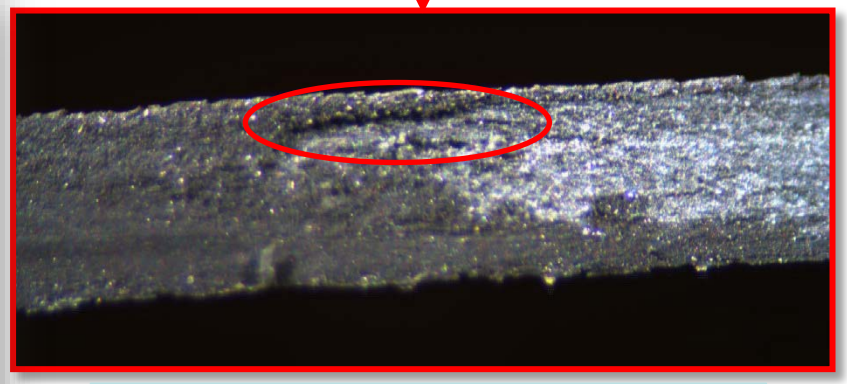
- Distinguish single-mode damage states based on UGW signals
- Individual damage modes: Pristine, Delamination, Matrix Crack, Fiber breakage

Methodology Summary

- Pitch-catch configuration with a mini-impactor as broadband excitation source and two R15 piezoelectric acoustic contact receivers
- Extraction of structure transfer function and quantify damage using a feature vector



Laminate ID	Layup
B-Pristine	[0/0/0/90/90/0/0/0]
B-Matrix Crack	[0/0/0/**90**/**90**/0/0/0]
B-Fiber Breakage	[**0**/**0**/**0**/90/90/0/0/0]
B-Delamination	[0/0/0/90//90/0/0/0]
Q-Pristine	[45/90/-45/0/0/-45/90/45]
Q-Matrix Crack	[45/**90**/-45/0/0/-45/90/45]
Q-Fiber Breakage	[-45/**0**/45/90/90/45/0/-45]
Q-Delamination	[45/90/-45/0//0/-45/90/45]



Quasi-isotropic fiber “breakage”

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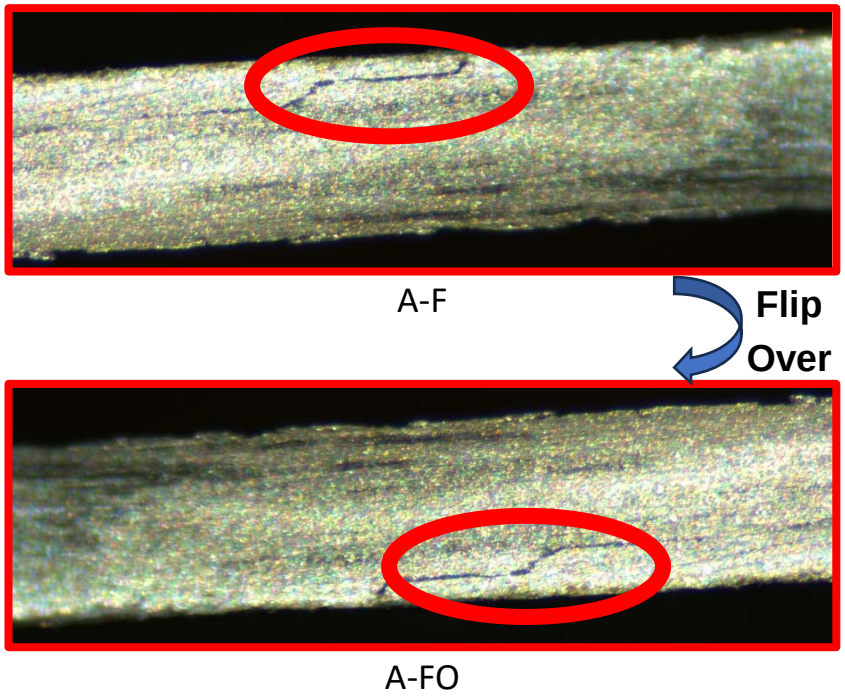
Damage Manufacturing

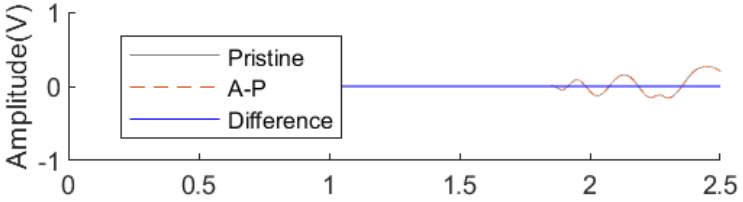
- Damage sites are placed at a designated layer, e.g.,
  - A-F is near sensing surface
  - Flipping panel over gives A-FO with damage farther from sensing surface
  - Same for A-M, A-MO, B-F, B-FO etc

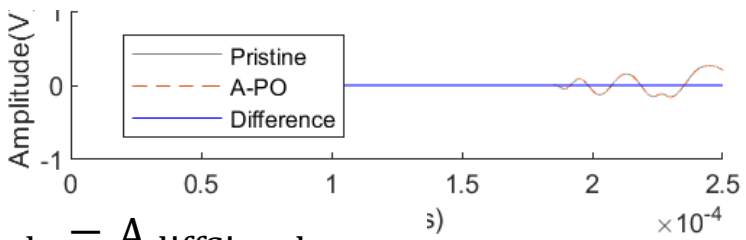


ID	Damage Type	Layup	Thickness (mm)
A-P	Pristine	[0/90/0/90/0/0/90/0/90/0]	1.85
A-PO	Pristine	[0/90/0/90/0/0/90/0/90/0]	1.85
A-F	Fiber breakage	[0/90/0/90/0/0/90/0/90/0]	1.85
A-FO	Fiber breakage	[0/90/0/90/0/0/90/0/90/0]	1.85
A-M	Matrix crack	[0/90/0/90/0/0/90/0/90/0]	1.85
A-MO	Matrix crack	[0/90/0/90/0/0/90/0/90/0]	1.85
A-D	Delamination	[0/90/0/90/0//0/90/0/90/0]	1.85
A-DO	Delamination	[0/90/0/90/0//0/90/0/90/0]	1.85
B-P	Pristine	[0/0/0/90/90/90/90/0/0/0]	1.85
B-PO	Pristine	[0/0/0/90/90/90/90/0/0/0]	1.85
B-F	Fiber breakage	[0/0/0/90/90/90/90/0/0/0]	1.85
B-FO	Fiber breakage	[0/0/0/90/90/90/90/0/0/0]	1.85
B-M	Matrix crack	[0/0/0/90/90/90/90/0/0/0]	1.85
B-MO	Matrix crack	[0/0/0/90/90/90/90/0/0/0]	1.85
B-D	Delamination	[0/0/0/90/90//90/90/0/0/0]	1.85
B-DO	Delamination	[0/0/0/90/90//90/90/0/0/0]	1.85
Q-P	Pristine	[0/45/90/-45/-45/90/45/0]	1.51
Q-PO	Pristine	[0/45/90/-45/-45/90/45/0]	1.51
Q-F	Fiber breakage	[0/45/90/-45/-45/90/45/0]	1.51
Q-FO	Fiber breakage	[0/45/90/-45/-45/90/45/0]	1.51
Q-M	Matrix crack	[0/45/90/-45/-45/90/45/0]	1.51
Q-MO	Matrix crack	[0/45/90/-45/-45/90/45/0]	1.51
Q-D	Delamination	[0/45/90/-45//-45/90/45/0]	1.51
Q-DO	Delamination	[0/45/90/-45//-45/90/45/0]	1.51

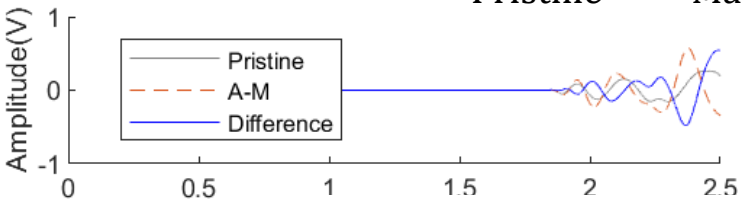
Difference Signals Normalized

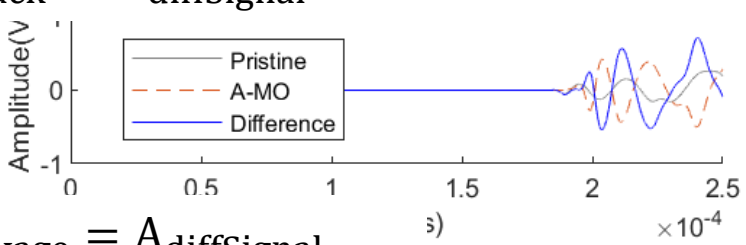
$$A_{Pristine} - A_{Pristine} = A_{diffSignal}$$



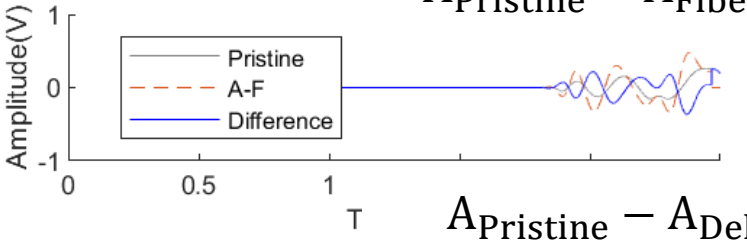


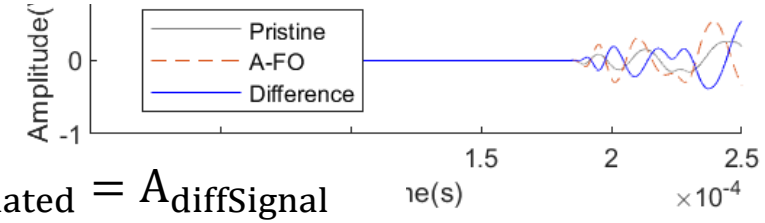
$$A_{Pristine} - A_{Matrix\ crack} = A_{diffSignal}$$



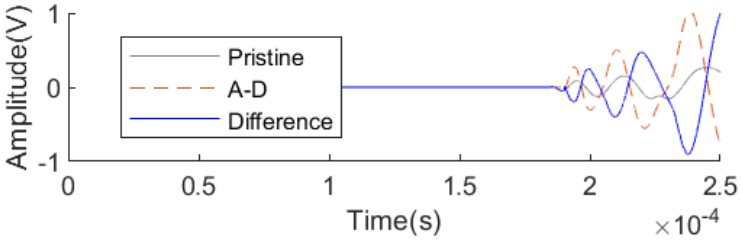


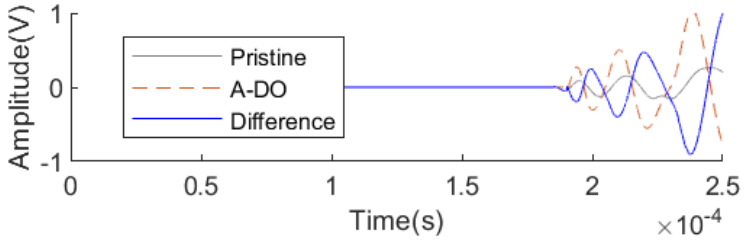
$$A_{Pristine} - A_{Fiber\ breakage} = A_{diffSignal}$$



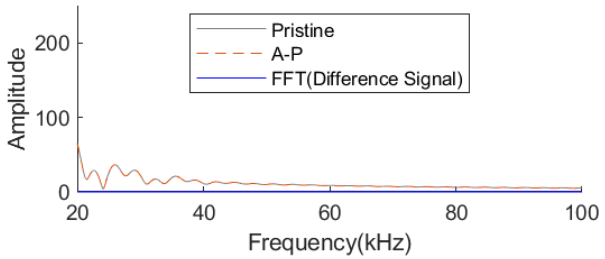


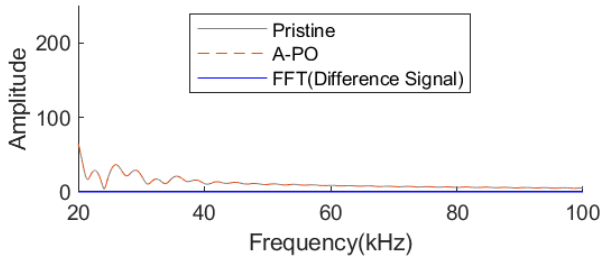
$$A_{Pristine} - A_{Delaminated} = A_{diffSignal}$$

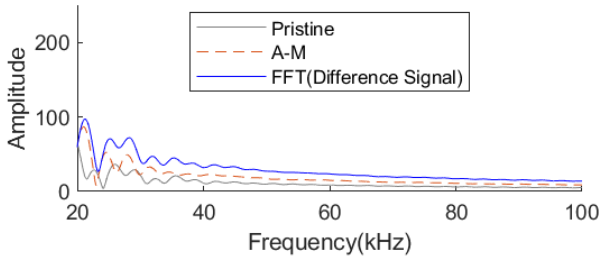


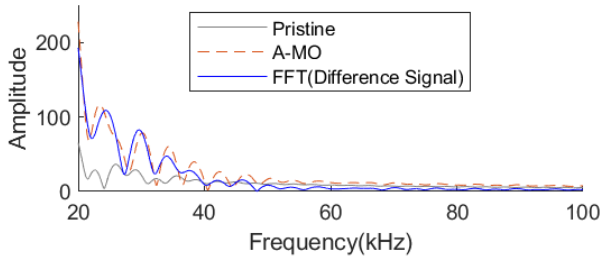


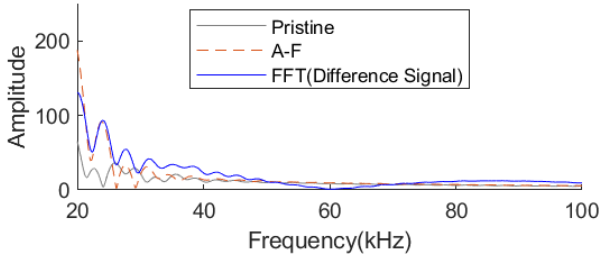
Difference Signals FFT

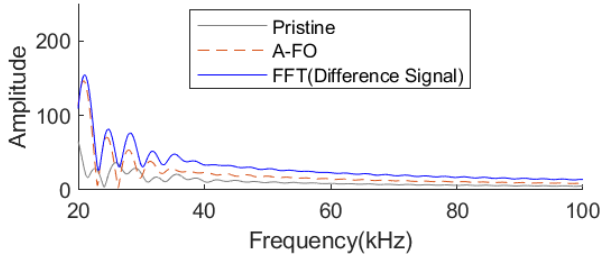


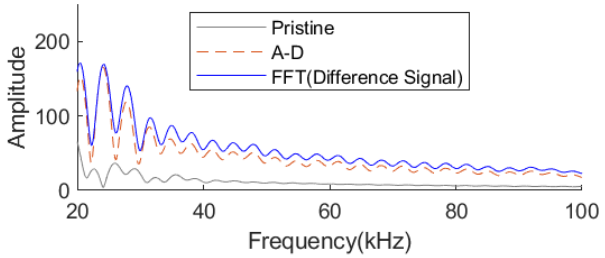


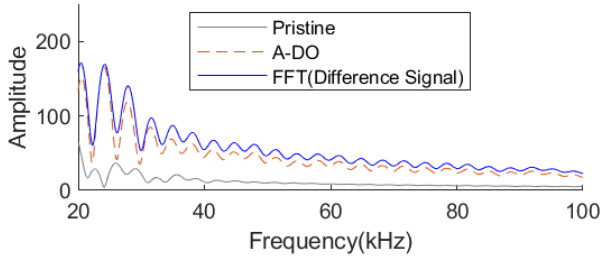






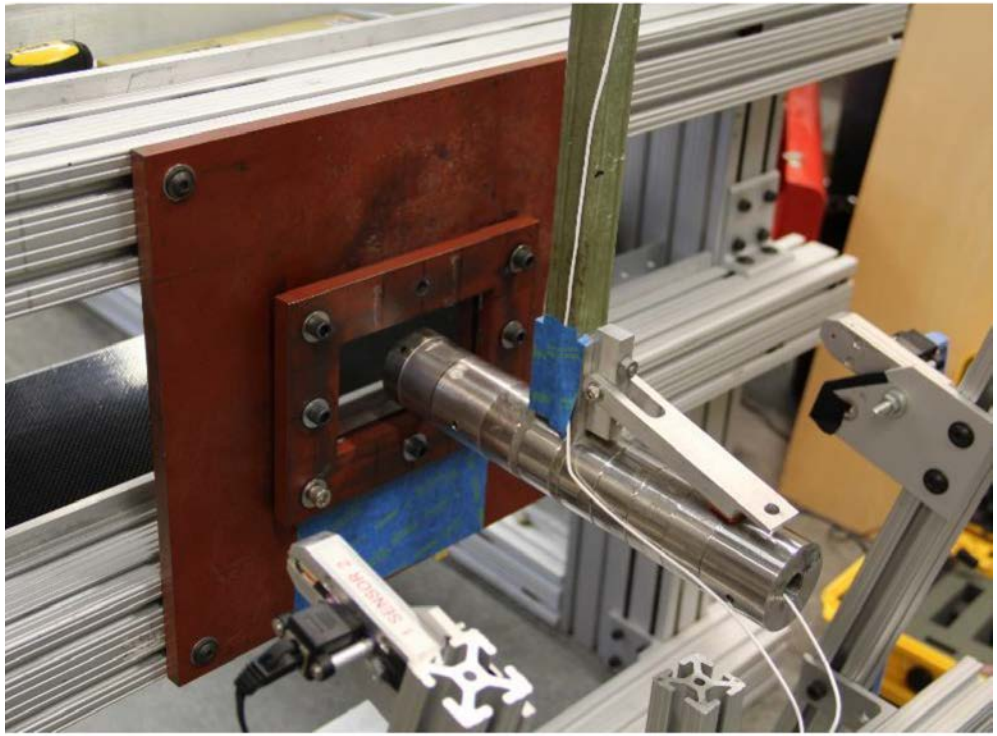






Impact Damage to Thermoplastic Composites

- Recently-started basic study on damage characteristics
  - Damage Initiation
  - Damage Modes
  - Damage Size/Area Comparison
- Thermoplastic vs Thermoset
  - Std Modulus / 8552 Toughened Epoxy
  - High Modulus / LMPAEK
- Varying Impact Tip Diameter
  - 16, 25.4, 101.6 mm (5/8, 1.0, 4.0 in.)



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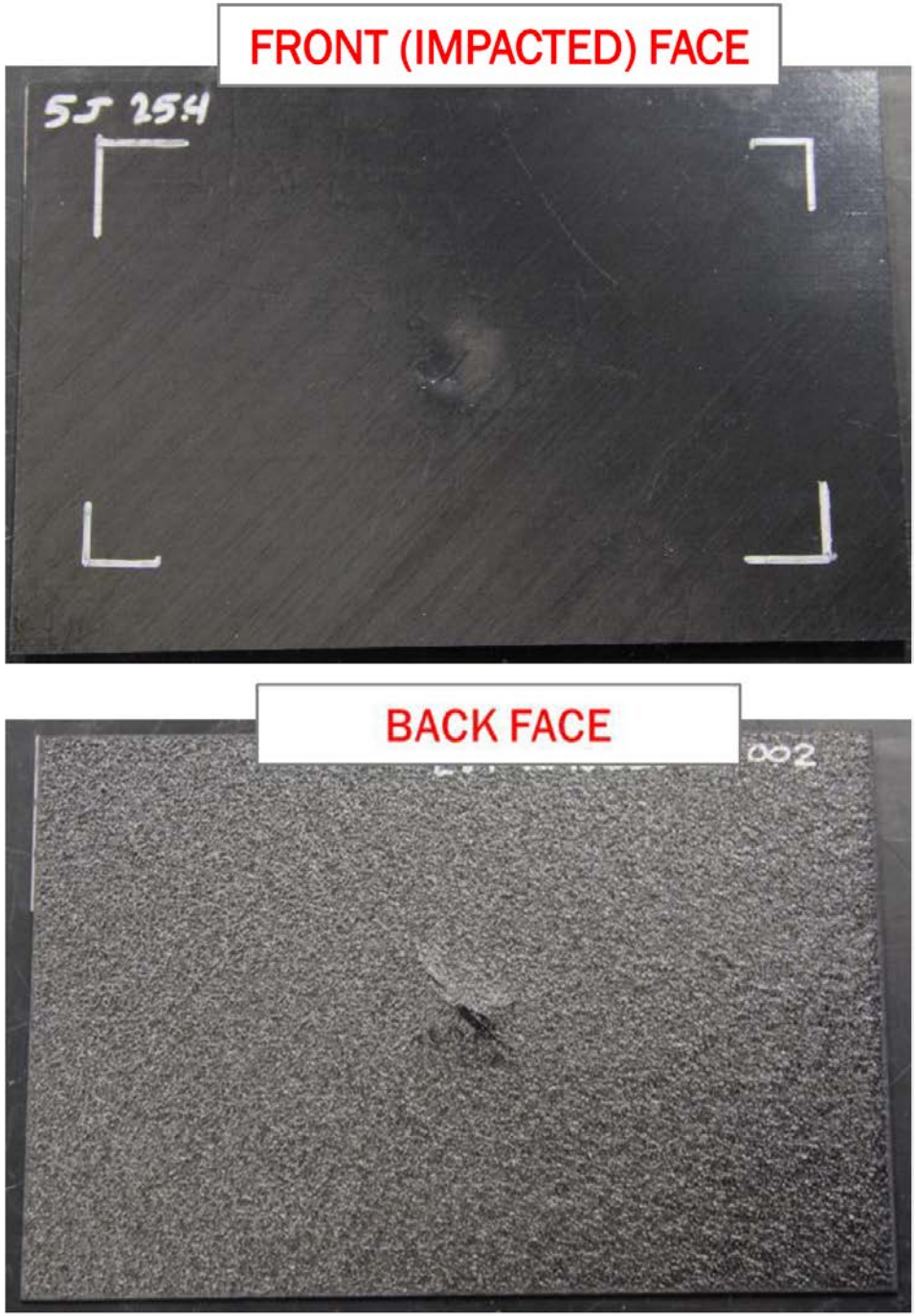
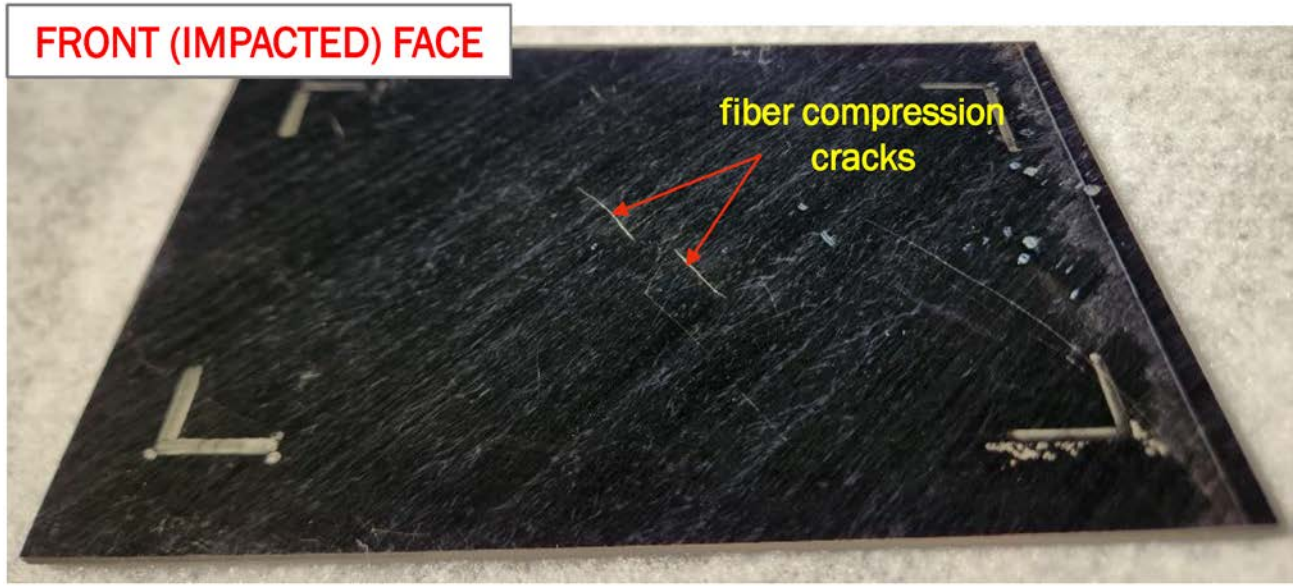
Typical Thermoset Initial Damage Mode

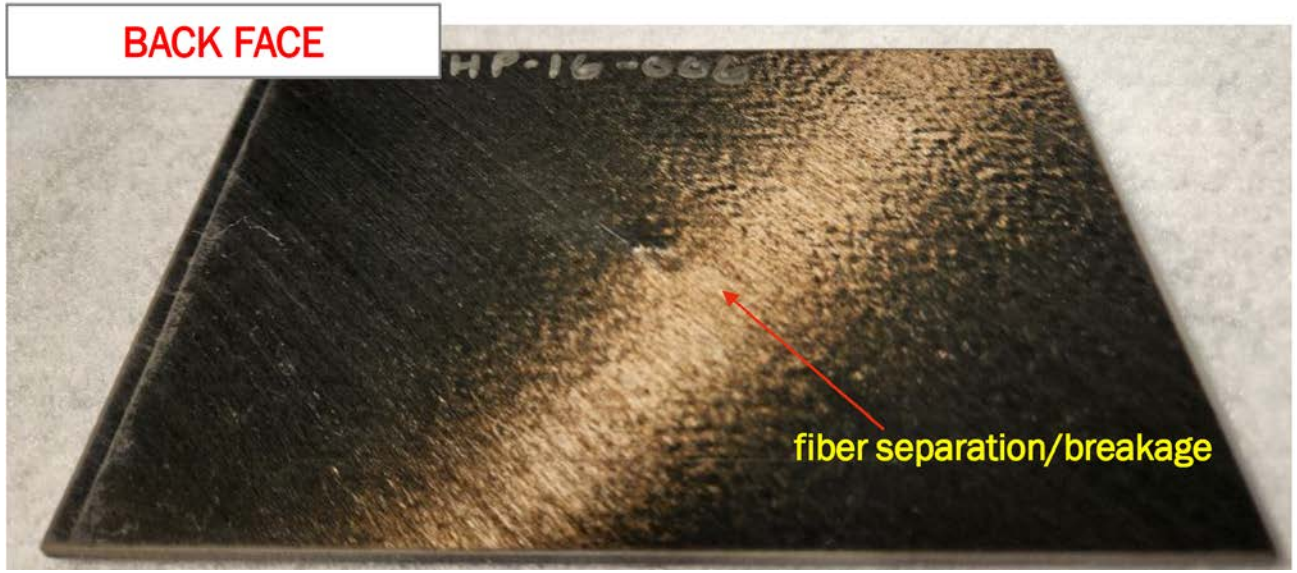
- 8 Plies
- 5J impact with a 25.4mm diameter tip
- Damage area of 360 mm^2
- Surface dent of 0.61 mm
- Fiber breakage mostly on backside



Typical Thermoplastic Initial Damage Mode

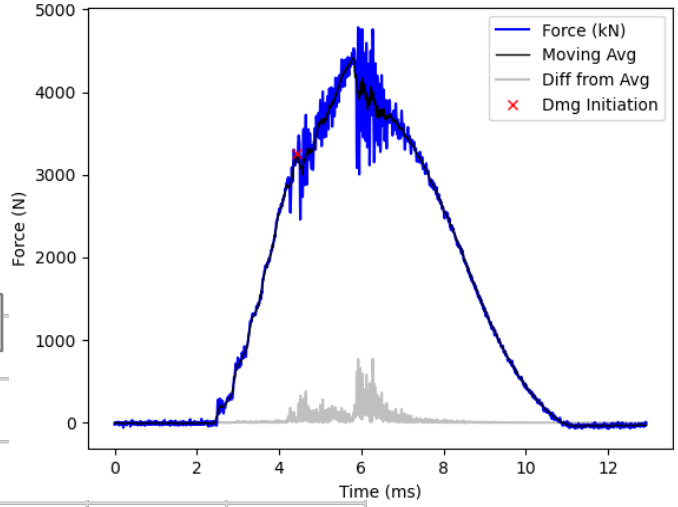
- 16 Plies
- 30J impact with a 25.4mm diameter tip
- Damage area of 364 mm^2
- Surface dent of 0.32 mm
- Fiber breakage on front side

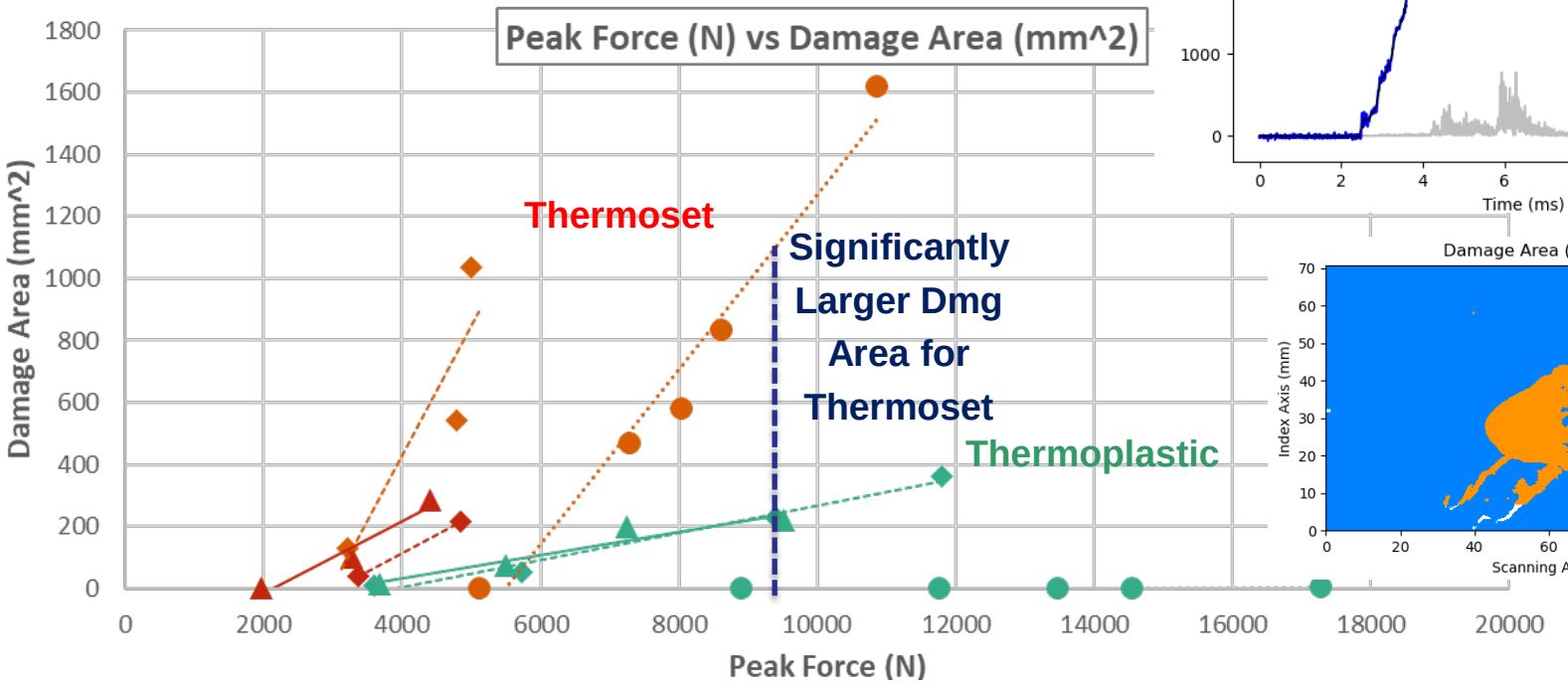




Peak Force vs Damage Area: 16 ply

- Force vs Time measured for each test
- Damage Initiation Force more informative than Impact Energy





16 mm Dia. Impactor

- Std Modulus/8552 (Expired)
- Std Modulus/8552
- High Modulus/LMPAEK

25.4 mm Dia. Impactor

- Std Modulus/8552 (Expired)
- Std Modulus/8552
- High Modulus/LMPAEK

101.6 mm Dia. Impactor

- Std Modulus/8552 (Expired)
- Std Modulus/8552
- High Modulus/LMPAEK

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Conclusions

Detection:

- Scanning UGW system robustly detects internal damage in stringer-skin stiffened composite panels
  - scan from external-side only over large areas
  - confidently detects damage – Yes/No result
  - can localize detection along scan – e.g., stringer heel crack vs cap damage
- Composite plates with manufactured individual damage modes were investigated
  - UGW measurements show different characteristics for Fiber, Matrix, Delam.

Residual Strength:

- Well-known Average Stress Criterion model for notched composites provides framework for correlating NDE information to residual strength
  - conventional c-scan (or A-scan) gives overall impact damage size a
  - UGW dispersion curves provide critical damage length scale a_k (equivalent to a_o for hole)
  - estimates based on UGW match with test-measured strength reduction

Thermoplastic composite impact damage: differences observed in damage mode sequence and damage size characteristics in comparison to thermoplastic matrix.

Future Work

- 1-D line scans for individual damage modes differentiation
  - machine learning to be applied for differentiation of signals and features
  - extend method for case of combined-mode damage states
- Deeper investigation of relationship between Average Stress notched strength criterion and UGW-measured characteristic length parameters
- Thermoplastic impact damage study
  - continued basic study on flat plates
  - welded/joined components – doublers, stiffeners
  - re-think impact damage rules developed for thermosets in application to high toughness thermoplastics

Benefits to Aviation

- NDE-based tools directly informing about residual strength are needed
- Using NDE to estimate residual strength degradation can help make decisions on continued service vs repair action
- Fundamental understanding of impact damage to thermoplastic composites and built-up structures