Impact Damage Tolerance Guidelines for Stiffened Composite Panels

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Participants

- **Principal Investigators & Researchers**
  - PI: Prof. Hyonny Kim
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  - Graduate Students
    - PhD:

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

    - MS: none

- **FAA Technical Monitor:** Lynn Pham
- **FAA Sponsors:** Larry Ilcewicz & Cindy Ashforth
- **Other FAA Personnel Involved:** Ahmet Oztekin

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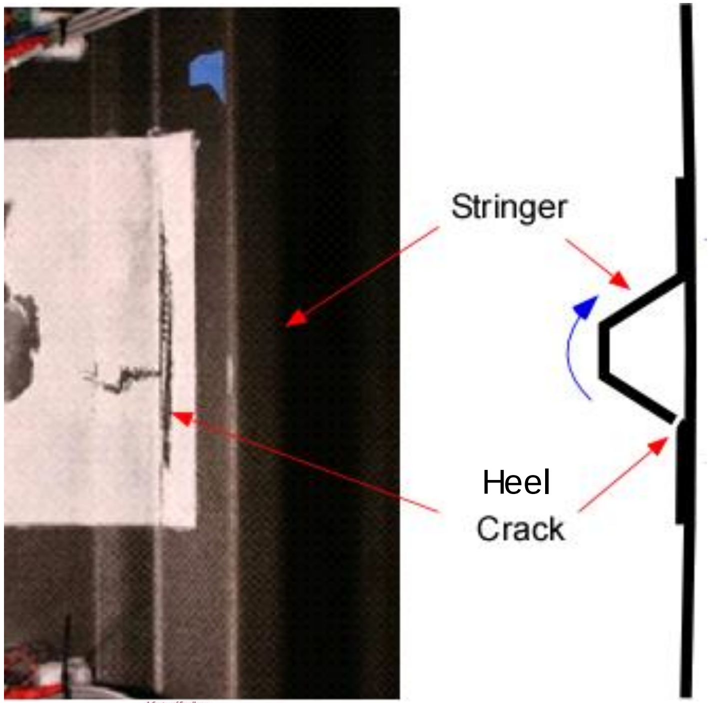
Motivation

- Impact to composite structures can cause internal damage
  - difficult to detect via visual inspection
- Ultrasonic guided wave (UGW) based non-destructive evaluation (NDE) 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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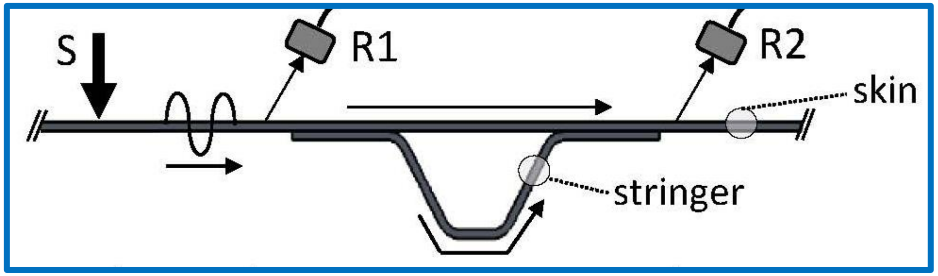
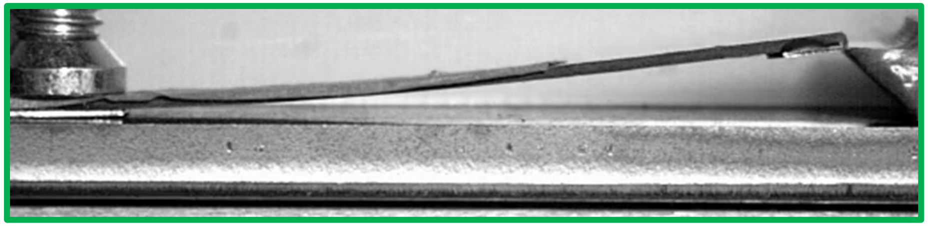
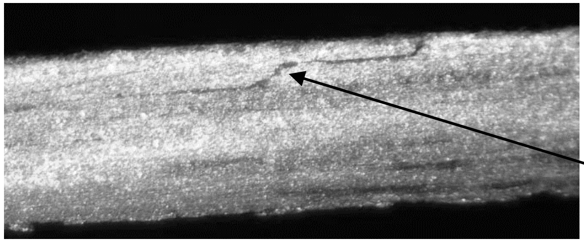
Previous Results Summary (Up to Spring 2022)

- UGW based detection of impact damage in composite panels
  - wave dispersion curves extraction for healthy and damaged panels
  - approximation of reduced laminate properties in damage zone
- Mini impactor parameterized – tool for exciting broadband UGW in structures
- Open hole tension specimens tested for correlation with UGW
- UGW study of “single” mode damage states







Fiber break in single 0 deg. Ply (Manufactured)

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Recent Results

- Topic 1: Damage Detection Via Elastic Property Identification From Dispersion Curves
- Topic 2: Residual Strength Estimation From UGW
- Topic 3: Extracting Damage Mode in Composite Panels Through Measured Wave Characteristics

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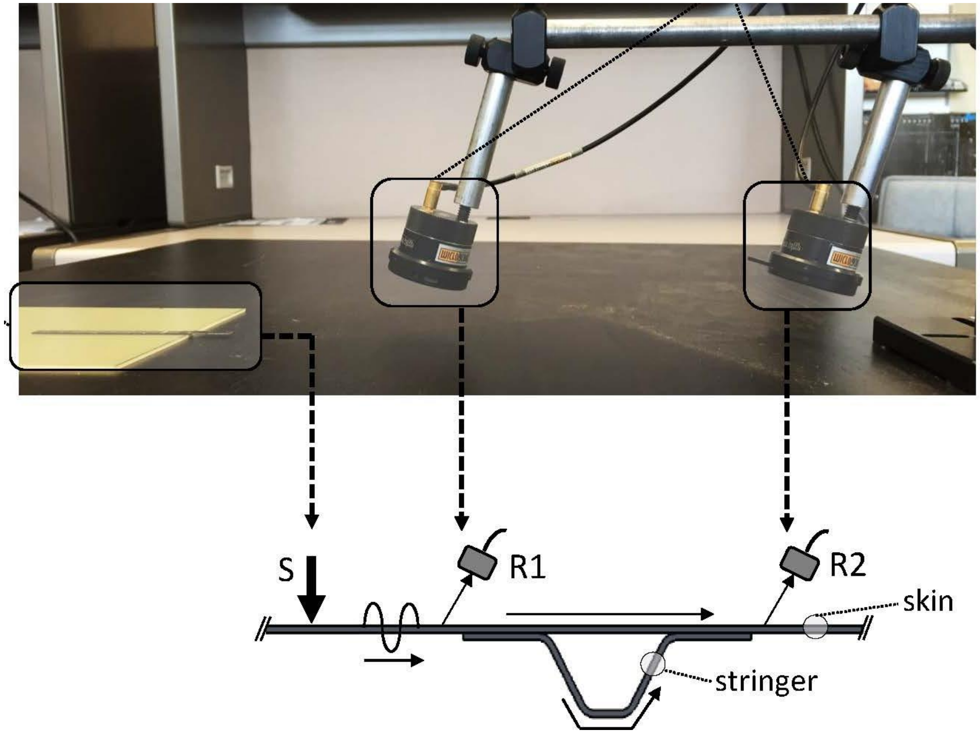
Topic 1. Damage Detection and Elastic Property Identification by Inversion of UGW Dispersion Curves

Objectives

- Develop scanning inspection system with external-only access to detect internal damage.
- Relate the measured dispersion curves to internal damage.
  - described as degradation of elastic properties due to impact damage



Methodology

- Use dual-output scanning system to extract phase-velocity dispersion curves of the stiffened panel from a single excitation.
- Estimate engineering elastic moduli at each scanning position.
  - Estimate degradation in damage zone via optimization routine
  - Use Semi-Analytical Finite Element (SAFE) method as a forward model

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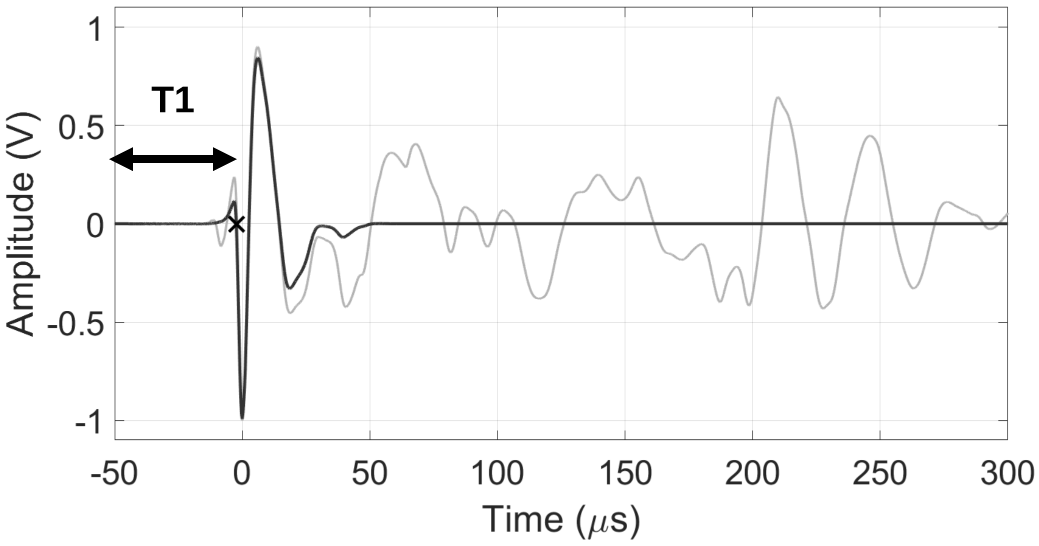
Phase Slope Method to Extract Dispersion Curves with a Single Ultrasonic Excitation

- Phase velocity curves estimated from the difference in phase slope of the measurements from the two air-coupled receivers.
- Coarse & fine phase tracing algorithm employed to eliminate the "π" error.

Phase velocity from the differential of phase spectra

$$c_p = \frac{-\omega L}{\phi_{R_2 win}(\omega) - \phi_{R_1 win}(\omega) - \omega(T_2 - T_1)}$$

Phase spectrum estimation by truncating the coarse phase T1



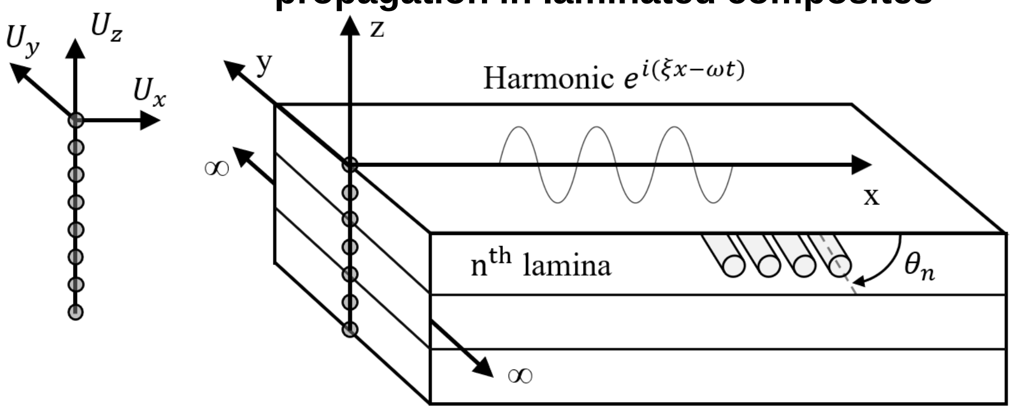
Inversion of Flexural Mode Dispersion Curve

- Simulated Annealing algorithm used to identify the engineering constants for the given layup.
- An objective function set as the discrepancy between “trial” dispersion curve and the measured curve.

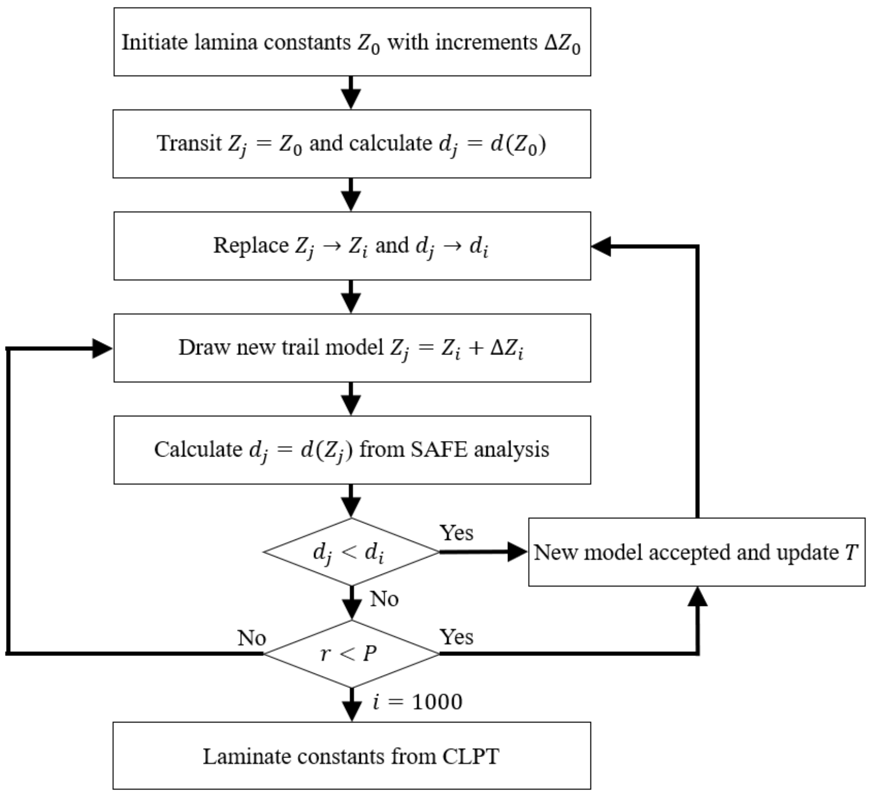
Objective Function In Simulated Annealing Optimization

$$d = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{c_{p,pred}(\omega_i) - c_{p,exp}(\omega_i)}{c_{p,exp}(\omega_i)}\right)^2}$$

SAFE model of guided wave propagation in laminated composites

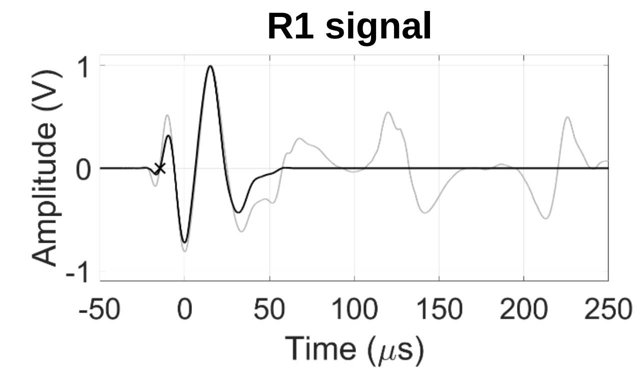


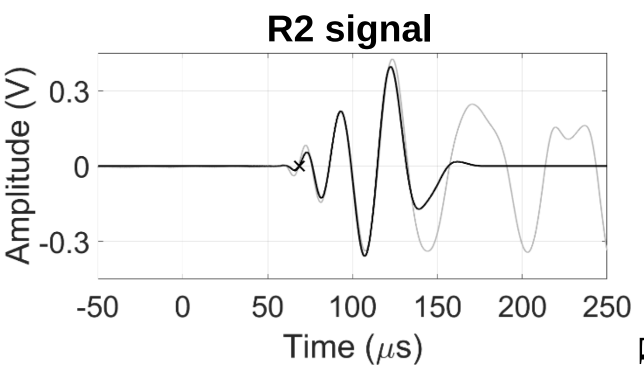
Laminate Constants Identification

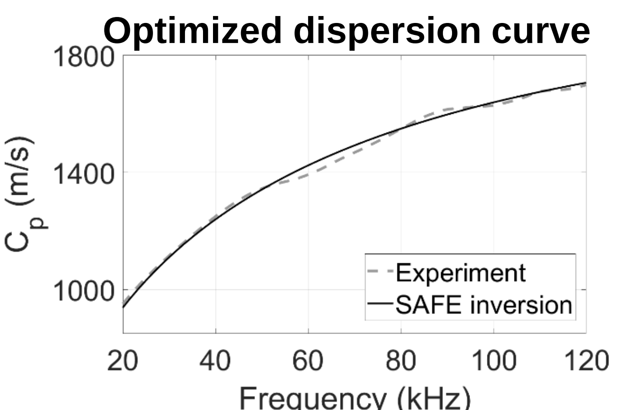


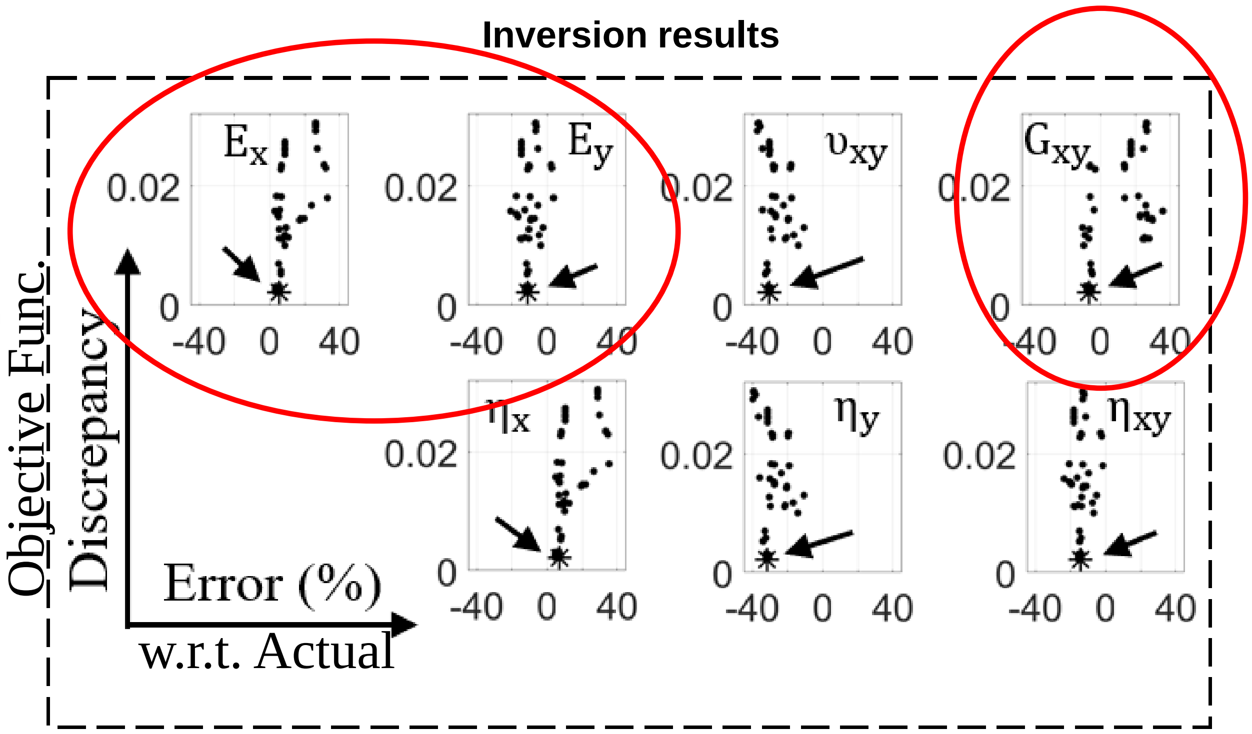
Proof of Concept on CFRP Laminate (“Skin Only”)

- Anisotropic [0/45/0/-45/0]s, Hexcel282PW carbon/epoxy.
- From UGW dispersion curves, in-plane elastic constants (Ex, Ey, Gxy) identified within 10% error.







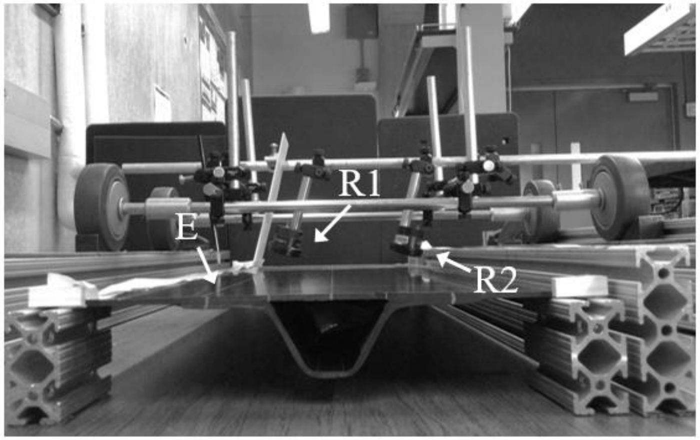


Flange & Cap Impact Damage

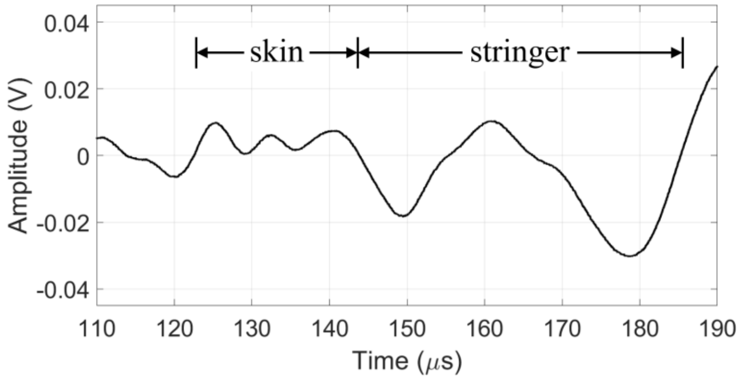
Lamina constants of curved composite

E_{11} (GPa)	E_{22} (GPa)	G_{12} (GPa)	G_{23} (GPa)	ν_{12}	ν_{23}	ρ (kg/m^3)
160	8.97	6.21	3.45	0.28	0.36	1550

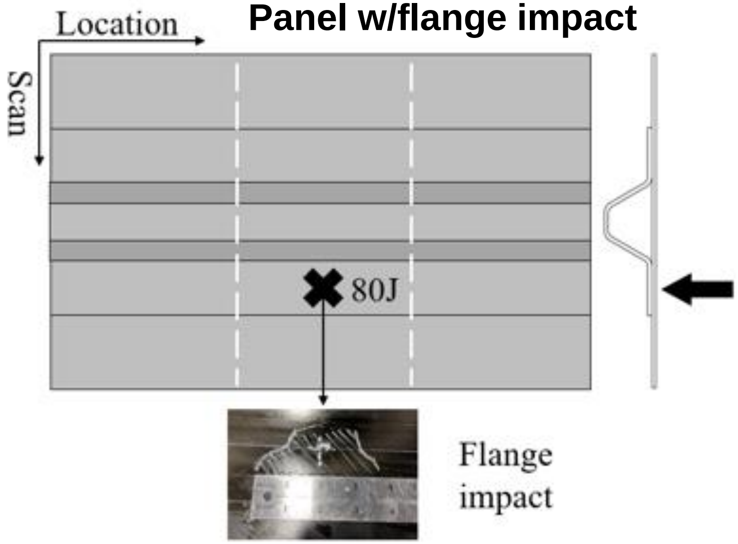
SIDO Vehicle Setup



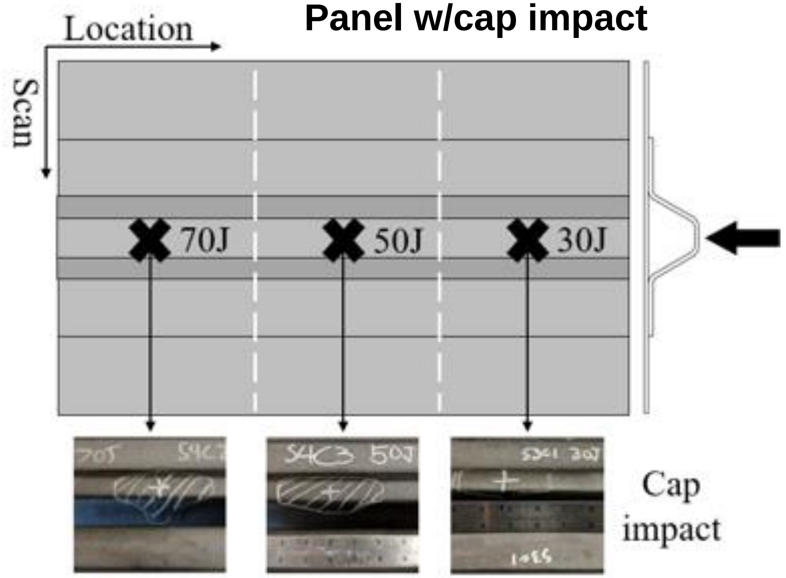
Mode Separation in R2



Panel w/flange impact

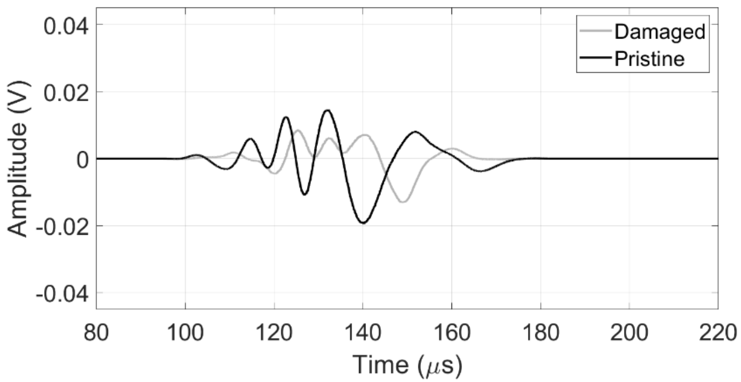


Panel w/cap impact

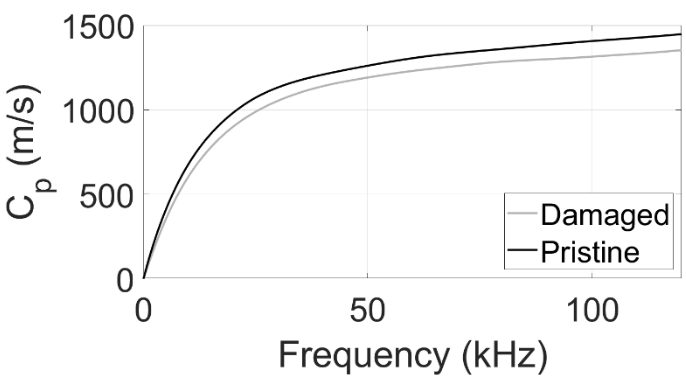


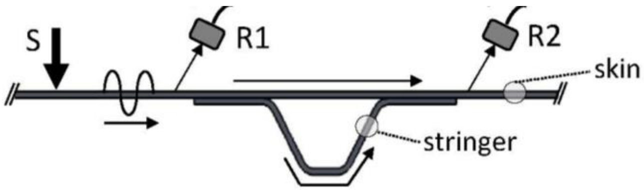
Results for Flange Impact Damage

Comparison of skin mode in R2

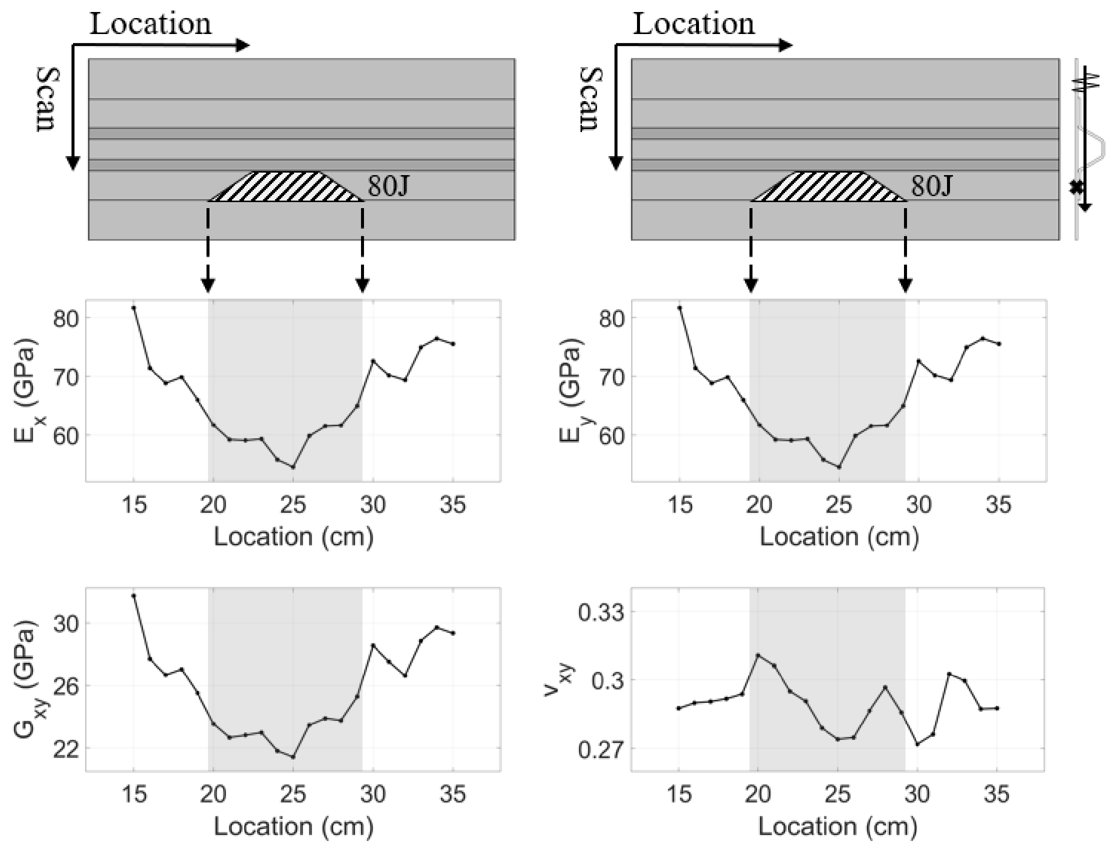


Drop in phase velocity due to impact





In-plane engineering constants inversion results



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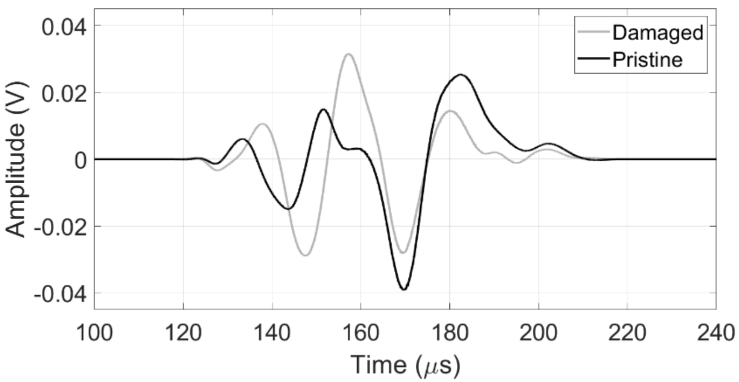
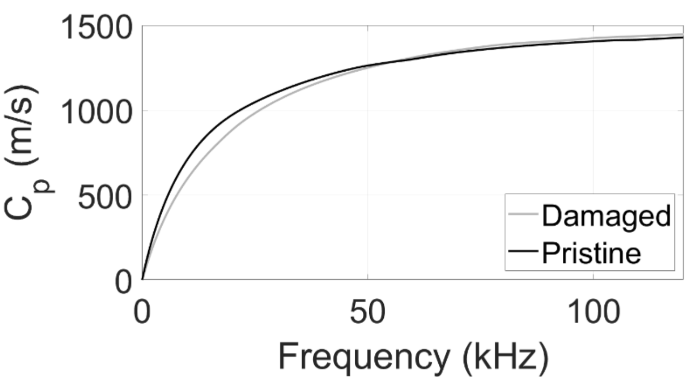
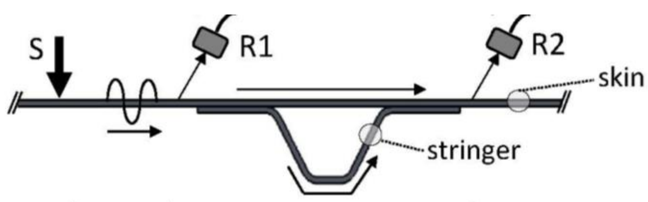
Results for Cap Impact Damage

Comparison of skin mode in R2

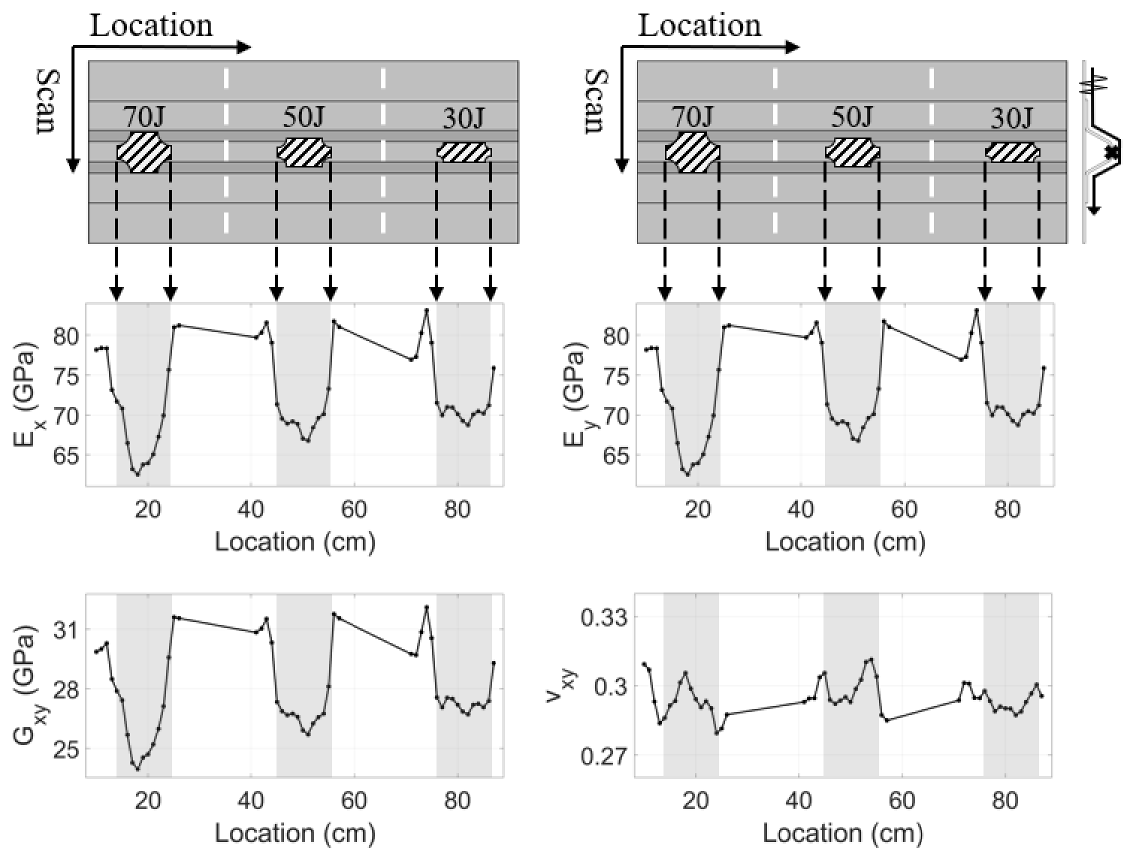


Drop in phase velocity due to impact





In-plane engineering constants inversion results



Damage location and size detected.

Damage severity expressed as degraded in-plane elastic properties.

Next steps: further refinement and relate to stiffened panels residual strength reduction

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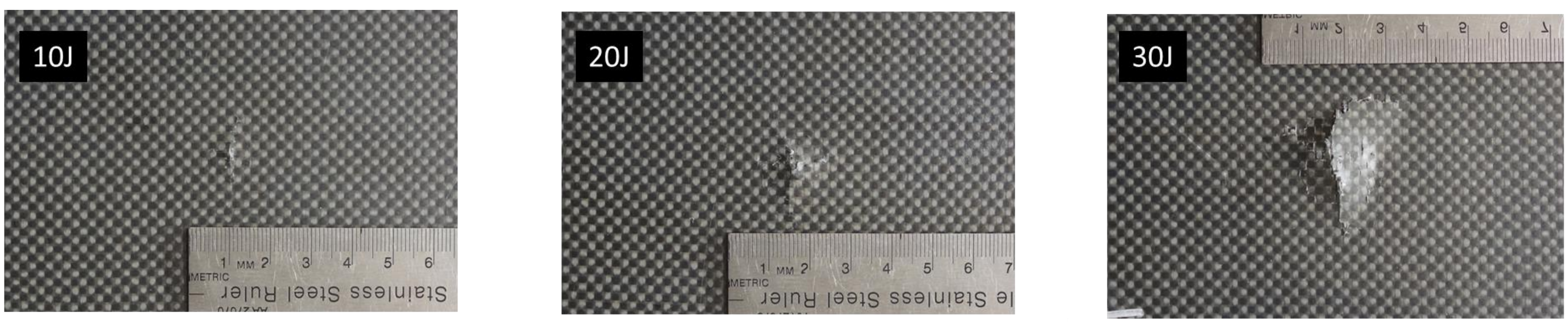
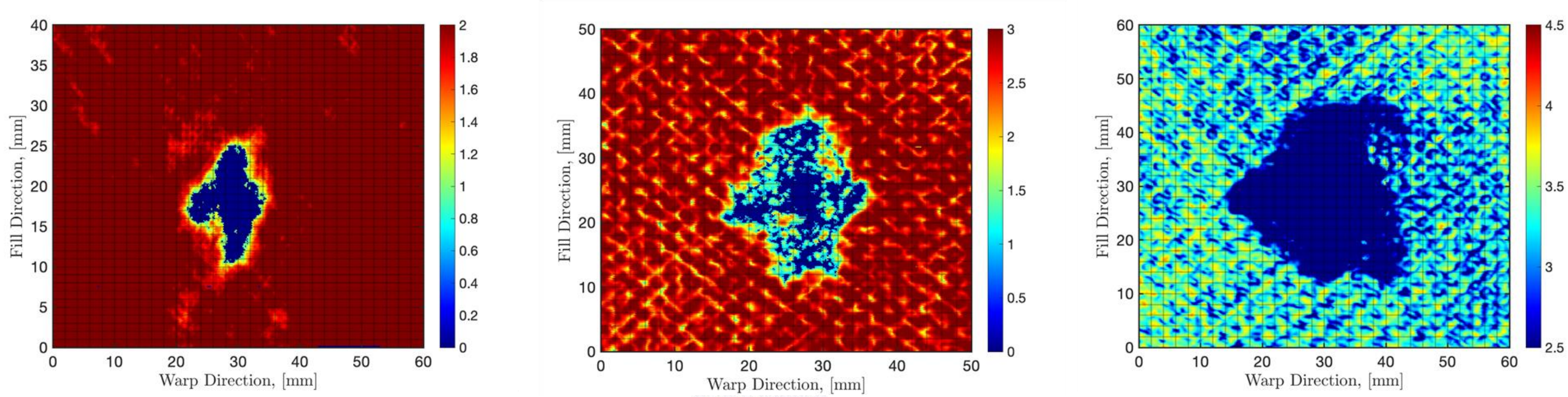
Topic 2. Residual Strength Estimation From UGW

- Objective
  - Estimate impact-damaged panel residual strength using UGW NDE phase velocity dispersion measurements
- Methodology Summary
  - 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

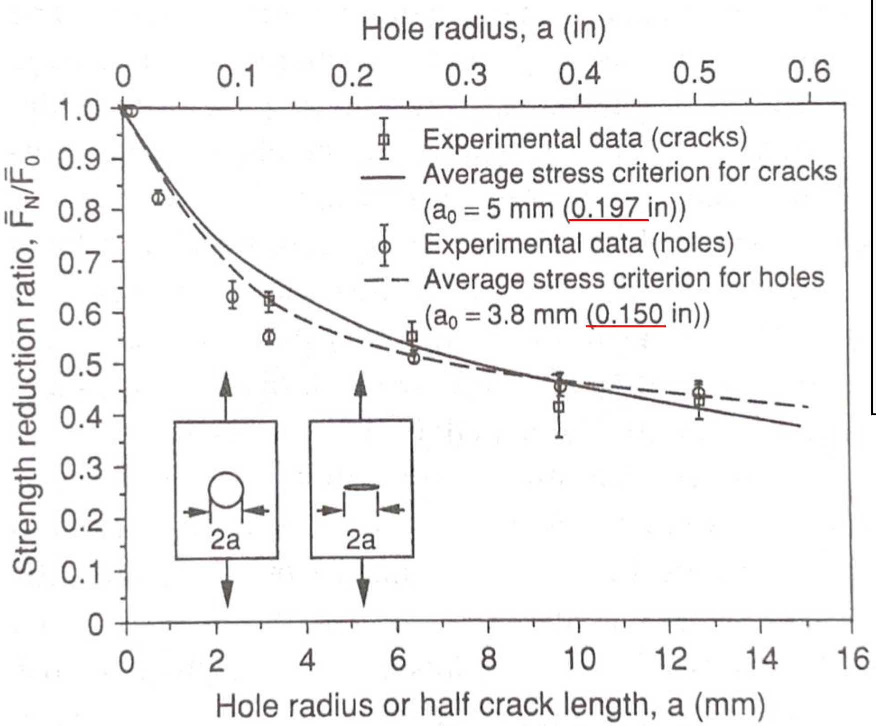


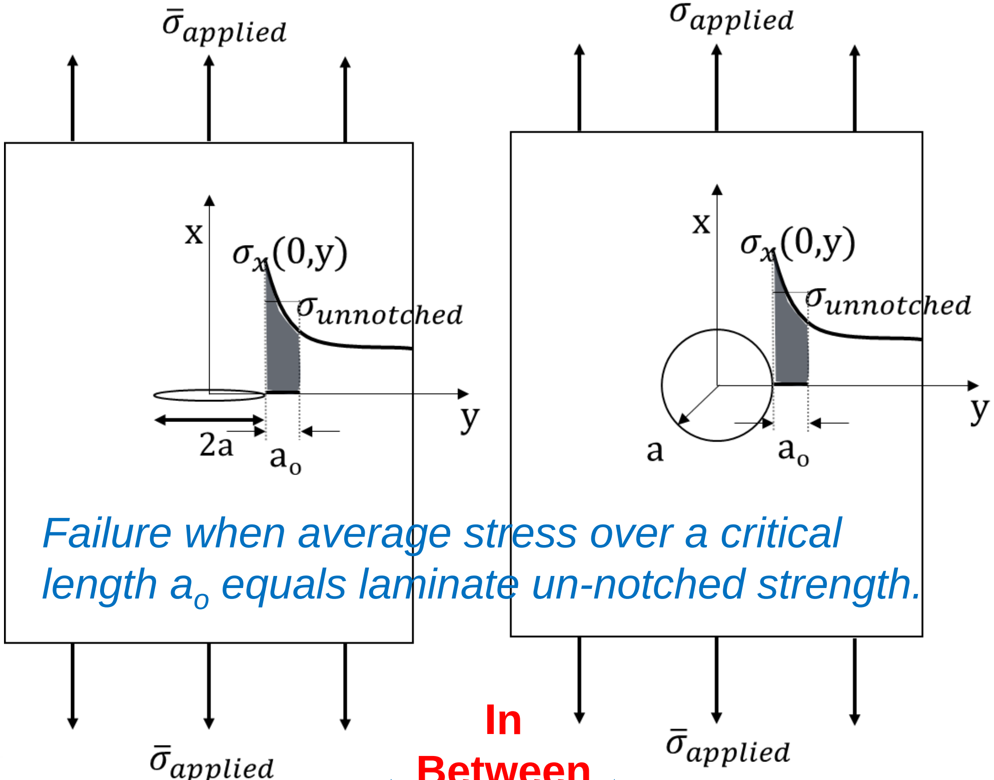


Average Stress Semi-Empirical Notched Strength

Average Stress Failure Criterion:

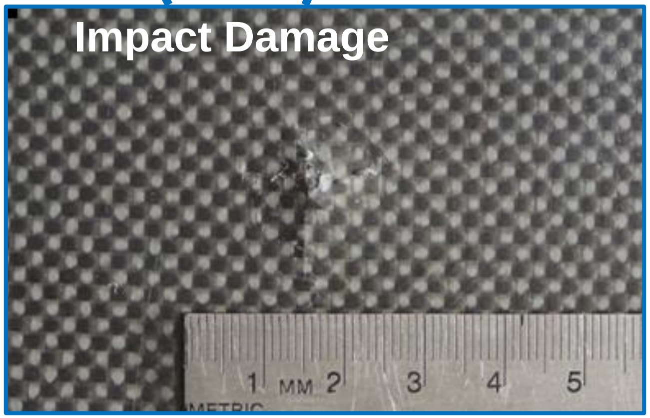
$$\frac{1}{a_o}\int_{a}^{a+a_o} \sigma_x(0,y) = \sigma_{unnotched}$$





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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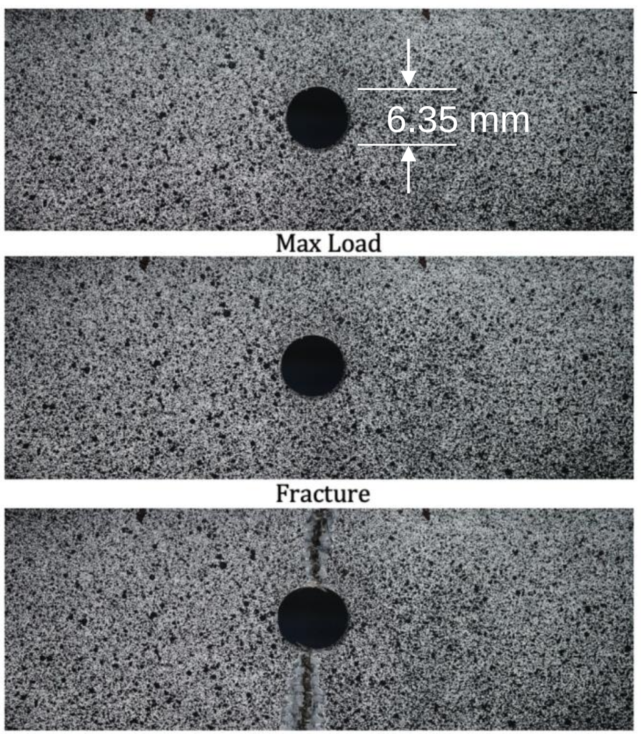
Open Hole and Impact Damage Residual Strength

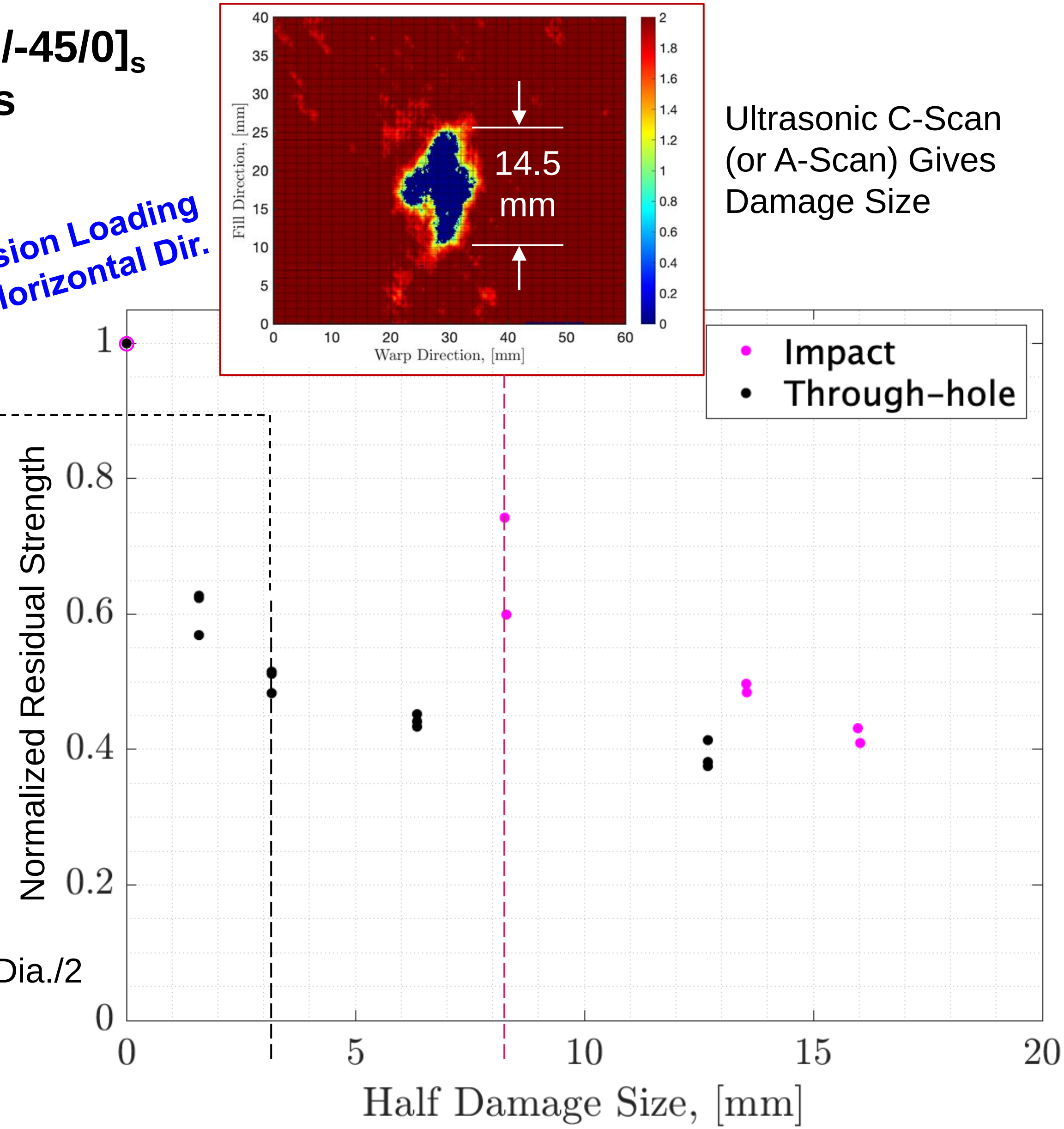
Residual Strength for $[0/45/0/-45/0]_s$ PW Carbon/Epoxy Laminates

1. Open Through-Hole
2. Impact Damage

Tension Loading in Horizontal Dir.

Initial





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

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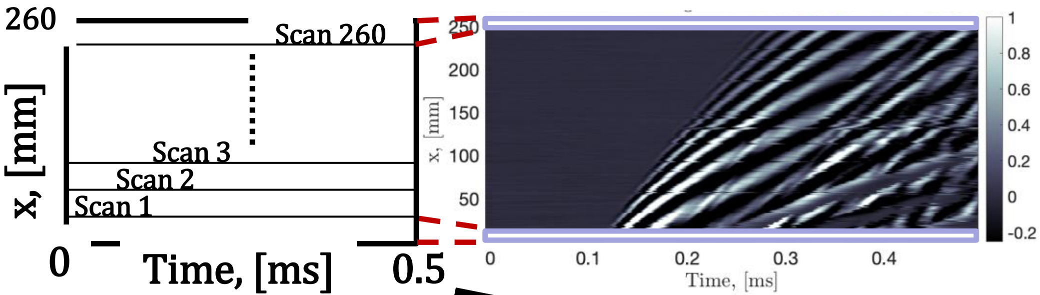
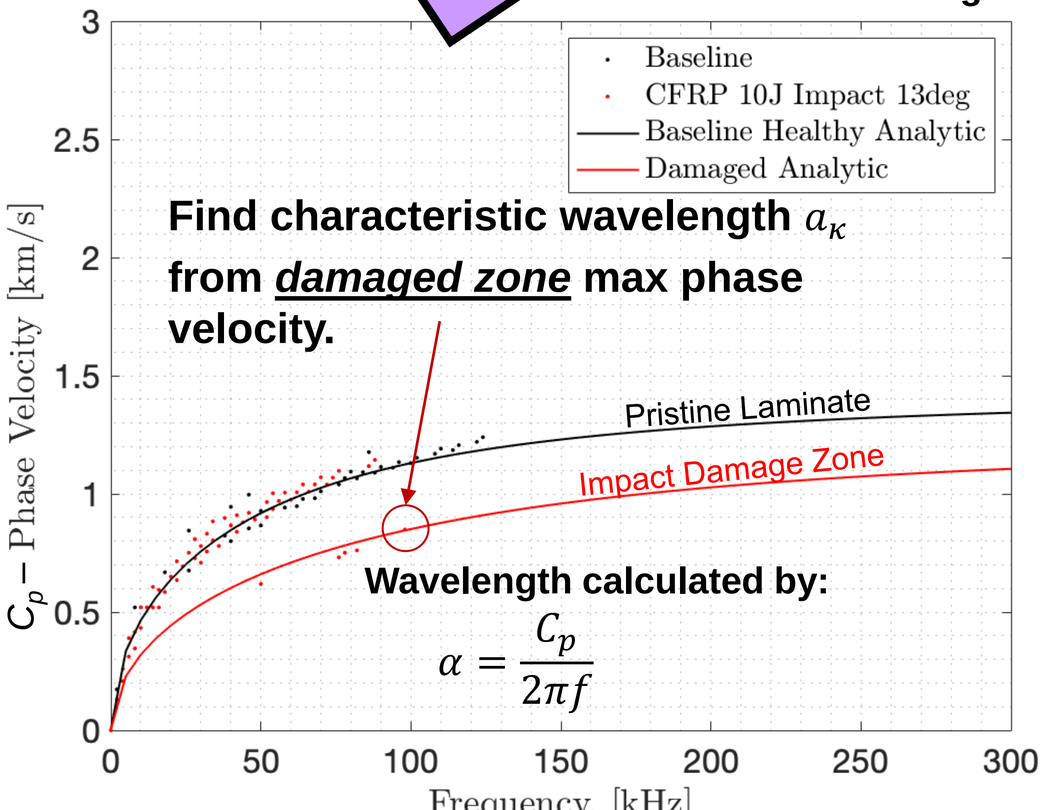
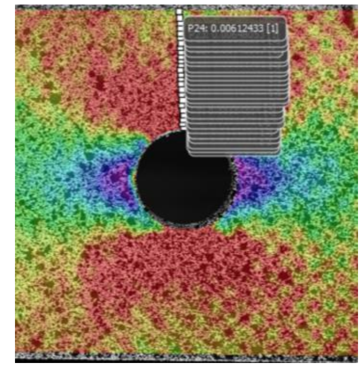
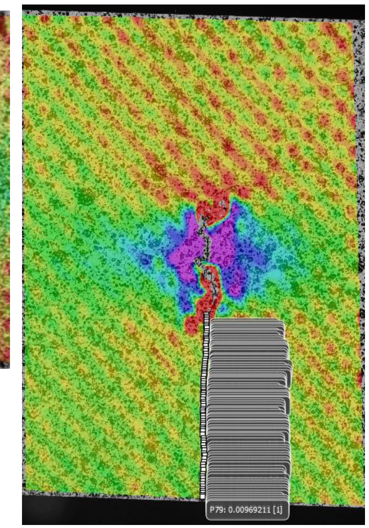
UGW Characteristic Wavelength and Experim. SCF



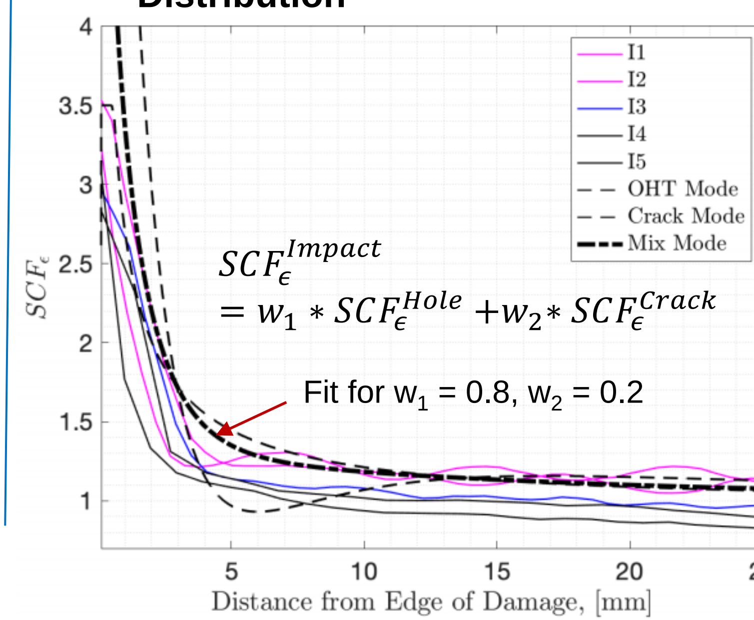
Construct Dispersion Curve via WAVSVD Processing







Experimental Strain Stress Concentration Distribution



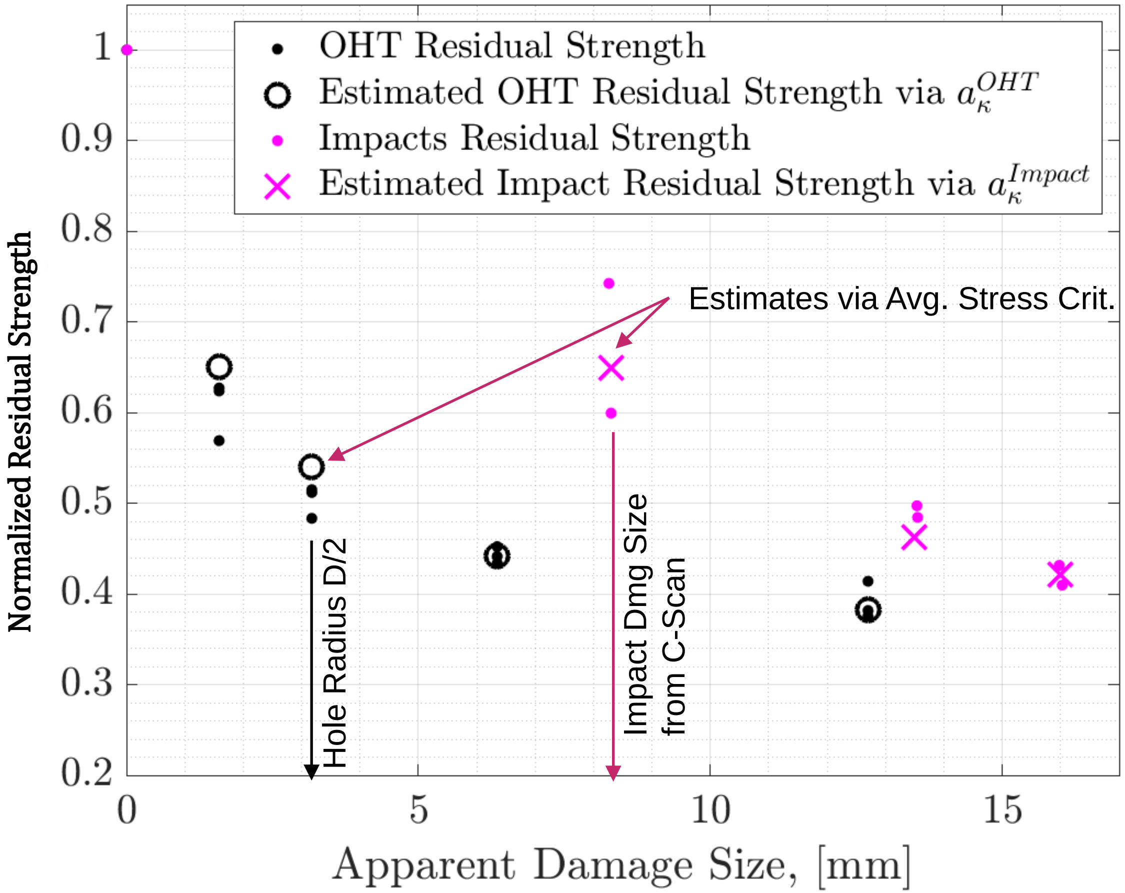
NDE-Correlated Residual Strength Estimate

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) gives estimate that strongly correlates with residual strength vs damage size test data.



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).

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Topic 3. 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

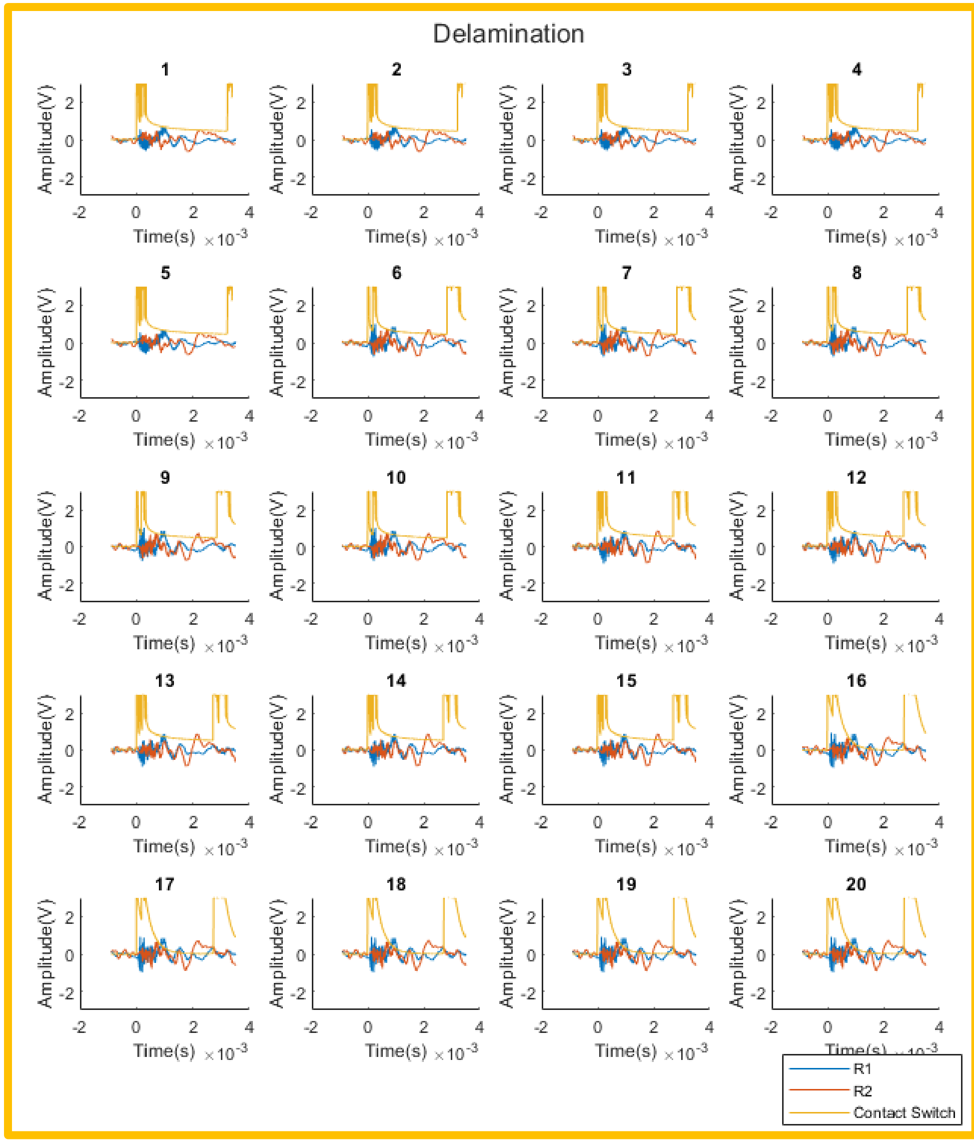
Methodology Summary

- 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”

UGW Signal Processing and Damage Identification



Pristine | Delaminated | Matrix Crack | Fiber Breakage

20 signals collected

Determine the best signal with the highest cross-correlation to other signals *xcorr*(R1)

Gate R1 signal based on R1 boundary reflections

Gate R2 signal based on R2 boundary reflections

Normalize signal by dividing each of the signal by absolute *max*(R1)

FFT of R1 and R2 signals

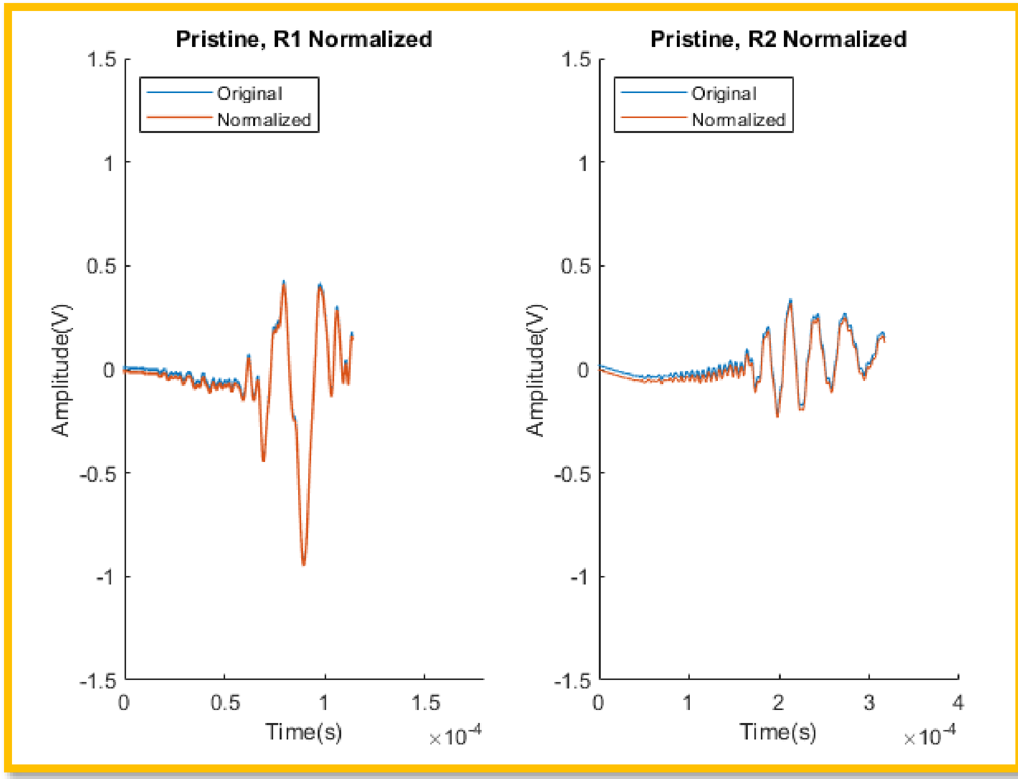
Deconvolution

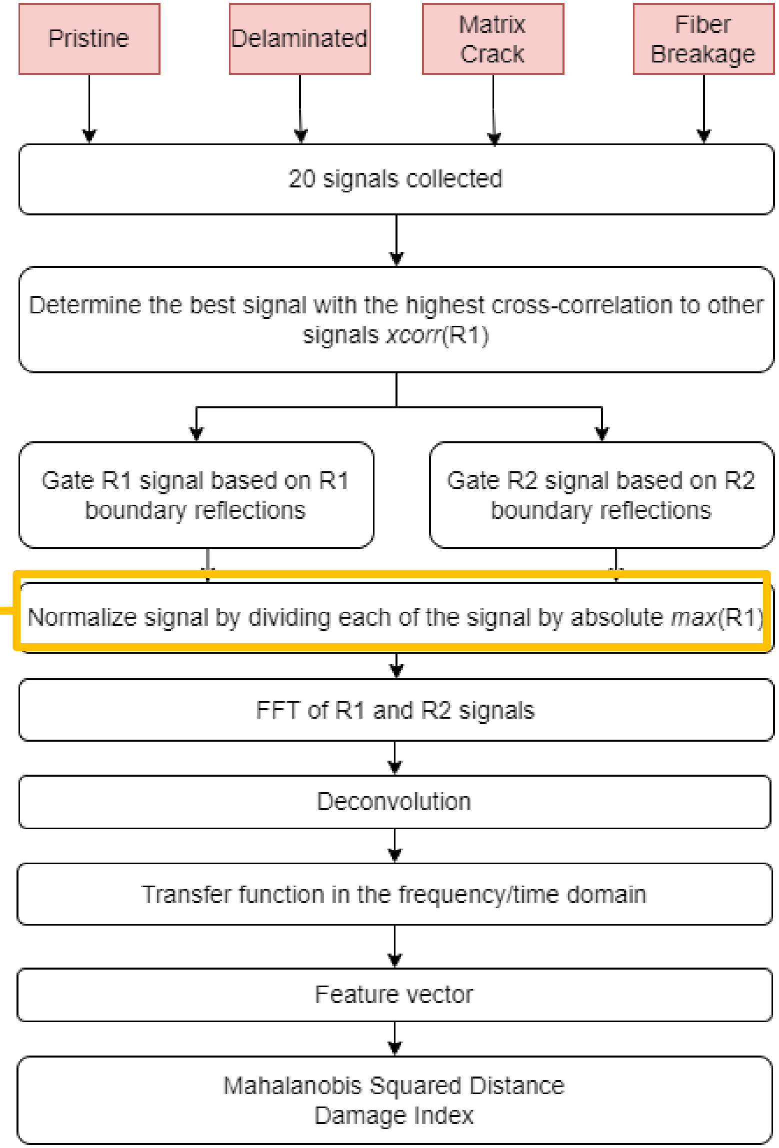
Transfer function in the frequency/time domain

Feature vector

Mahalanobis Squared Distance Damage Index

UGW Signal Processing and Damage Identification





- Signals gated to remove signal reflection due to free boundaries
- Time-domain measurements at R1 and R2 are normalized based on the maximum peak of R1

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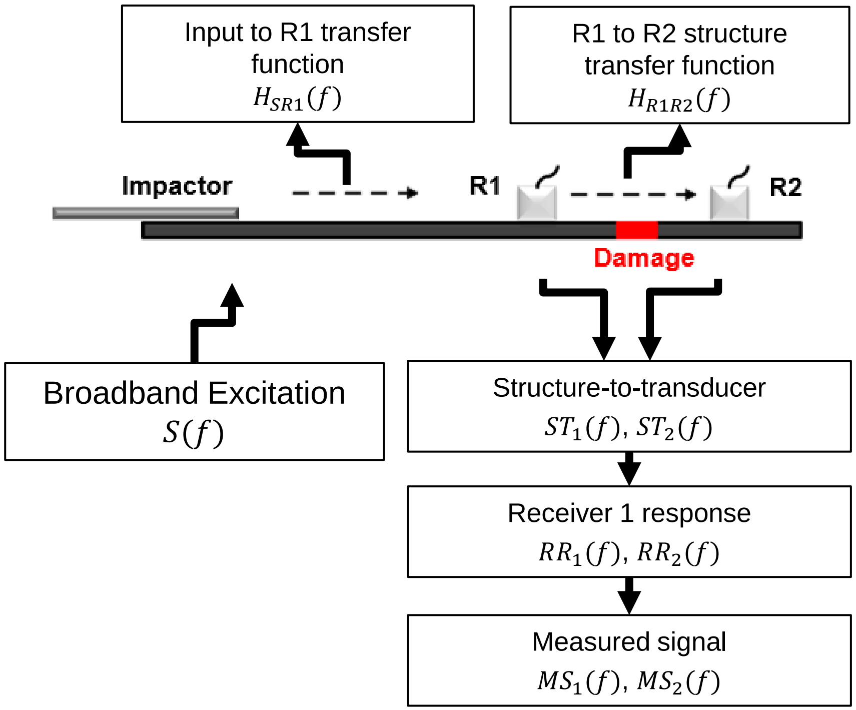
UGW Signal Processing and Damage Identification

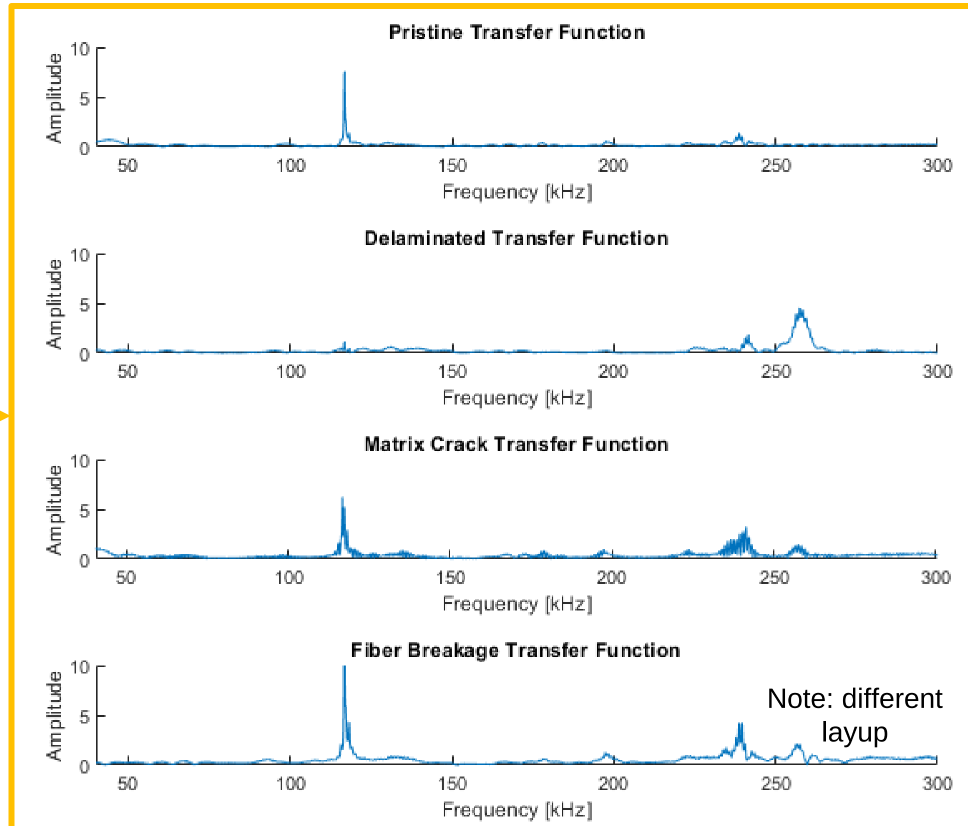
- The structure transfer function (TF) is extracted using the following algorithm

$$MS_1(f) = S(f)H_{SR1}(f)RR_1(f) + ST_1(f)$$

$$MS_2(f) = S(f)H_{SR1}(f)H_{R1R2}(f)RR_2(f) + ST_2(f)$$



$$\frac{\langle CrossPower \rangle}{\langle AutoPower \rangle} = \frac{|S(f)H_{SR1}(f)|^2 H_{R1R2}(f)}{|S(f)H_{SR1}(f)|^2} = H_{R1R2}(f)$$



Transfer function in the frequency/time domain

Feature vector

Mahalanobis Squared Distance
Damage Index

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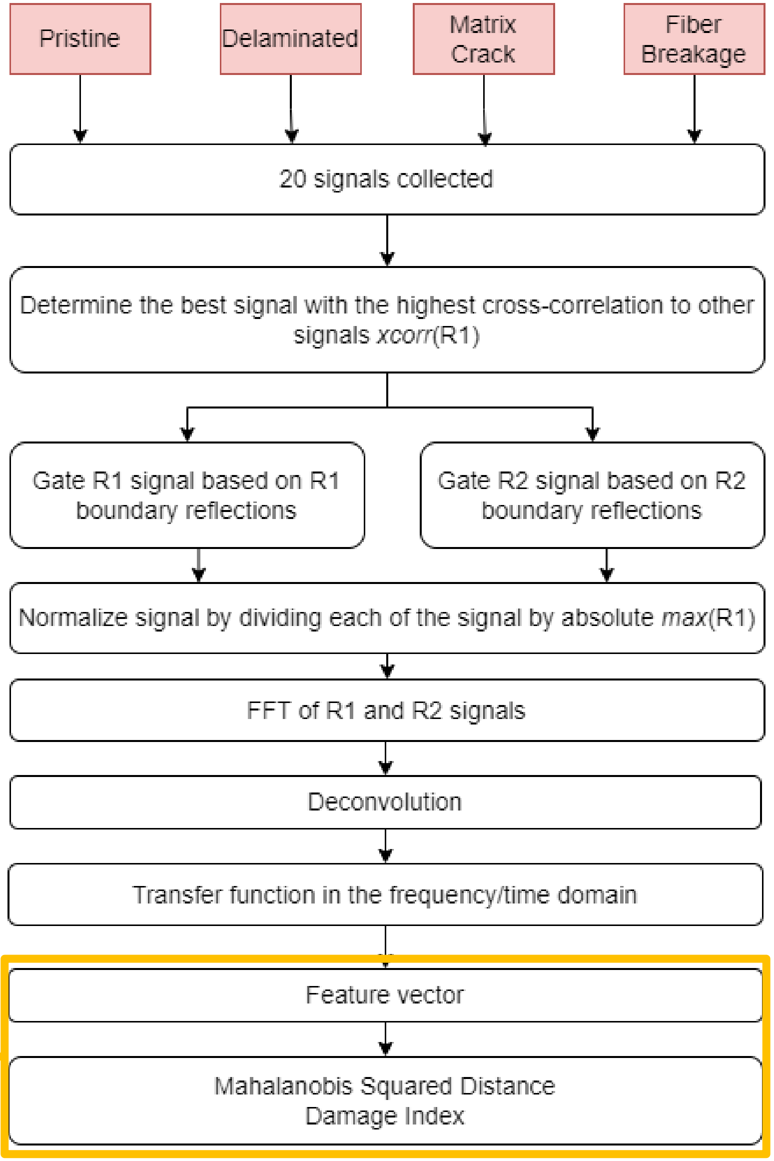
UGW Signal Processing and Damage Identification

$$\frac{\langle CrossPower \rangle}{\langle AutoPower \rangle} = \frac{|S(f)H_{SR1}(f)|^2 H_{R1R2}(f)}{|S(f)H_{SR1}(f)|^2} = H_{R1R2}(f)$$



Feature Vector captures differences with how the waveform interacts with defects

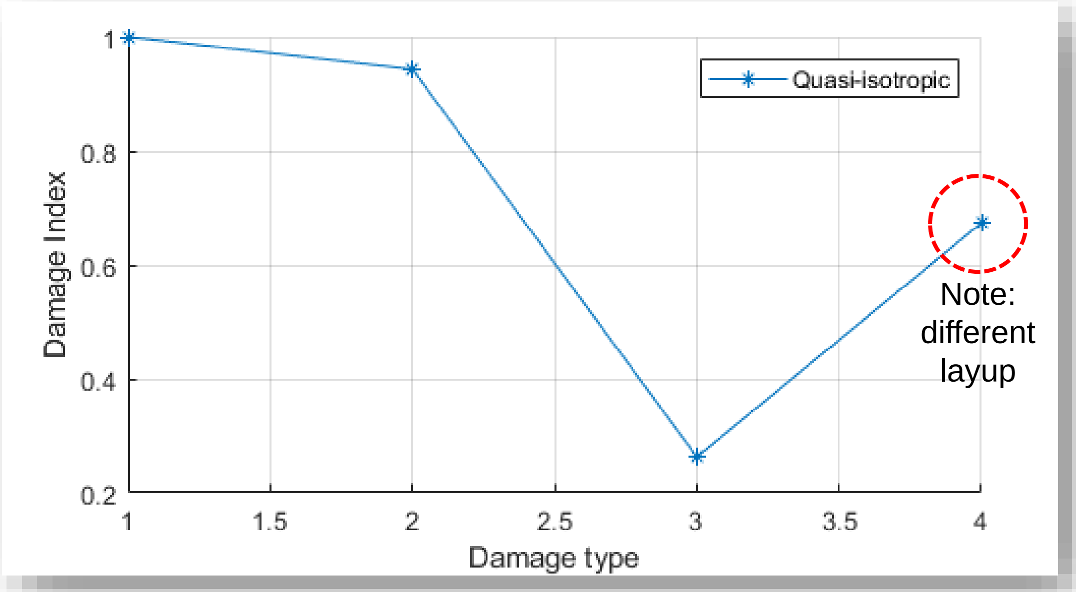
- RMS of $H_{R1R2}(t)$, transfer function in time domain
  - Signal strength and magnitude
- Skewness of $H_{R1R2}(t)$, transfer function in time domain
  - Signal shape and phase distribution
- Max FFT of $H_{R1R2}(f)$, transfer function in frequency domain
  - Signal attenuation

Mahalobis Squared Distance used as the Damage Index:

$$(\boldsymbol{x} - \overline{\boldsymbol{x}})\boldsymbol{C}^{-1}(\boldsymbol{x} - \overline{\boldsymbol{x}})^{\boldsymbol{T}}$$

Results and Discussion

- The transfer function in the frequency domain, normalized cross-power spectrum varies for each damage type.
- From the transfer function, different damage types distinguishable - can allow damage classification.



Damage Type	Laminate ID	Layup
1	Q-Pristine	[45/90/-45/0/0/-45/90/45]
2	Q-Delamination	[45/90/-45/0//0/-45/90/45]
3	Q-Matrix Crack	[45/90/-45/0/0/-45/90/45]
4	Q-Fiber Breakage	[-45/0/45/90/90/45/0/-45]

Pristine plate acts as a baseline; value = 1

Work in progress:

- Continue scans for different damage modes.
- ID other discerning features
- For combined damage modes – is reconstruction possible?

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Conclusions

- Scanning UGW system detects internal damage in stringer-skin stiffened composite panels.
  - scan from external-side only
  - tracking drop in estimated engineering constants maps with impact damage locations in the stringer flange and in the stringer cap
- Composite plates with manufactured individual damage modes were investigated in 1-D line scans for damage detection.
  - extracted structure transfer function used to determine damage types
- The well-known Average Stress Criterion model for notched composites is shown to serve as an effective basis for correlating NDE information to estimates of residual strength
  - model needs: damage size a and critical length a_o
  - 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)

Future Work

- Test the elastic constants identification method on a larger variety of damage in the stiffened panels.
- Improve inversion accuracy using combination of multiple wave modes (flexural, axial, etc.).
- Incorporate elastic constants degradation estimates into residual strength models.
- 1-D line scans for damage detection are ongoing – tests will be conducted on both sides of the plate to determine depth of damage.
- Extend 1-D line scan method for case of combined-mode damage states.
- Automate mini impactor mechanism and establish automatic data collection trigger system – will allow 20-50 repeat tests to be conducted faster.
- Investigate mathematical relationship between Average Stress notched strength criterion and UGW-measured characteristic length parameters.

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.