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Non-destructive Evaluation Methods for Detecting Major Damage in Internal Composite Structures

New Project Title: *Impact Damage Tolerance Guidelines for Stiffened Composite Panels*

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Participants

- **Principal Investigators & Researchers**
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  - Co-PI: Prof. Francesco Lanza di Scalea
  - Graduate Students
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    - MS: none

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

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

- **Industry Participation**
  - Boeing, Bombardier, UAL, Delta, DuPont, JC Halpin

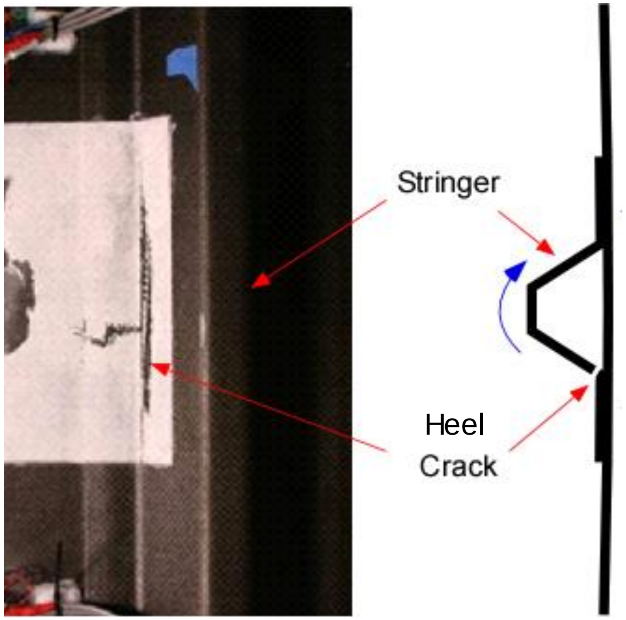
Motivation

- High energy Blunt Impact Damage (**BID**) of main interest:
  - involves large contact area, multiple structural elements
  - internal damage (cracked shear tie, frame, stringer heel crack) can exist with ***little/no exterior visibility***
- External-only NDE needed

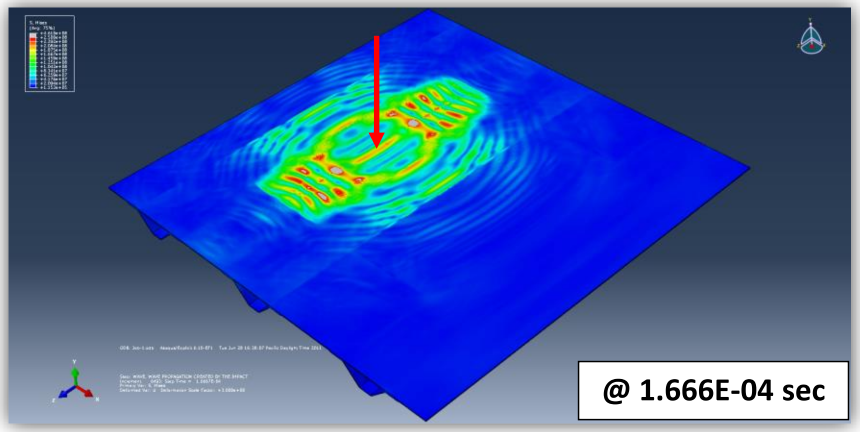
Overall Objectives:

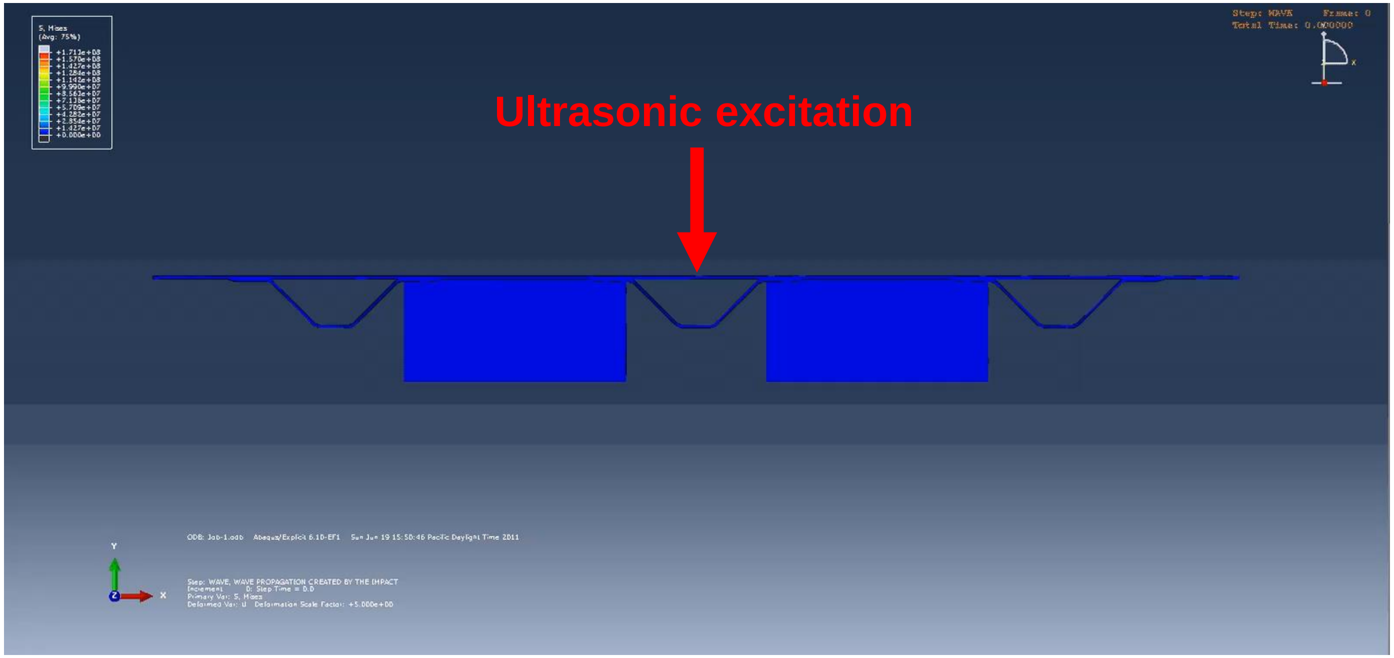
- Quantify detectable and non-detectable damage characteristics
- Relate Ultrasonic Guided Wave NDE measurements to damage state and residual strength

GSE Impact/Contact

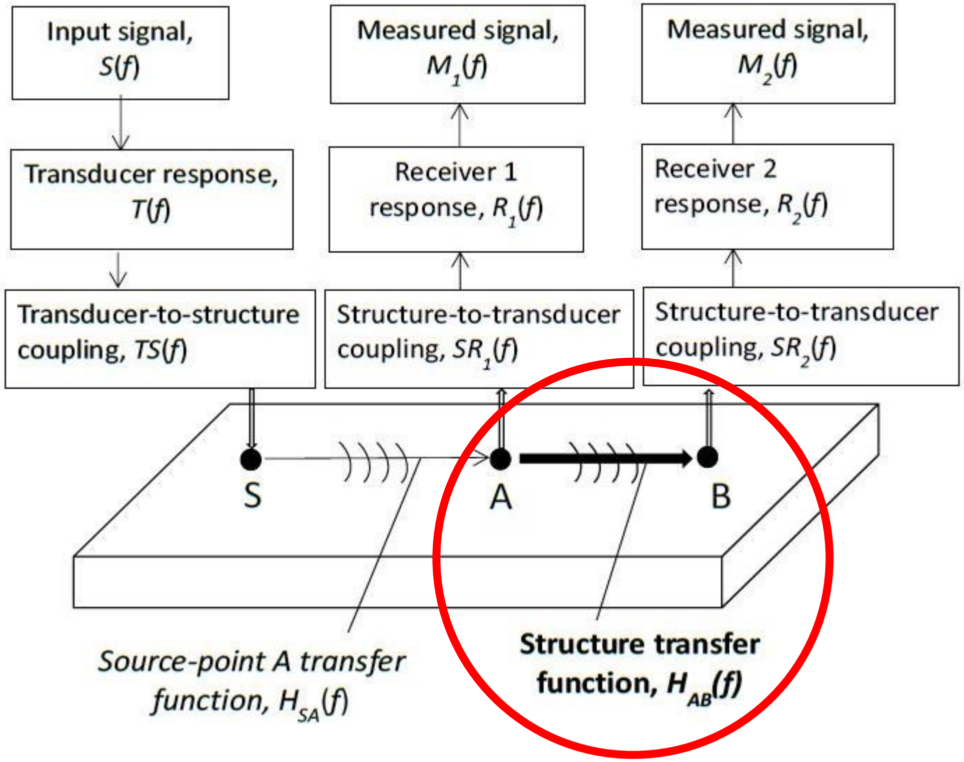


Ultrasonic Guided Waves: structure is a natural "waveguide"





Guided-Wave Transfer Function: Single-Input-Dual-Output Scheme (SIDO)



Input signal, $S(f)$

Transducer response, $T(f)$

Transducer-to-structure coupling, $TS(f)$

Measured signal, $M_1(f)$

Receiver 1 response, $R_1(f)$

Structure-to-transducer coupling, $SR_1(f)$

Measured signal, $M_2(f)$

Receiver 2 response, $R_2(f)$

Structure-to-transducer coupling, $SR_2(f)$

Source-point A transfer function, $H_{SA}(f)$

Structure transfer function, $H_{AB}(f)$

Receiver 1: $M_1(f) = S(f)\cdot T(f)\cdot TS(f)\cdot H_{SA}(f)\cdot SR_1(f)\cdot R_1(f)$

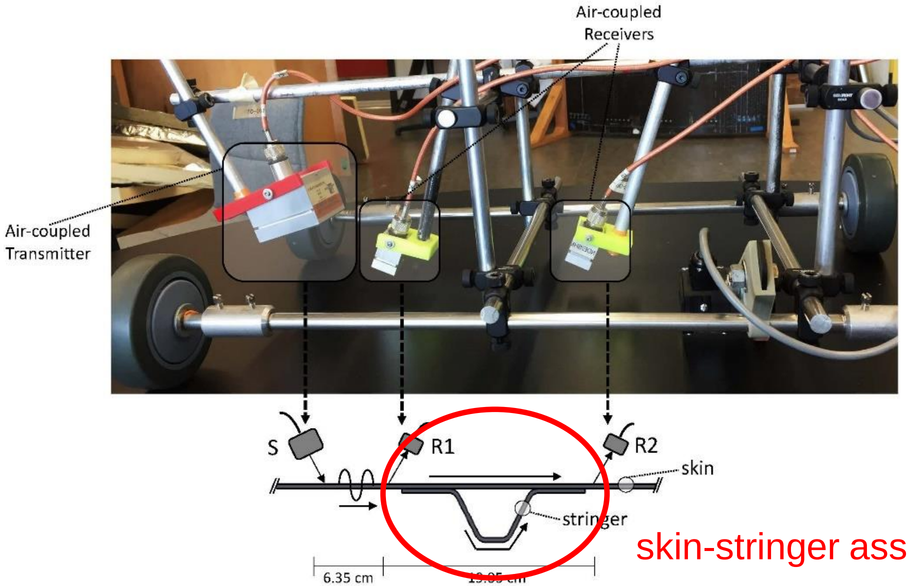
Receiver 2: $M_2(f) = S(f)\cdot T(f)\cdot TS(f)\cdot H_{SA}(f)\cdot \boxed{H_{AB}(f)}\cdot SR_2(f)\cdot R_2(f)$

$$\boxed{Deconv = \frac{M_2(f)}{M_1(f)} = \boxed{H_{AB}(f)}\cdot \cancel{\frac{SR_2(f)}{SR_1(f)}\cdot\frac{R_2(f)}{R_1(f)}}}$$

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

SIDO Transfer Function Scanning Systems

"AIR-COUPLED" SCANNER

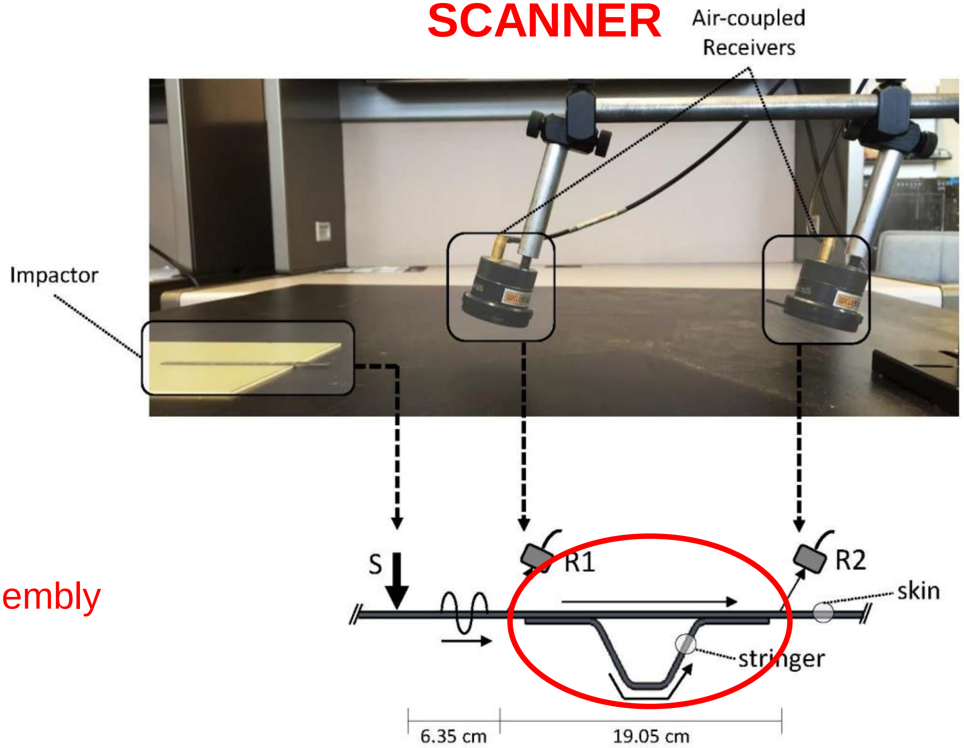


skin-stringer assembly

Piezocomposite transducers

"high" and "narrow" frequency band (110 – 210 kHz)

HYBRID "IMPACT/AIR-COUPLED" SCANNER



Mini-impactor + micro-machined capacitive transducers

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

CECAM center of excellence for composites and advanced materials

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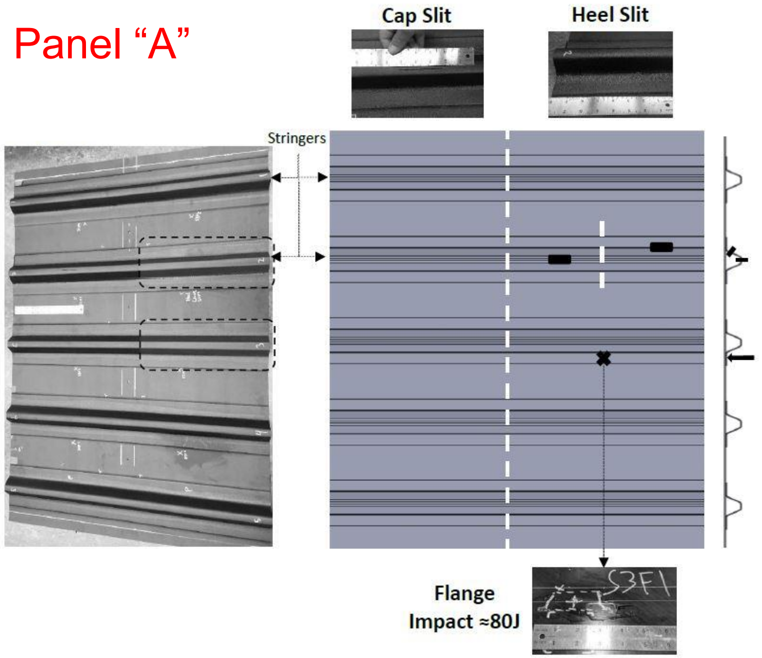
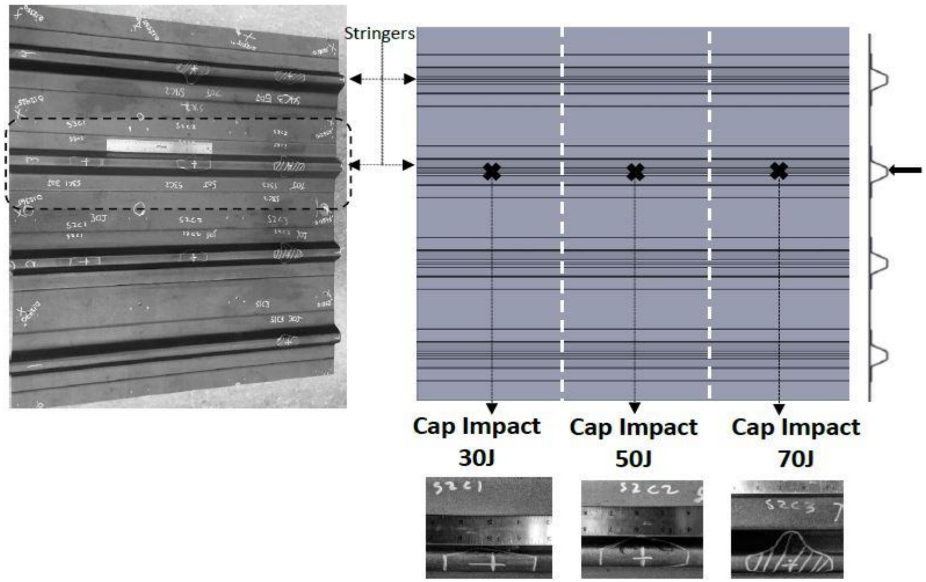
Test Panels

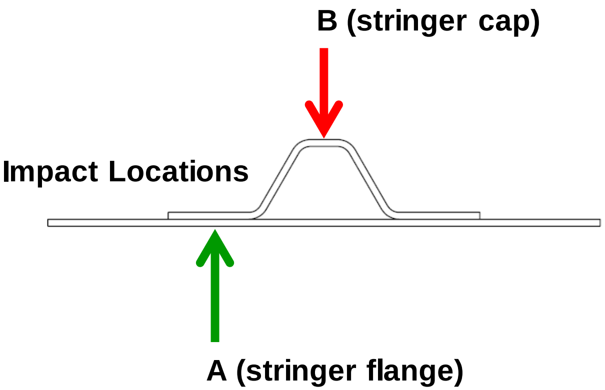
$[45/-45/0/45/90/-45/0/90]_s$ CFRP stiffened panels with hat-shaped, co-cured stringers

Panel “A”

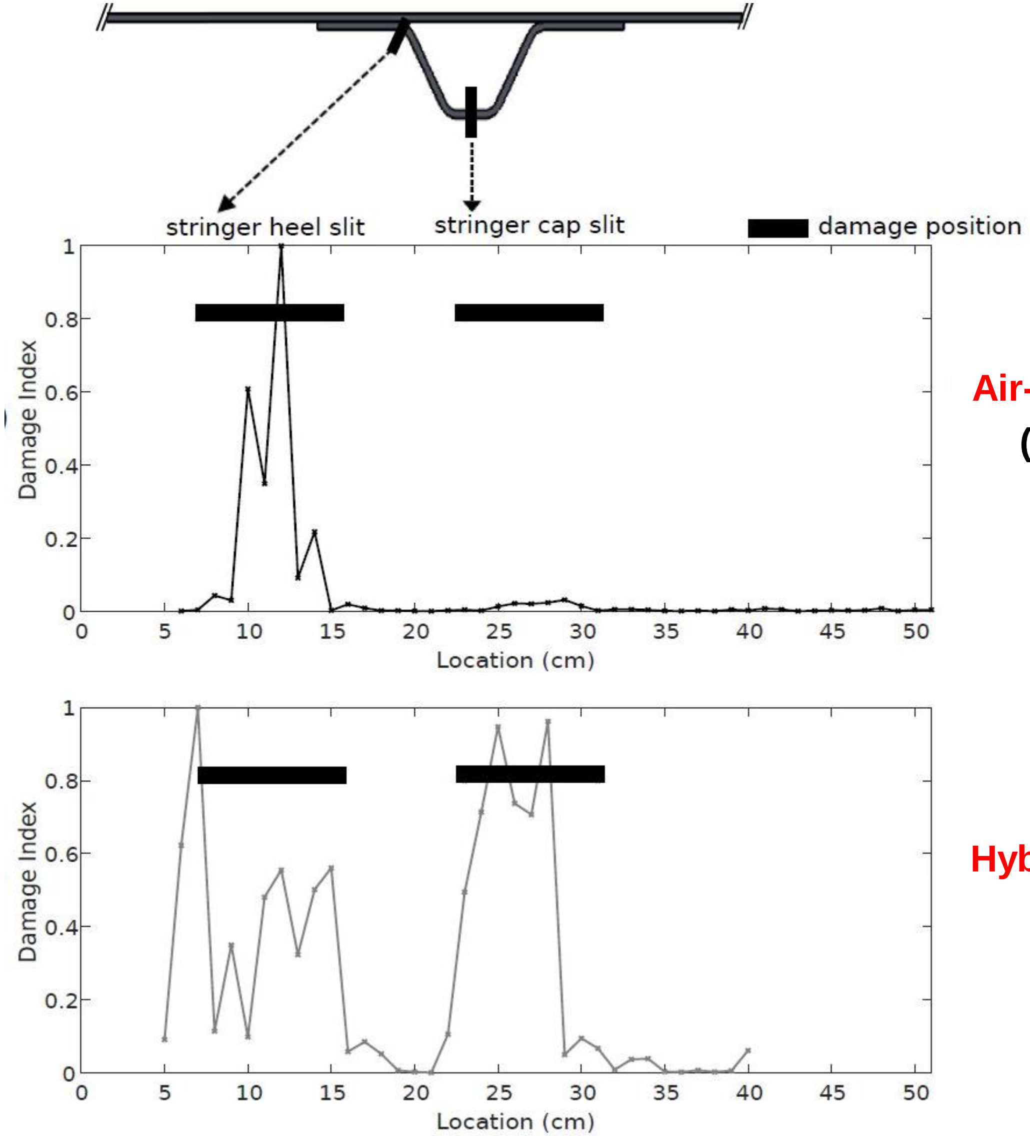


Panel “B”





Results: stringer heel slit and stringer cap slit



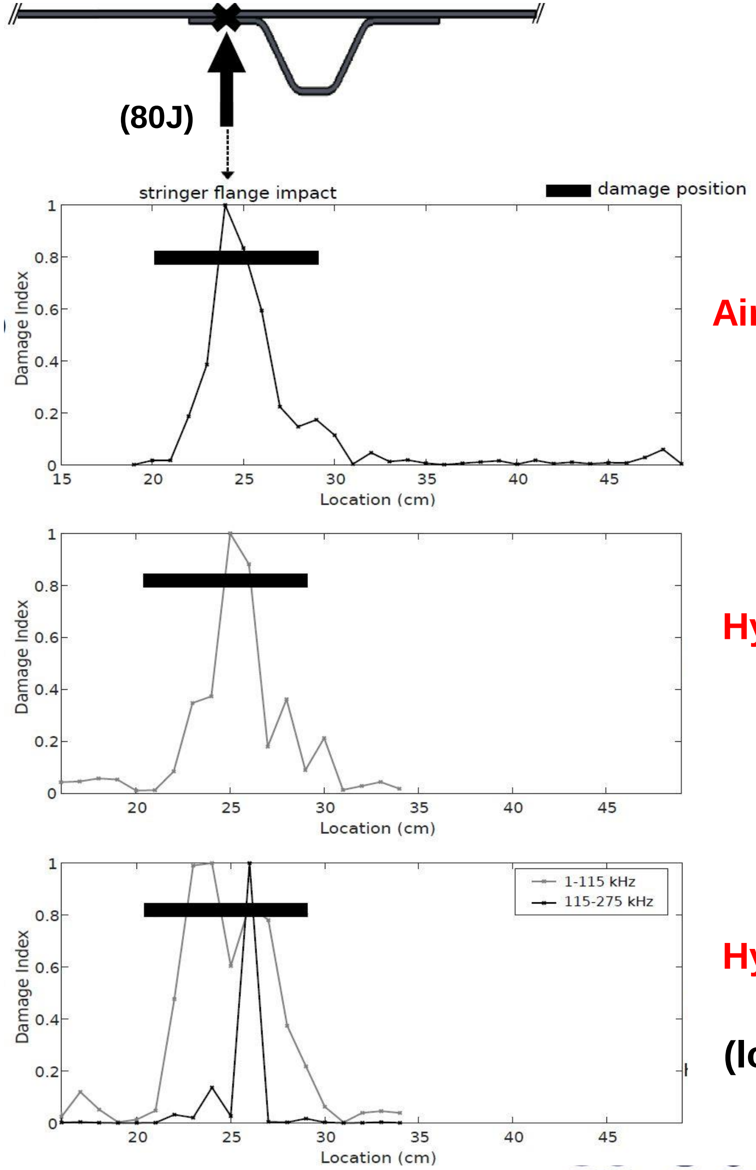
Air-coupled scanner

(110 – 210 kHz)

Hybrid impact/air-coupled scanner

(40 – 270 kHz)

Results: stringer flange impact



Air-coupled scanner

(110 – 210 kHz)

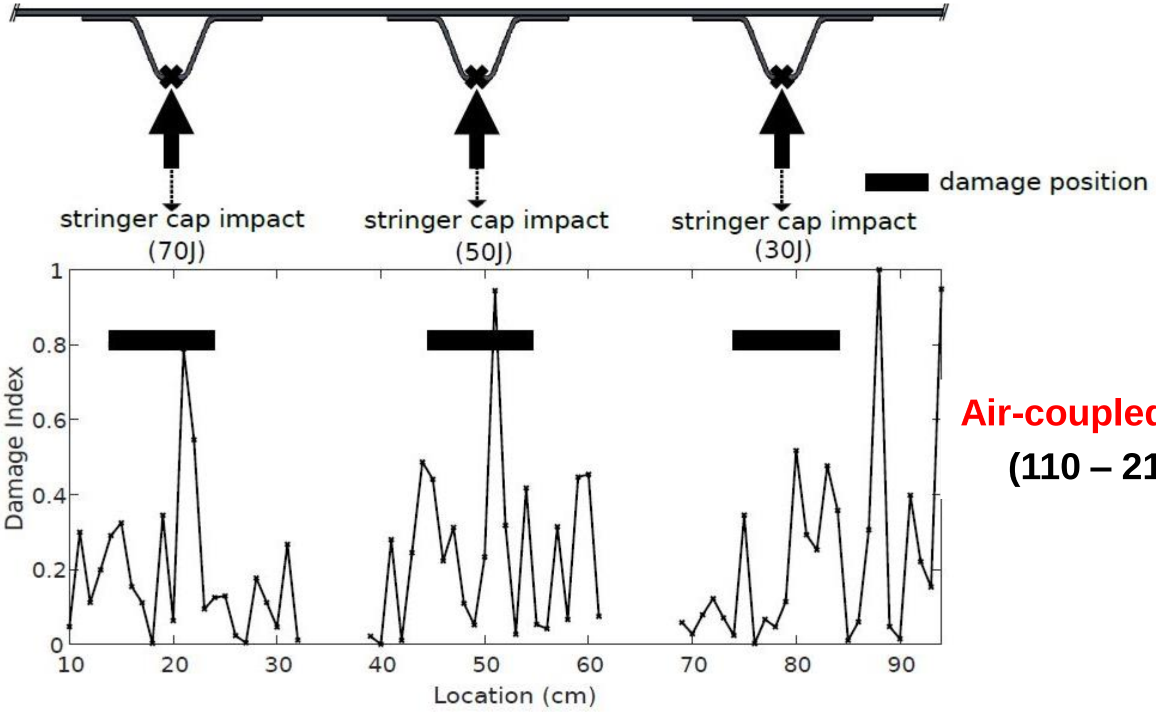
Hybrid impact/air-coupled scanner

(40 – 270 kHz)

Hybrid impact/air-coupled scanner

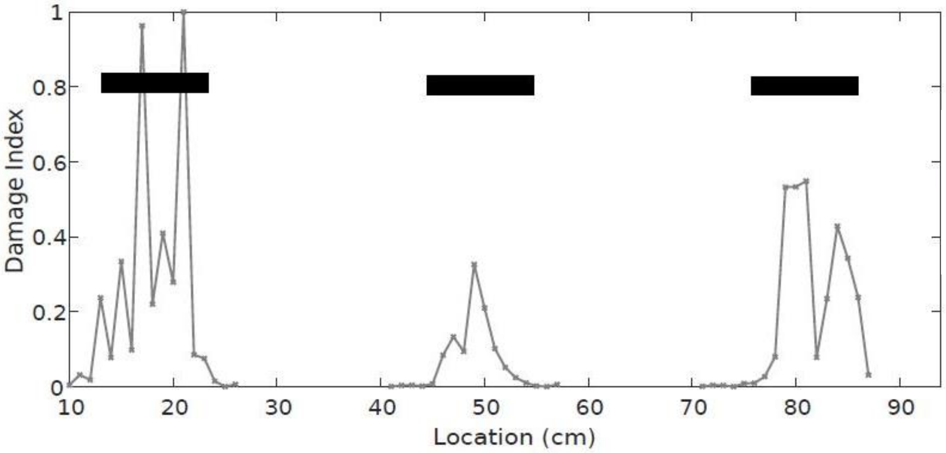
(low vs. high frequencies)

Results: stringer cap impacts



Air-coupled scanner

(110 – 210 kHz)

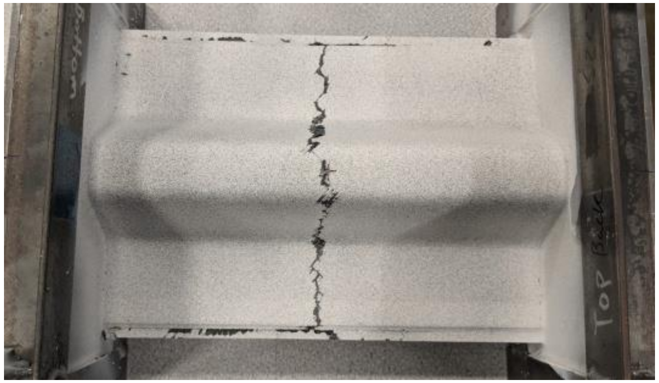


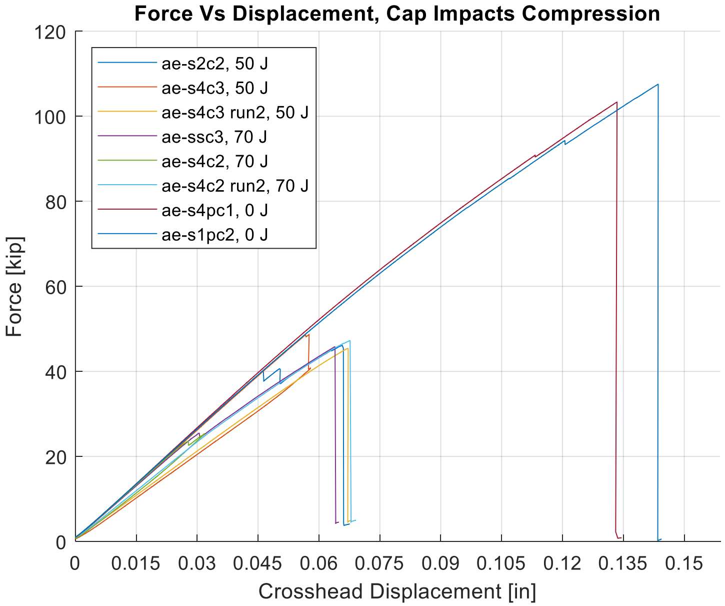
Hybrid impact/air-coupled scanner

(40 – 270 kHz)

Residual Compression Strength Tests of Impacted Panels

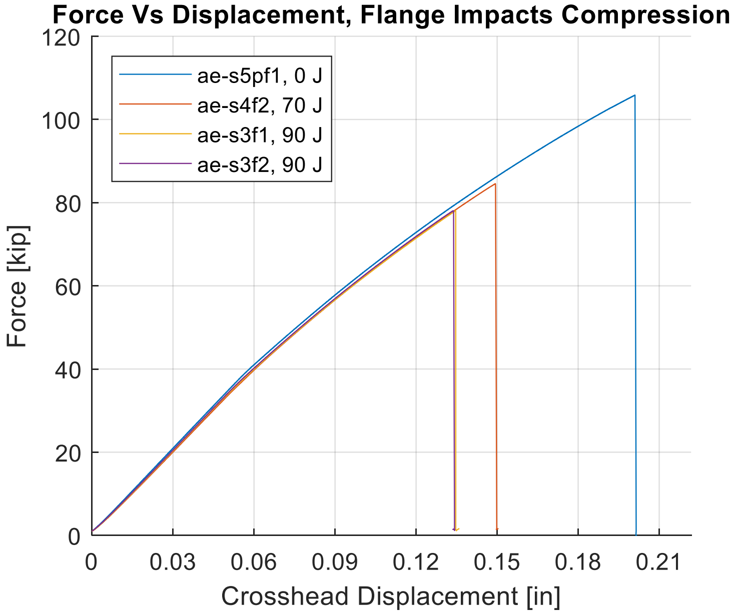
Cap impacts





Force Vs Displacement, Cap Impacts Compression

Flange impacts

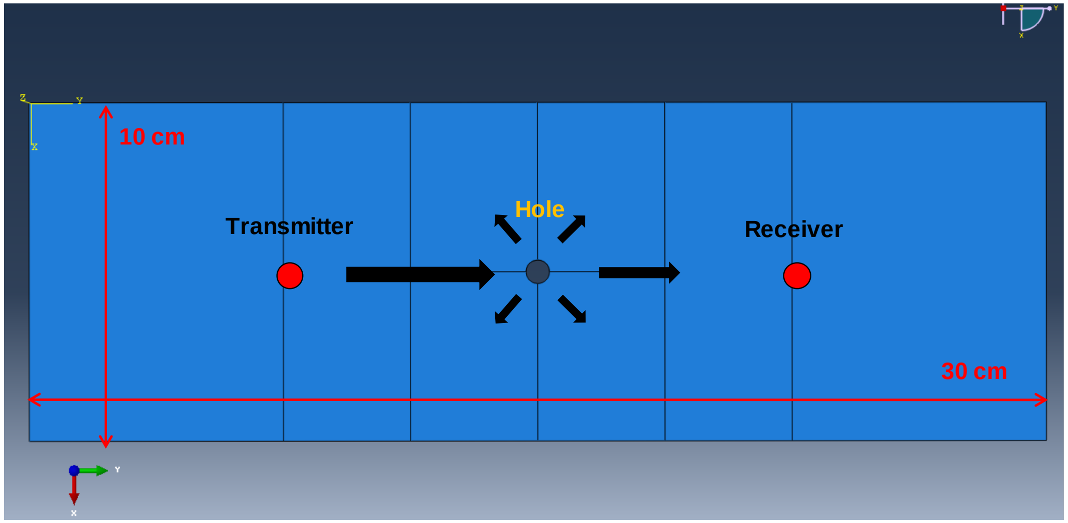


Force Vs Displacement, Flange Impacts Compression

Residual Strength Estimation from UGW Scattering

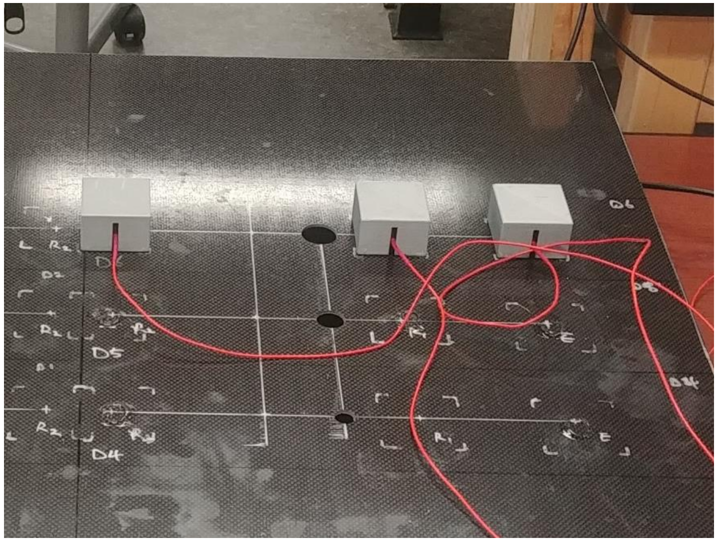
Finite Element Analysis

(isotropic plate. Holes from 0.05 mm to 50 mm dia, 150 kHz freq)

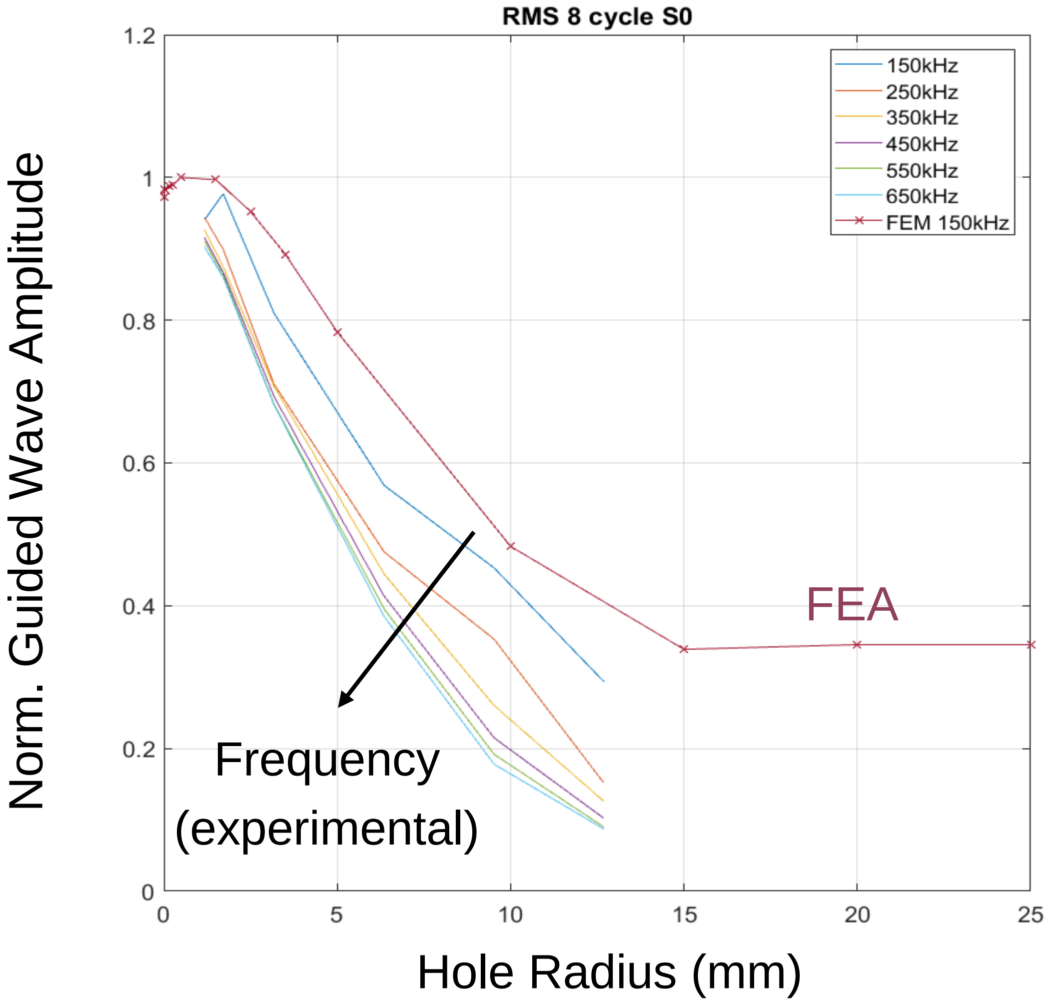


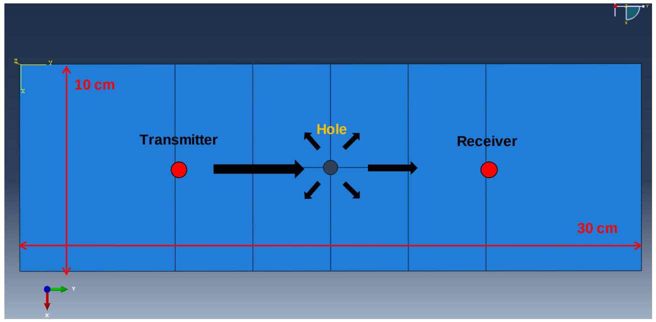
UGW Experiments

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



UGW Transmission Strength





Elastic Constants Identification from UGW Testing

Impact Damage causes change in UGW transmission.

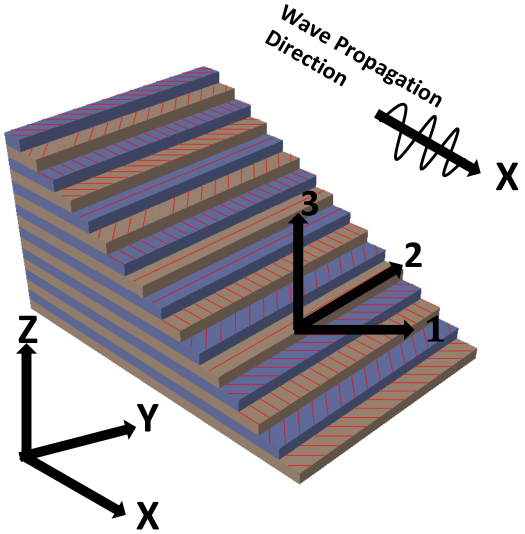
Why? Presence of damage directly relates to change in Elastic Constants → inverse problem.

Transversely isotropic lamina: five unknowns

$E_{11}, E_{22}, \nu_{12}, G_{12}$ and ν_{23}

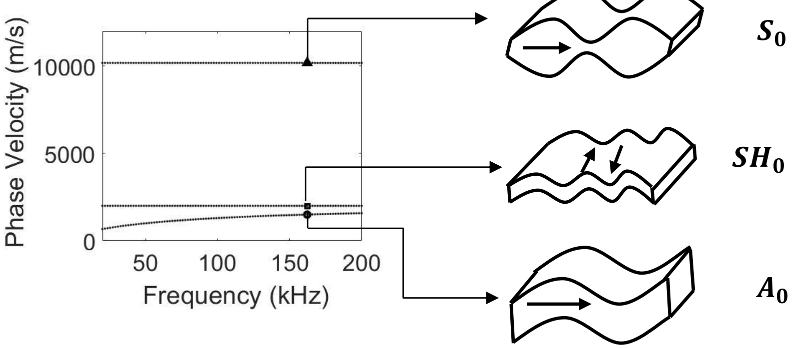
Engineering laminate properties from CLT: seven unknowns

$$\underbrace{E_x, E_y, \nu_{xy}, G_{xy},}_{\text{“in-plane”}} \underbrace{K_x, K_y, K_{xy}}_{\text{“out-of-plane”}}$$



- Use Guided-Wave Phase Velocity Dispersion Inversion and Simulated Annealing Optimization.
- Use SAFE method to solve forward problem.
- Utilize three fundamental guided-wave modes (S_0, A_0 and SH_0) propagating along a single direction (x).

Dispersion curves



Constants Identification Flowchart

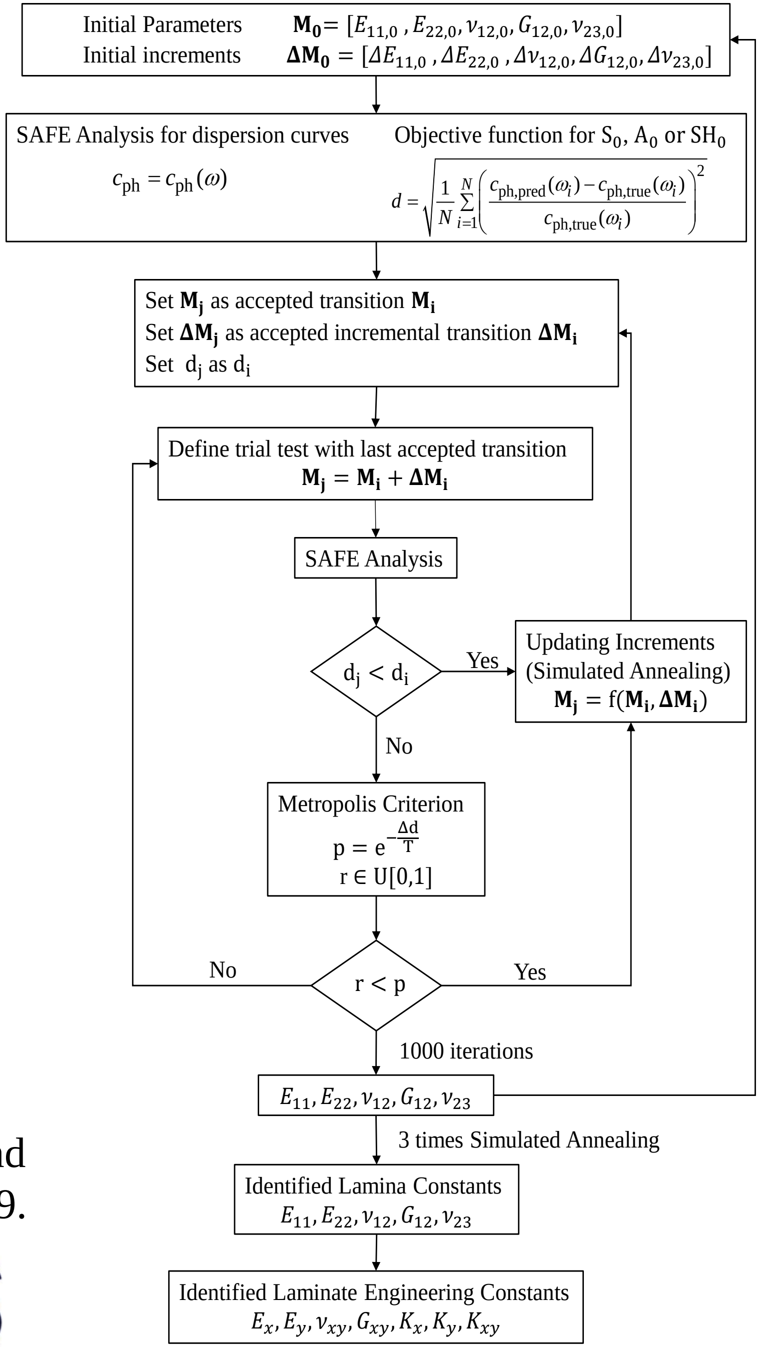
Objective function to minimize:

mismatch of phase velocity dispersion curves

$$\boxed{d=\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{c_{\mathrm{ph,pred}}(\omega_i)-c_{\mathrm{ph,true}}(\omega_i)}{c_{\mathrm{ph,true}}(\omega_i)}\right)^2}}$$

for S_0, A_0 and/or SH_0

Cui, R. and Lanza di Scalea, F., "On the identification of the elastic properties of composites by ultrasonic guided waves and optimization algorithms," <u>Composite Structures</u>, in press, 2019.



Initial Parameters $\mathbf{M_0} = [E_{11,0}, E_{22,0}, \nu_{12,0}, G_{12,0}, \nu_{23,0}]$

Initial increments $\mathbf{\Delta M_0} = [\Delta E_{11,0}, \Delta E_{22,0}, \Delta\nu_{12,0}, \Delta G_{12,0}, \Delta\nu_{23,0}]$

SAFE Analysis for dispersion curves

$$c_{\mathrm{ph}} = c_{\mathrm{ph}}(\omega)$$

Objective function for S_0, A_0 or SH_0

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

Set $\mathbf{M_j}$ as accepted transition $\mathbf{M_i}$

Set $\mathbf{\Delta M_j}$ as accepted incremental transition $\mathbf{\Delta M_i}$

Set d_j as d_i

Define trial test with last accepted transition

$\mathbf{M_j} = \mathbf{M_i} + \mathbf{\Delta M_i}$

SAFE Analysis

$d_j < d_i$

Yes

Updating Increments (Simulated Annealing)

$\mathbf{M_j} = f(\mathbf{M_i}, \mathbf{\Delta M_i})$

No

Metropolis Criterion

$p = e^{-\frac{\Delta d}{T}}$

$r \in U[0,1]$

No

$r < p$

Yes

1000 iterations

$E_{11}, E_{22}, \nu_{12}, G_{12}, \nu_{23}$

3 times Simulated Annealing

Identified Lamina Constants

$E_{11}, E_{22}, \nu_{12}, G_{12}, \nu_{23}$

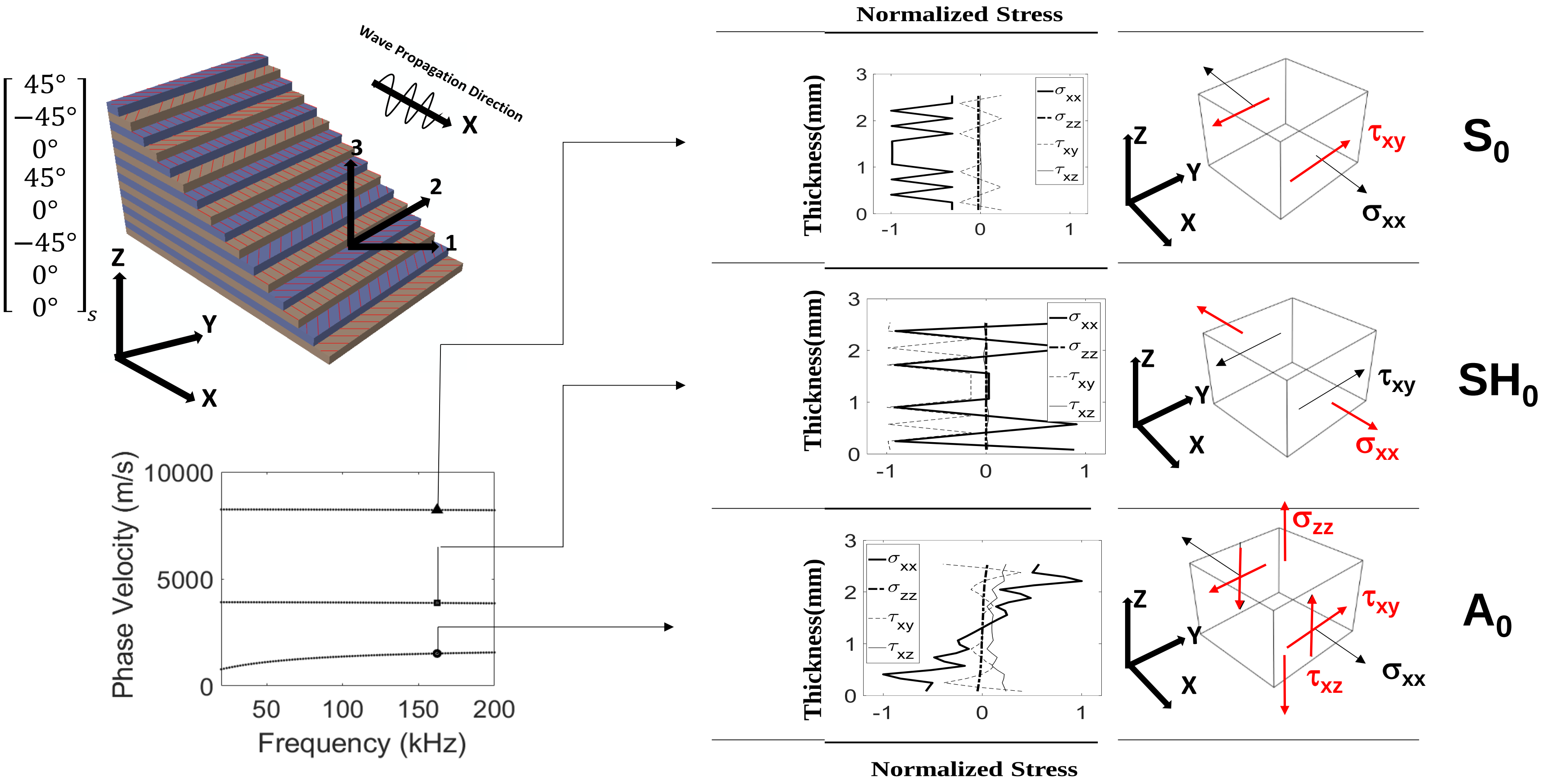
Identified Laminate Engineering Constants

$E_x, E_y, \nu_{xy}, G_{xy}, K_x, K_y, K_{xy}$

Constants Identification Results: anisotropic laminate

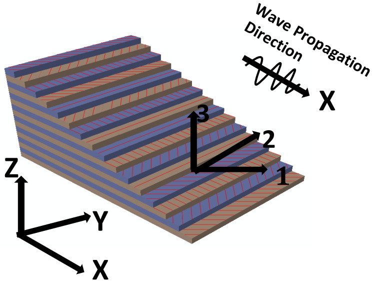
SAFE analysis

“normal - shear” coupling and “longitudinal - transverse” coupling !!

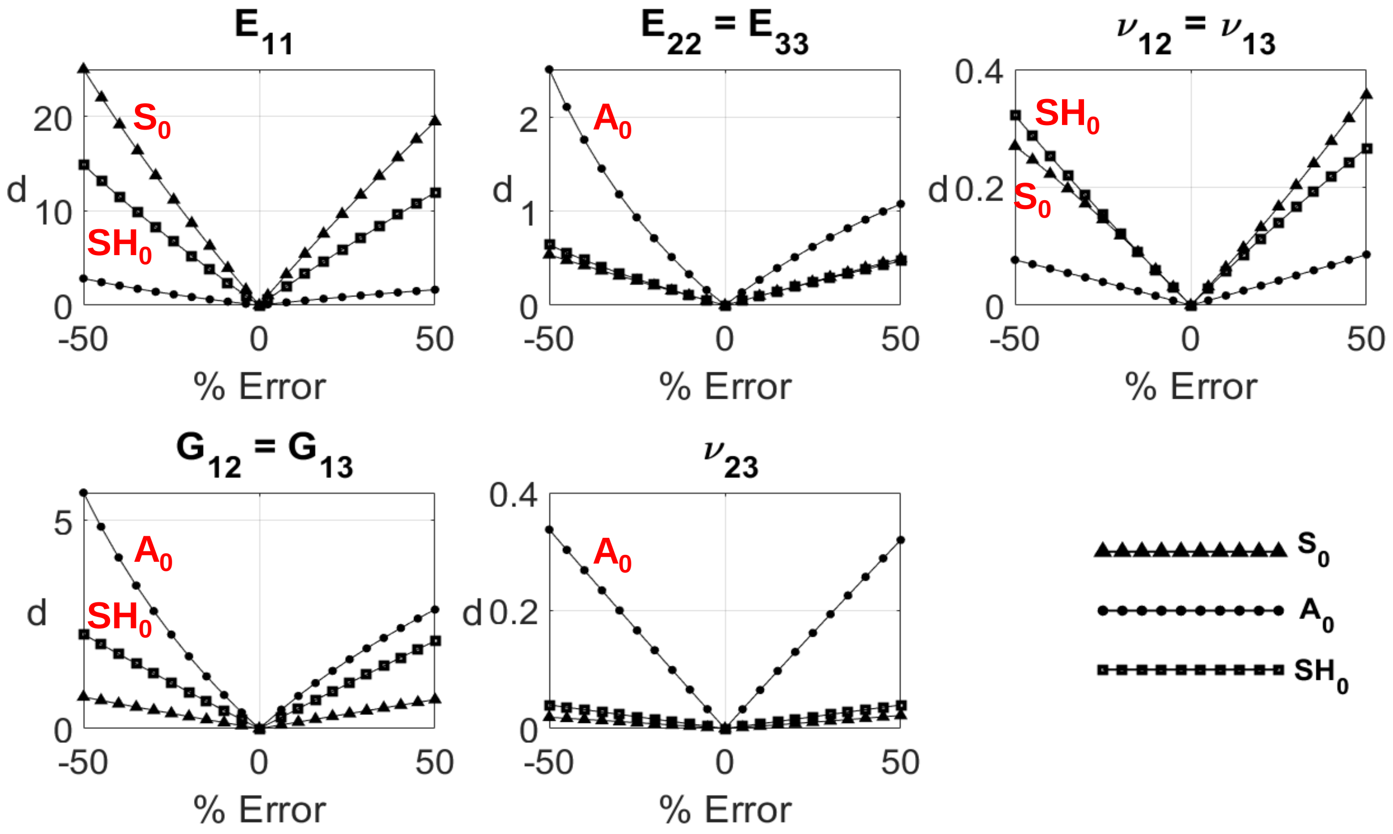


Constants Identification Results: anisotropic laminate – lamina properties (1D inversion)

Anisotropic Laminate

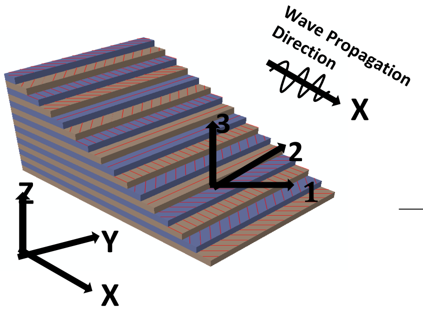


Lamina constants identification (1D Inversion)

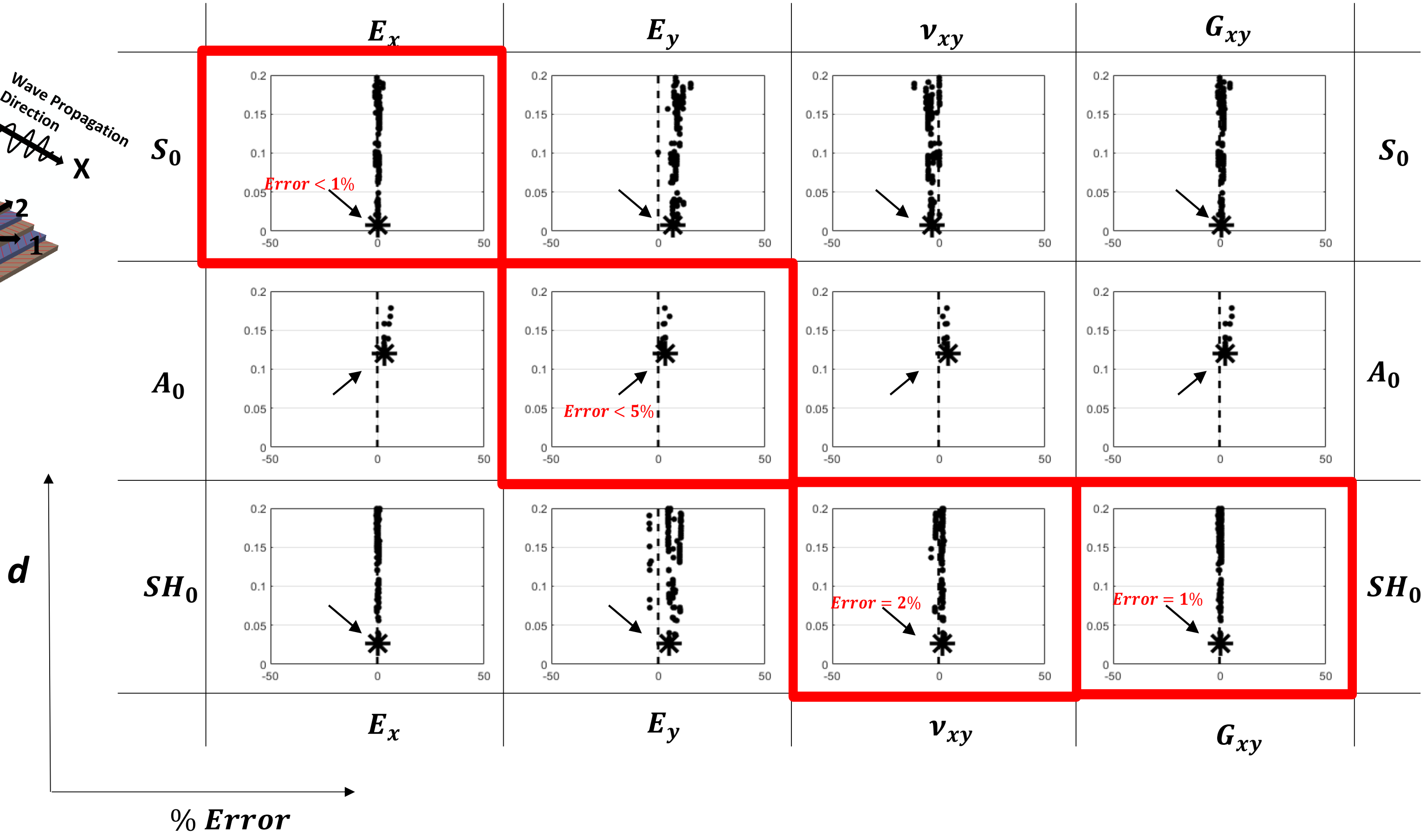


Constants Identification Results: anisotropic laminate engineering properties (in-plane)

Anisotropic Laminate

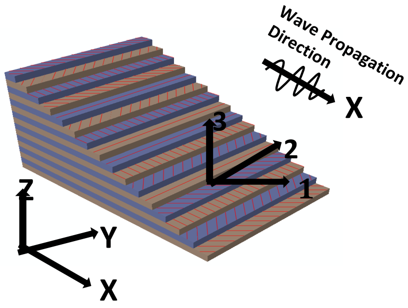


Engineering constants identification (in-plane)

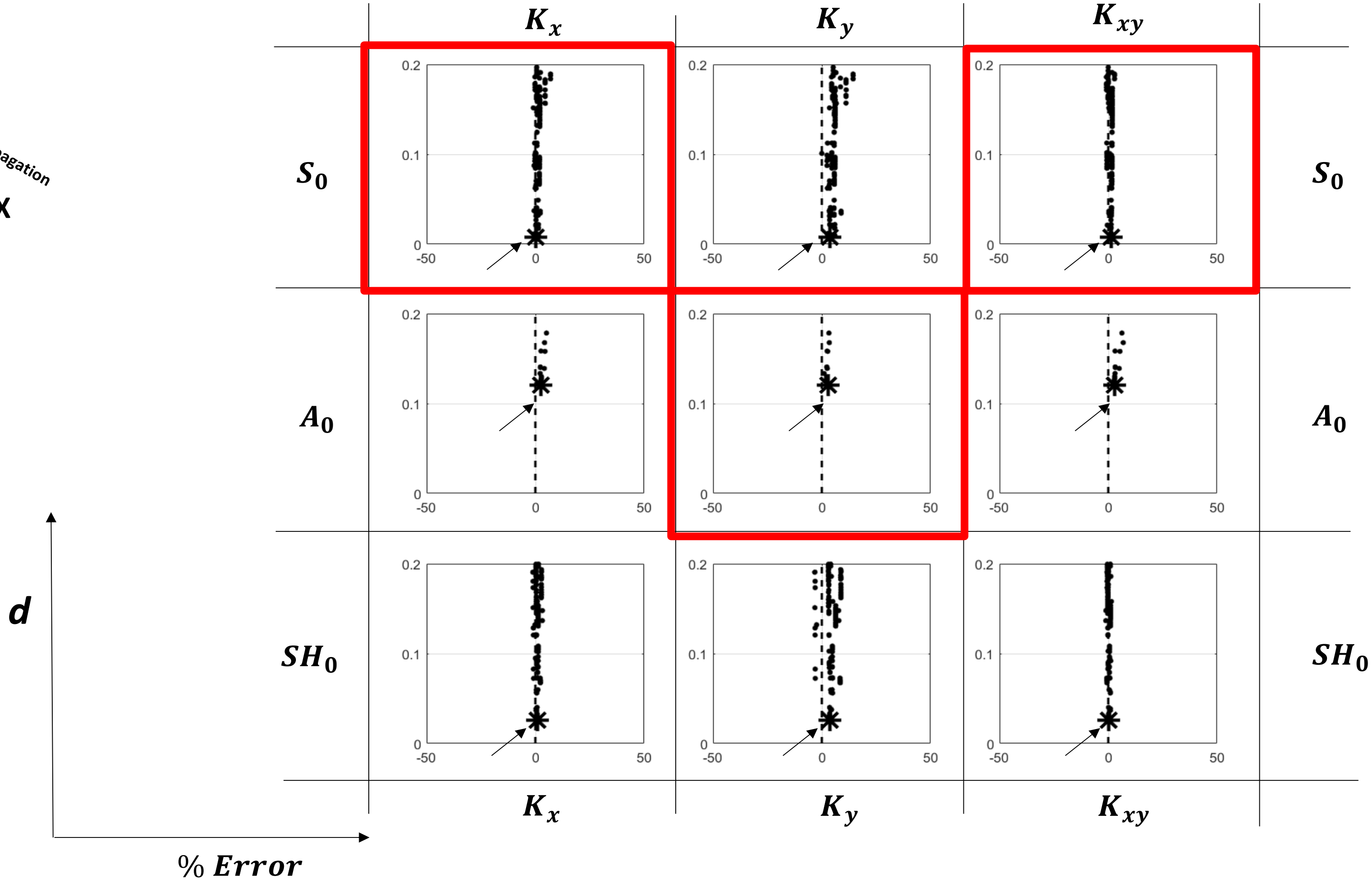


Constants Identification Results: anisotropic laminate engineering properties (out-of-plane)

Anisotropic Laminate



Engineering constants identification (out-of-plane)



Summary

- Methods of UGW testing investigated for inspection of impact damage in composite stiffened panels

- Two scanning systems based on UGW dual-output scheme:
  - non-contact "air-coupled" system (damage in skin and stringer flange)
  - hybrid "impact/air-coupled" system (damage in stringer cap)

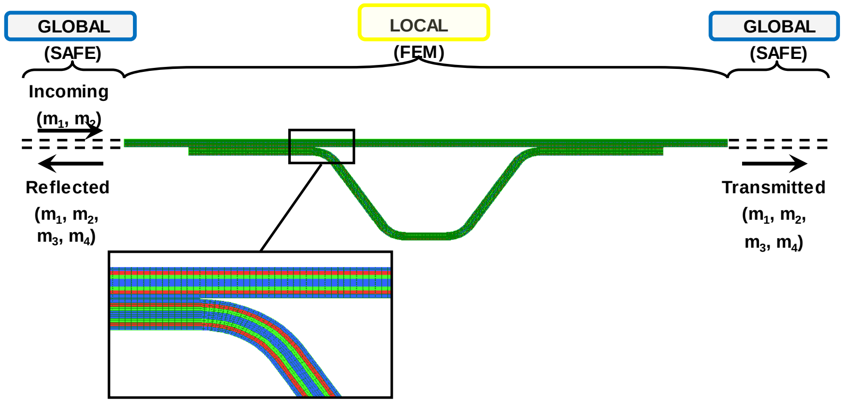
- UGW studies in plates with holes show relation between wave scattering and residual compression strength

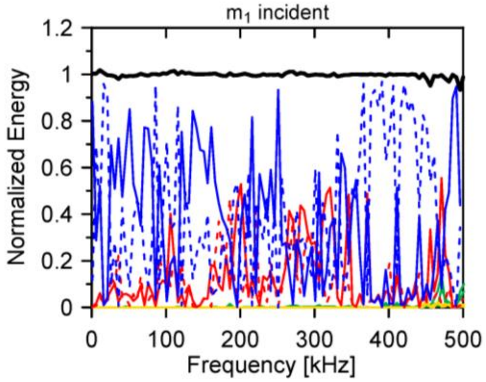
- Inverse procedure based on matching phase velocity UGW dispersion curves for identifying elastic properties of composite panels (lamina constants and laminate engineering constants)

Ongoing/Future Work

- Package mini-impactor into scanning system for automatic scan
- Expand elastic constants identification to impact damage for residual strength estimation
- Conduct additional analyses of wave scattering through various damage types/severity for residual strength estimation

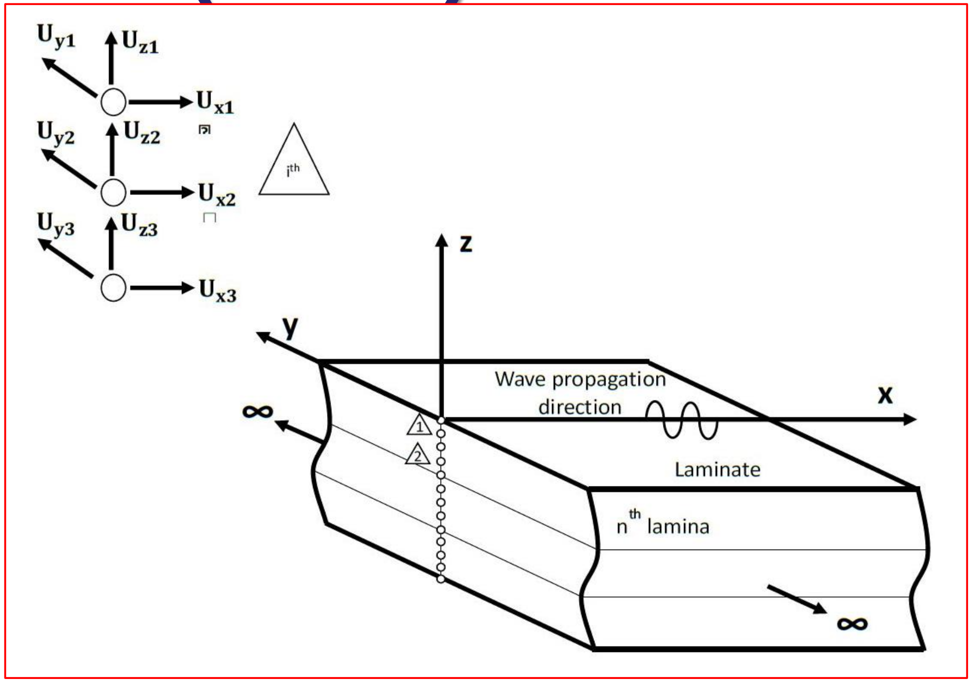
GLOBAL-LOCAL MODELS





EXTRA SLIDES

Guided-Wave Transfer Function: Semi-Analytical-Finite-Element (SAFE) method



Displacement field $$u^{(e)}(x,y,z,t) = \begin{bmatrix} \sum_{j=1}^{n} N_j(y,z)U_{xj} \\ \sum_{j=1}^{n} N_j(y,z)U_{yj} \\ \sum_{j=1}^{n} N_j(y,z)U_{zj} \end{bmatrix}^{(e)} e^{i(kx-\omega t)}$$

Lamina stiffness matrix $$\mathbf{C}_\theta = \mathbf{R}_1 \mathbf{C}\, \mathbf{R}_2^{-1}$$

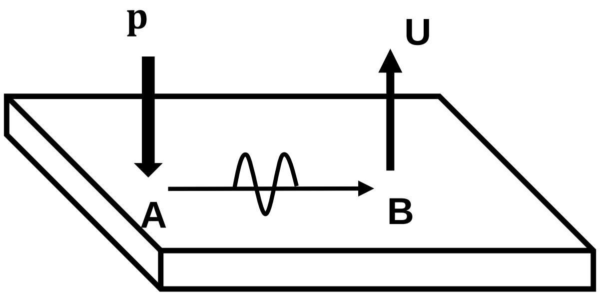
Eigenvalue problem $$[\mathbf{A} - k\,\mathbf{B}]_{2M}\, \mathbf{Q} = 0$$

Eigenvalues (ω, *k*): dispersion curves

Eigenvectors **U**: cross-sectional mode shapes

Transfer function (band-limited) – freq. domain

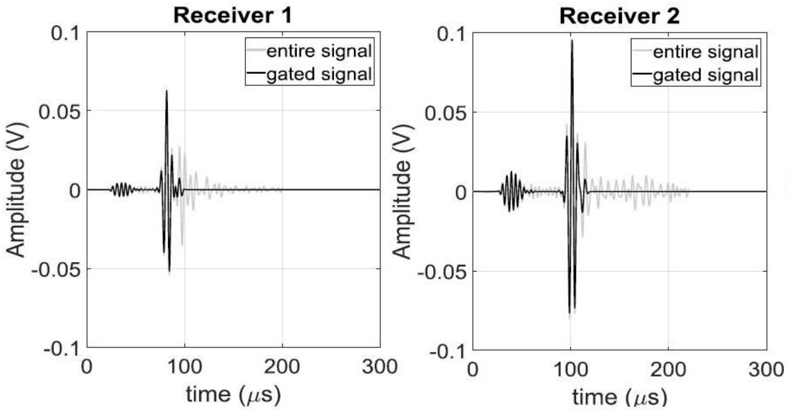
$$\mathbf{U} = \sum_{m=1}^{M} \alpha_m \mathbf{\Phi}_m^{Rup} \exp[ik(x - x_S)] \quad \text{with} \quad \alpha_m = -\frac{\mathbf{\Phi}_m^{L}\mathbf{p}}{B_m}$$

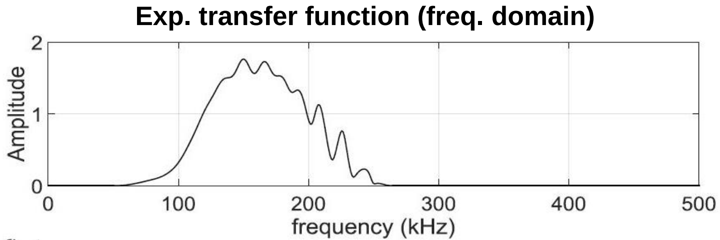


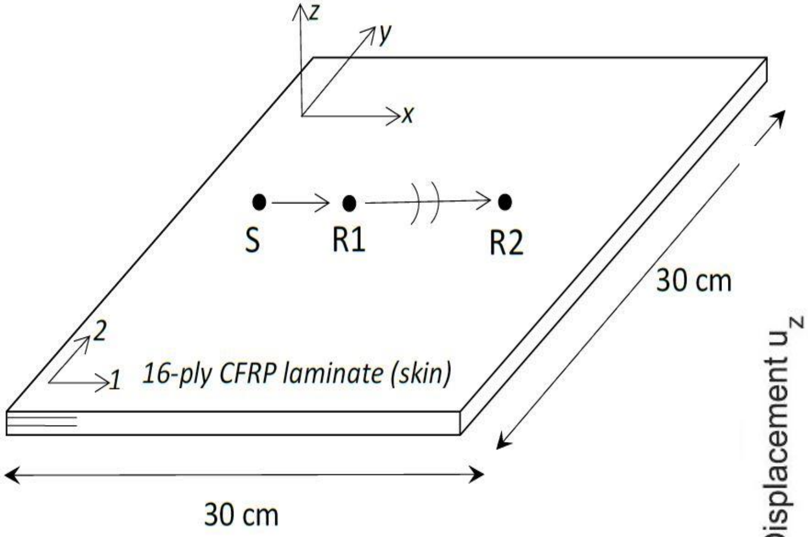
Transfer Function Comparison: Experimental vs. Numerical

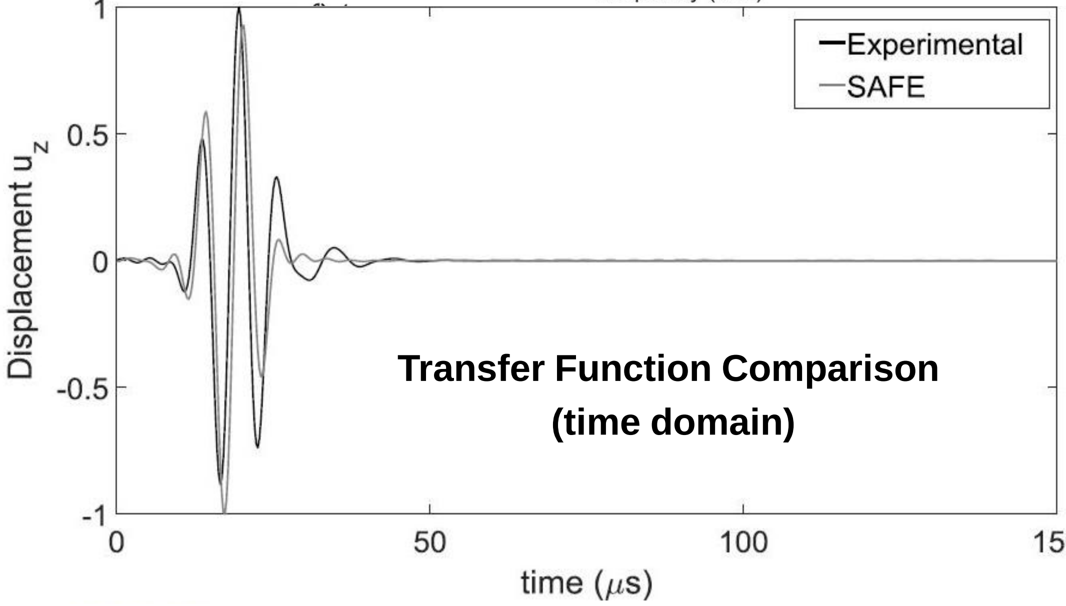
CFRP laminate, 16 plies, $[45/-45/0/45/90/-45/0/90]_s$.
(representative of B787 fuselage "skin")

SIDO scheme, Mistras PICO PZT transducers,
170 kHz excitation



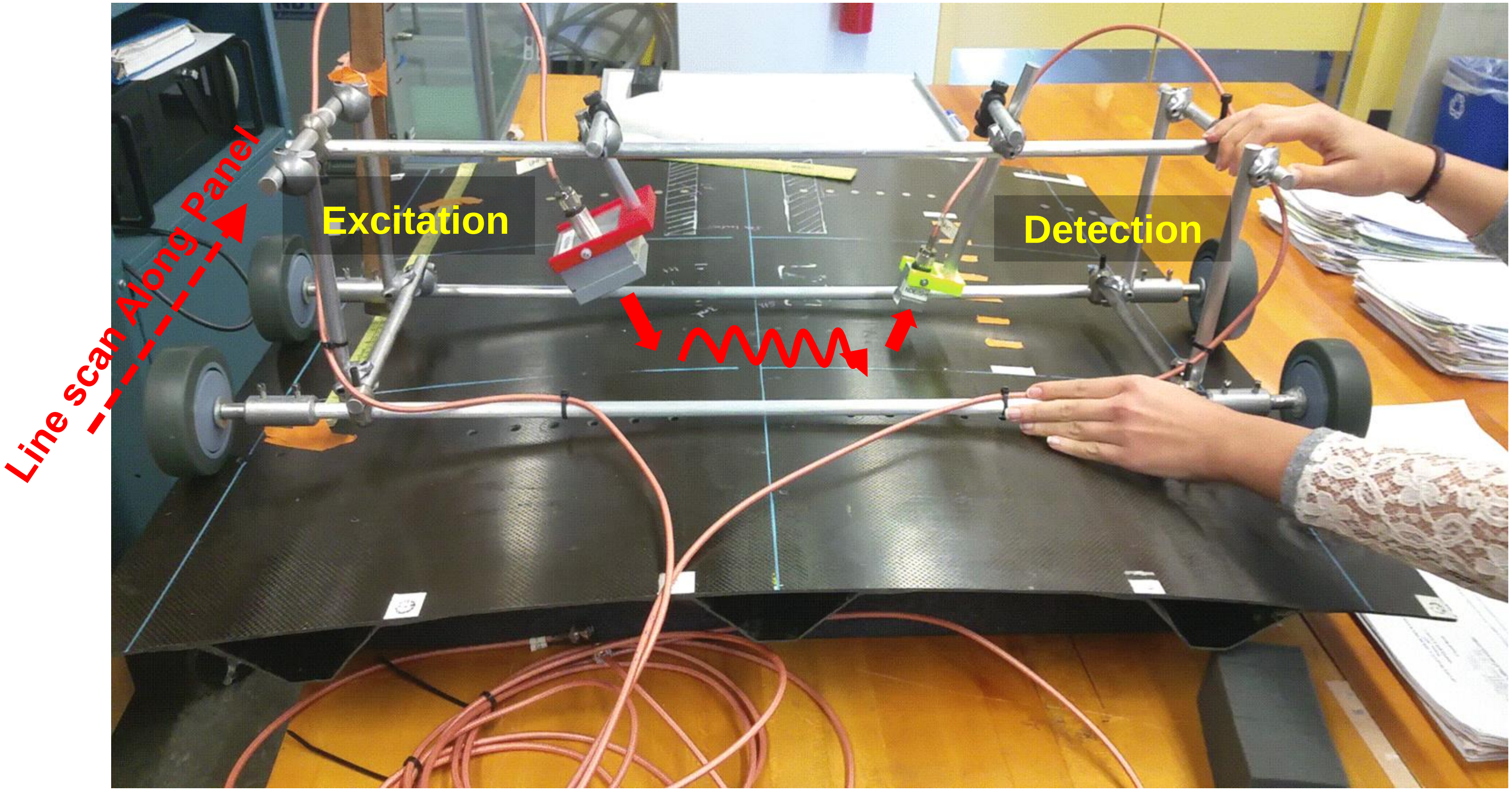

Exp. transfer function (freq. domain)




Transfer Function Comparison (time domain)

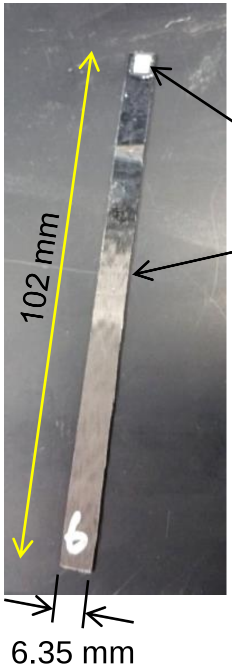
Non-Contact NDE Scanning Prototype

- Line scan approach with non-contact sensors on moving carriage
- Air-coupled piezocomposite transducers (170 kHz)



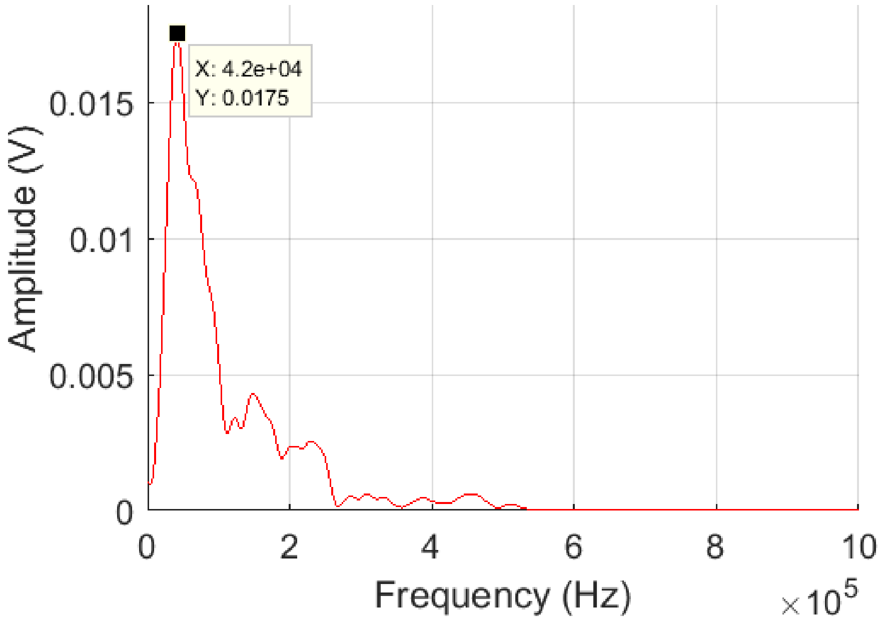
Mini-Impactor (probes interior + portable)

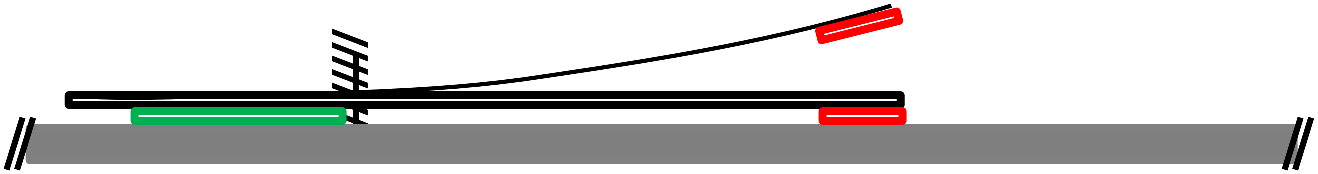
- Frequency range up to 500 kHz and peak intensity at 42 kHz



Aluminum Tip – 0.56 mm thick

Uni-directional Carbon/Epoxy $[0]_8$ Layup; 0.56 mm thick



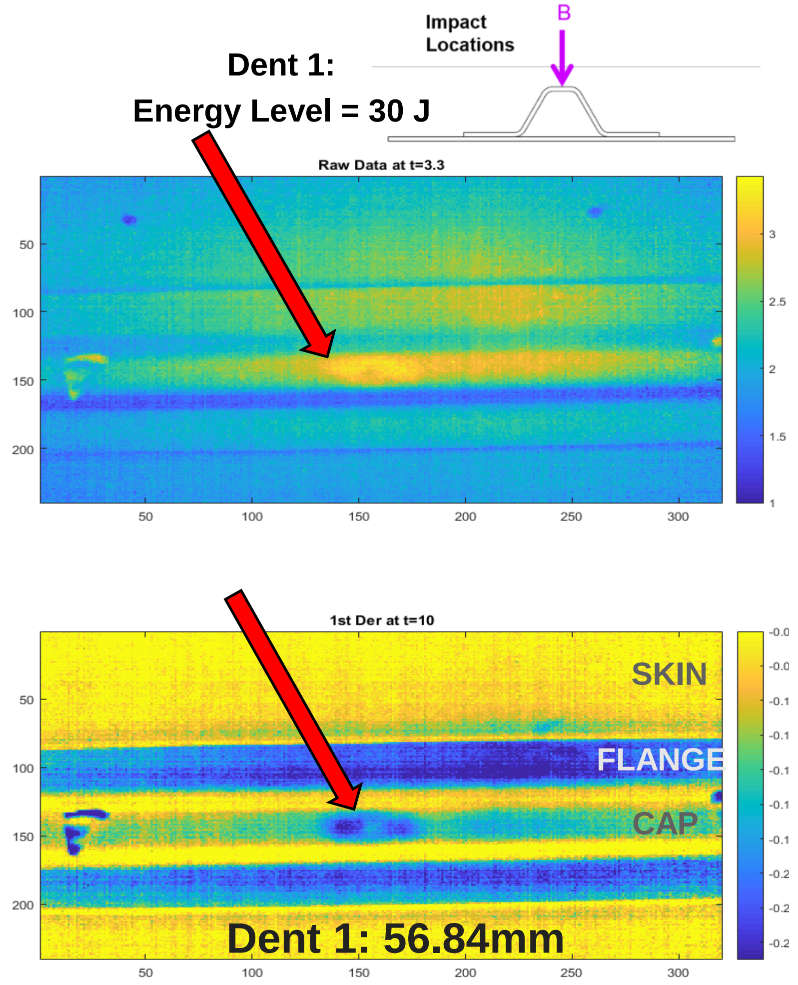


Courtesy of Eric Kim and Dr. Hyonny Kim

Thermography for Independent Damage Survey

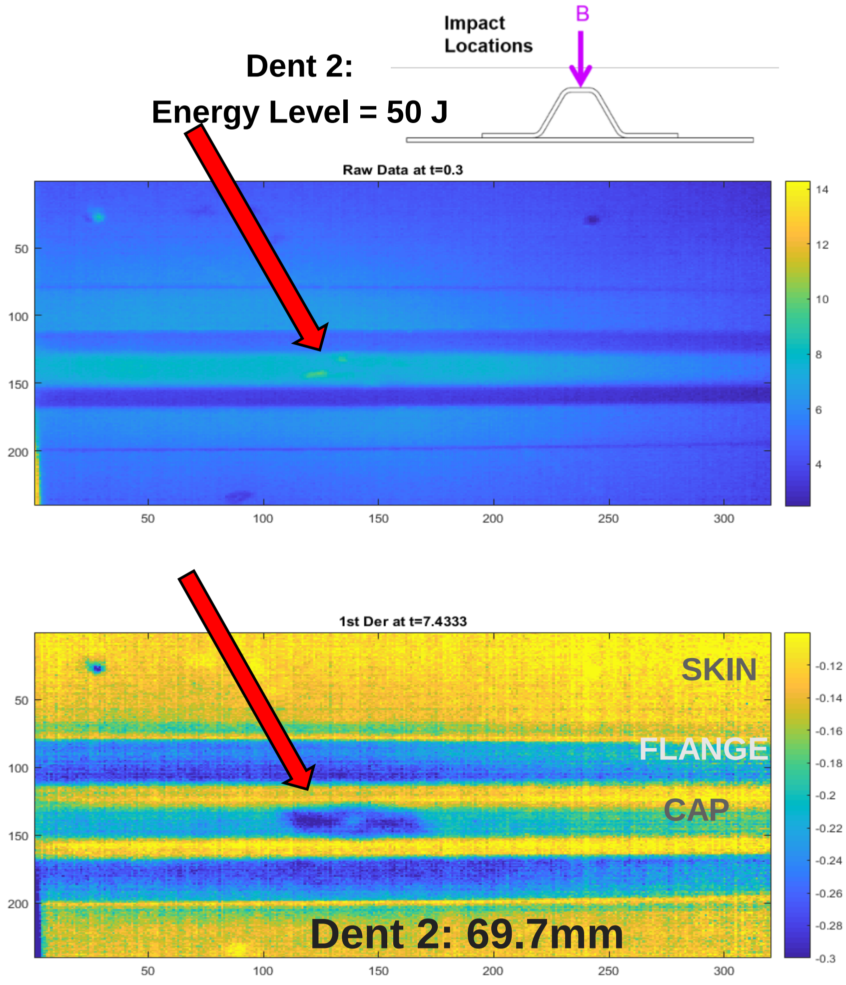
Thermography (TSR): ground truth of damage for quantitative damage survey

Dent 1:
Energy Level = 30 J



Dent 1: 56.84mm

Dent 2:
Energy Level = 50 J



Dent 2: 69.7mm

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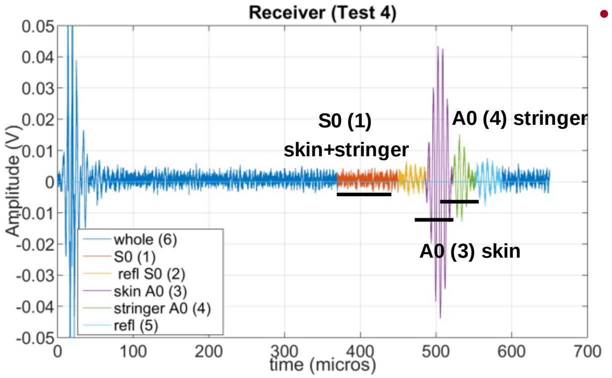
UCSD
NDE/SHM Lab

Statistical Analysis

Outlier Analysis:

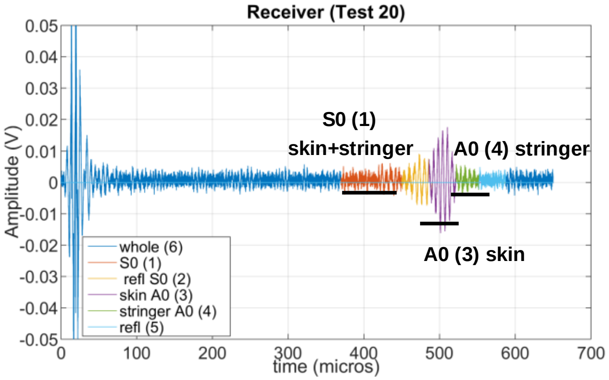
- Multivariate
- Multi-mode

Super-Vector for mode compounding



Baseline Signal
(six possible time gates)

Test Signal
(six possible time gates)



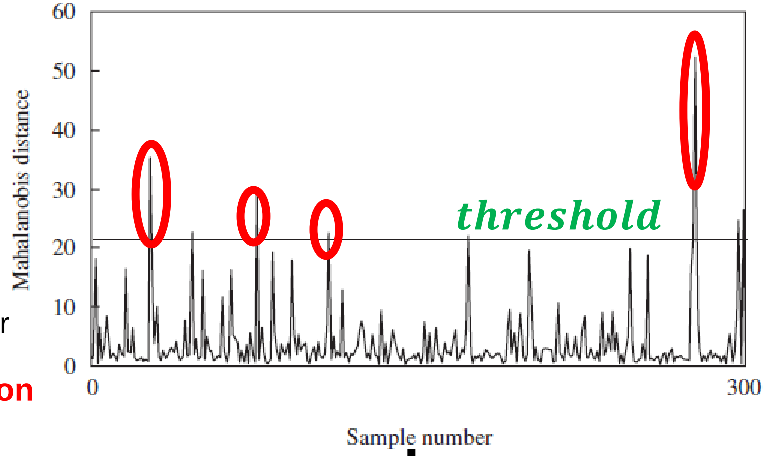
Feature
Super-Vector

$$x = \left\{ \begin{matrix} \begin{bmatrix} Max\ Ampl \\ Max\ Ind \\ Variance \\ Kurtosis \\ \dots \end{bmatrix}_{m1} \\ \begin{bmatrix} Max\ Ampl \\ Max\ Ind \\ Variance \\ Kurtosis \\ \dots \end{bmatrix}_{m2} \\ \begin{bmatrix} Max\ Ampl \\ Max\ Ind \\ Variance \\ Kurtosis \\ \dots \end{bmatrix}_{mN} \end{matrix} \right\}$$

Known Undamaged Region:
Baseline Vector
Average, Covariance
$\bar{x}, C$

Test Vector
x
Any Location

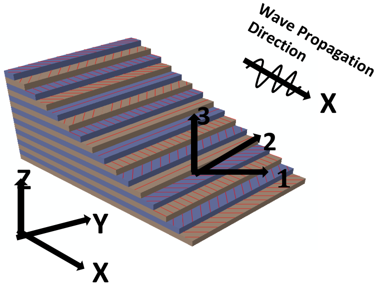
Damage Index (DI) :
(Mahalanobis Squared Distance)
$$(x - \dot{x}) * C^{-1} * (x - \dot{x})^T$$



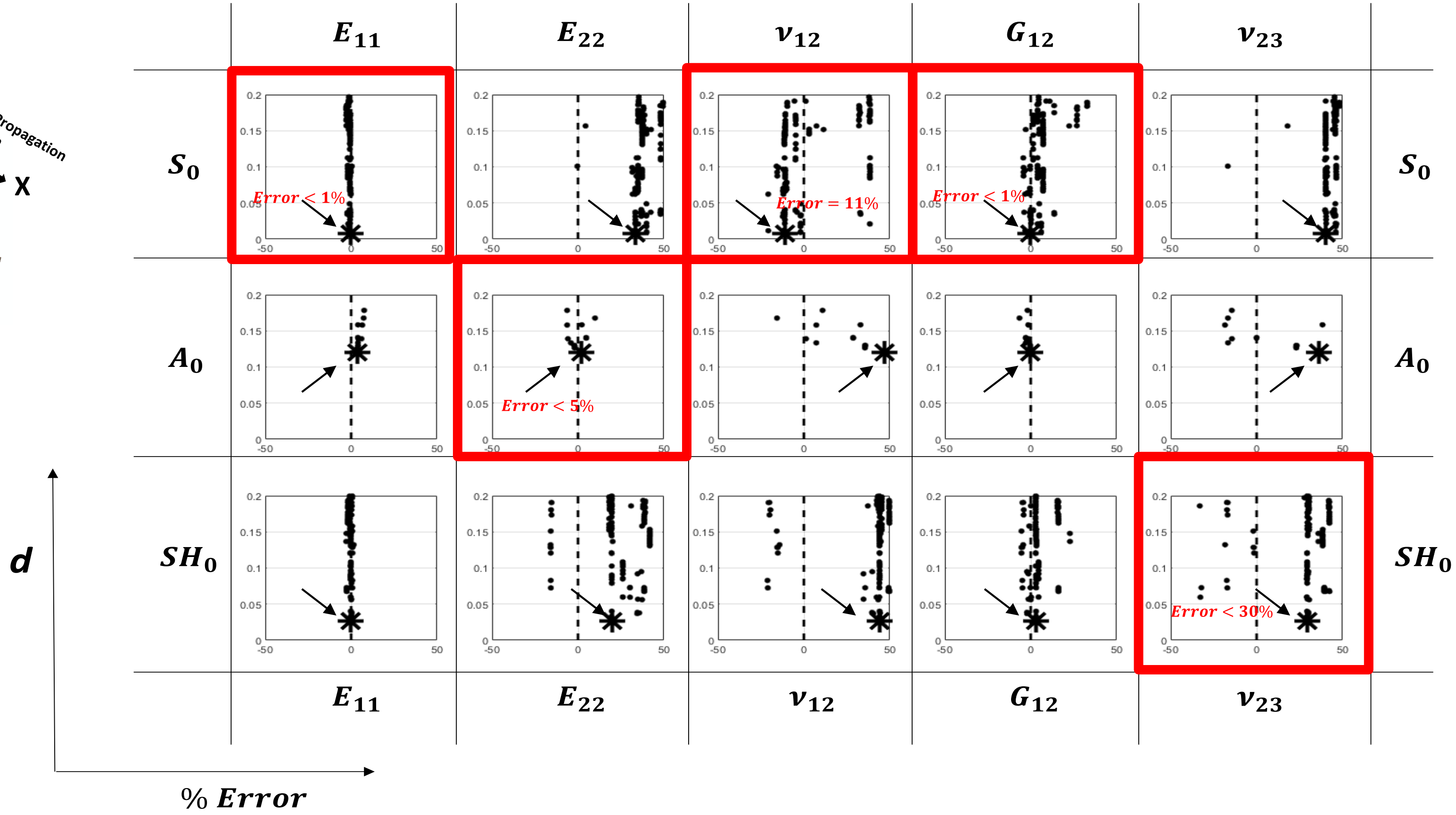
$If\ DI > threshold \Rightarrow$ **DEFECT**

Constants Identification Results: anisotropic laminate – lamina constants (5D inversion)

Anisotropic Laminate



Lamina constants identification (5D Inversion)



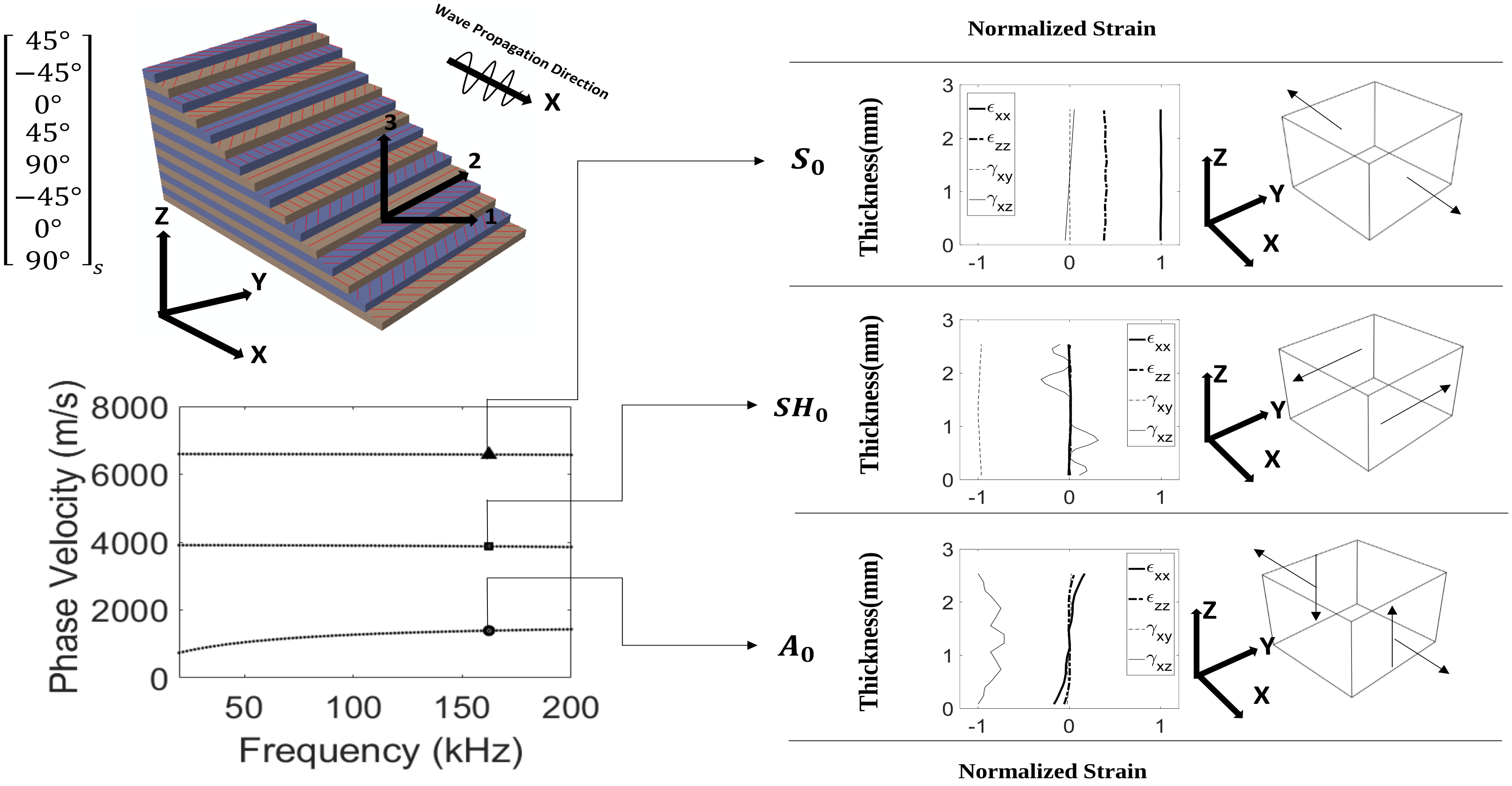
CECAM

JAMS
JOINT ADVANCED MATERIALS & STRUCTURES CENTER OF EXCELLENCE

A Center of Excellence AMTAS Advanced Materials in Transport Aircraft Structures

Property Identification Results: quasi-isotropic laminate

SAFE analysis



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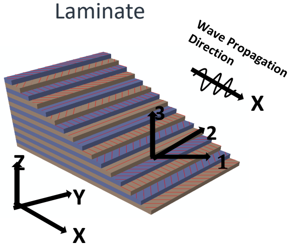
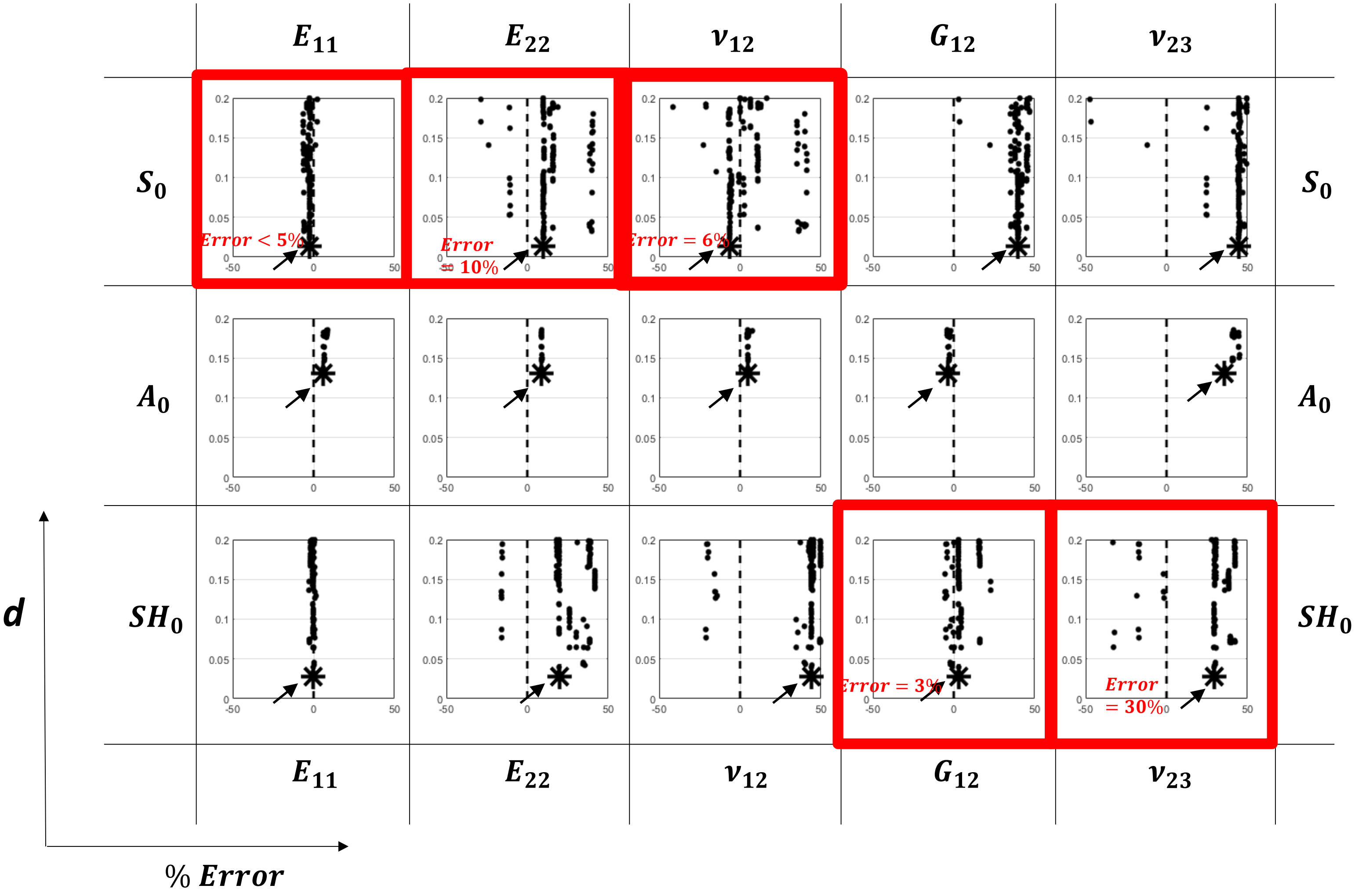
UCSD
NDE/SHM Lab

Property Identification Results: quasi-isotropic laminate

Quasi-Isotropic Laminate



Lamina constants identification (5D Inversion)



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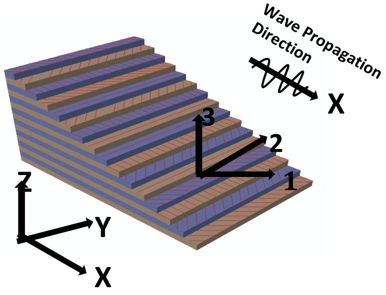
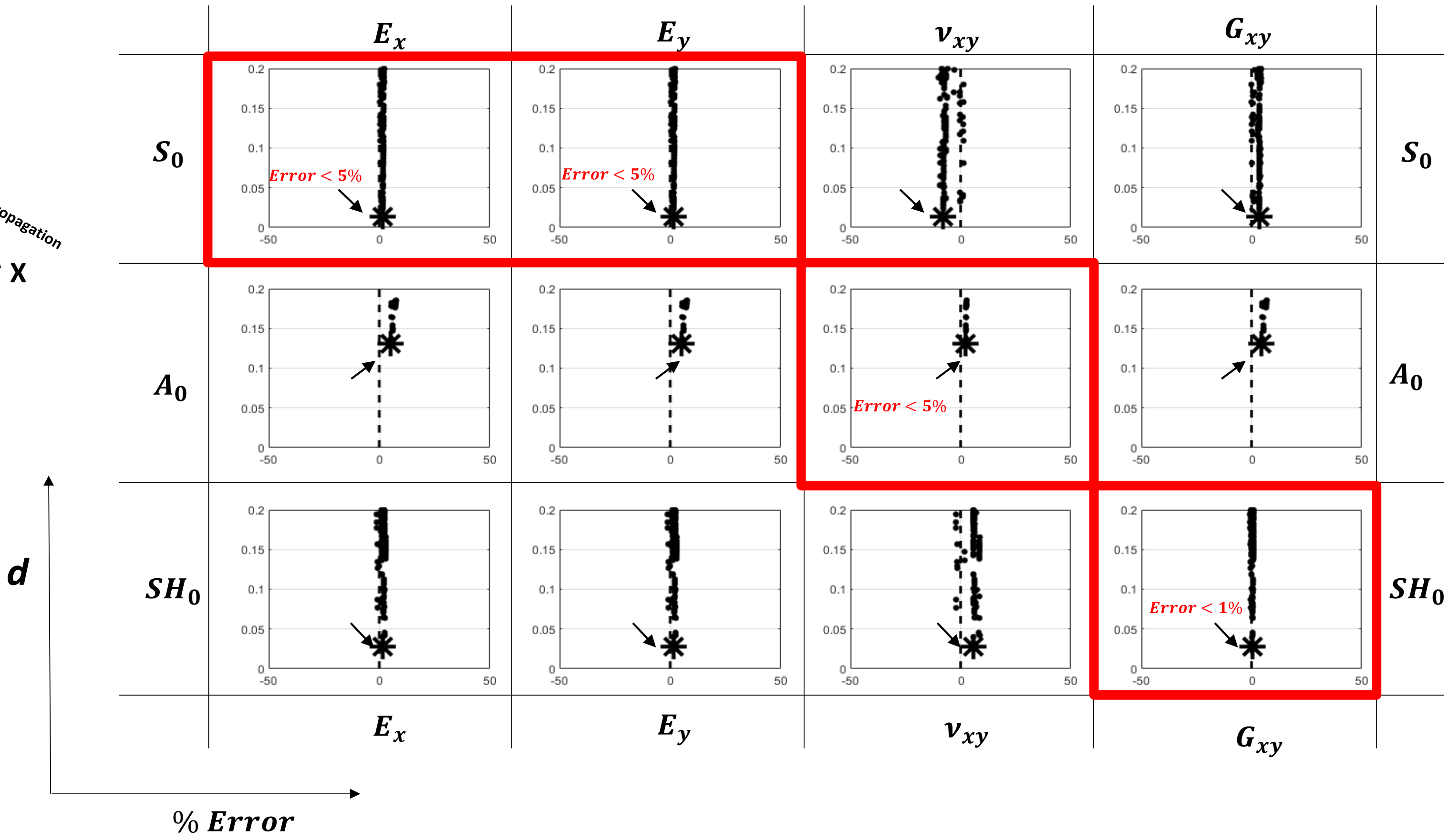
UCSD NDE/SHM Lab

Property Identification Results: quasi-isotropic laminate

Quasi-Isotropic Laminate



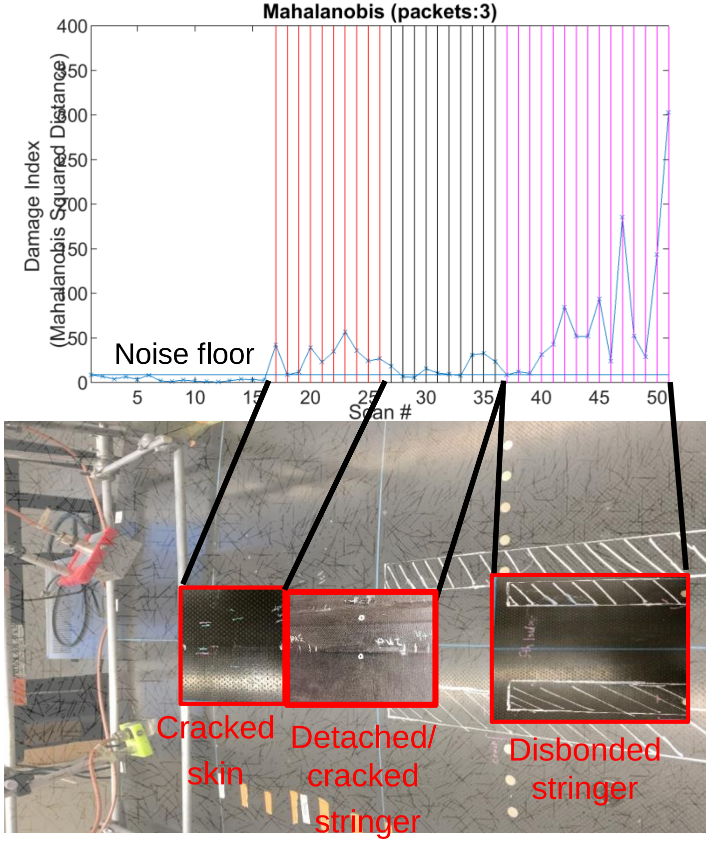
Engineering constants identification (4D Inversion)



Non-Contact NDE Scanning Prototype

Statistical Analysis Results:

(Skin modes only)



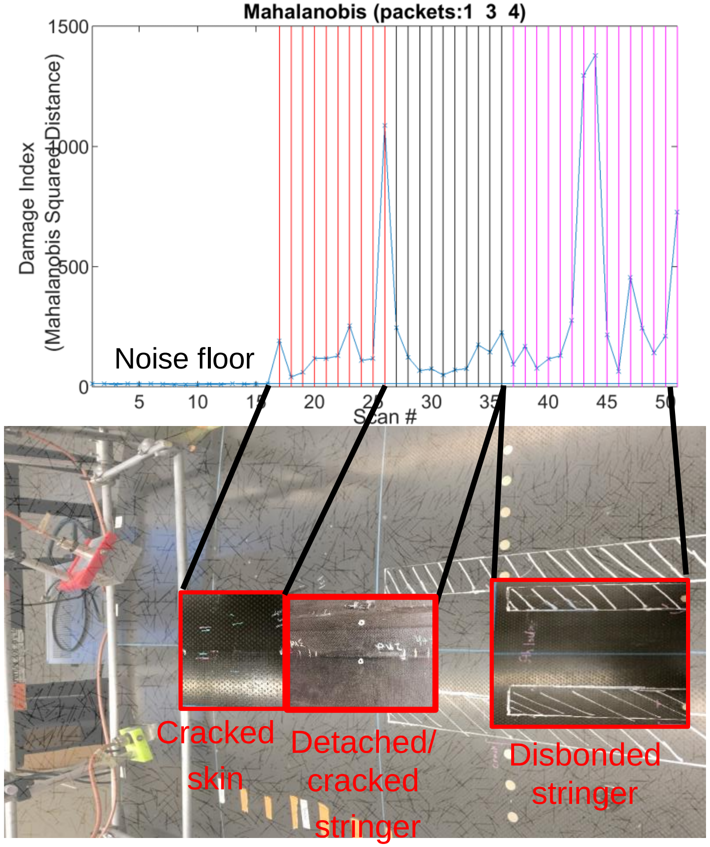
Non-Contact NDE Scanning Prototype

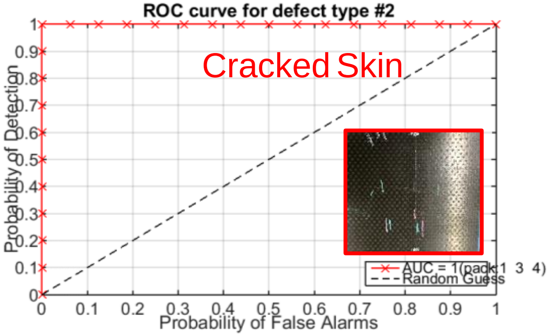
Outlier Analysis Results:

(Skin + Stringer modes)

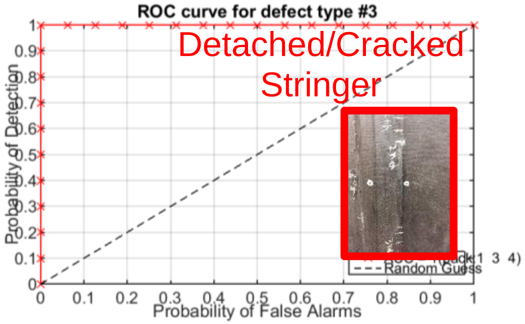
ROC curves

for performance assessment

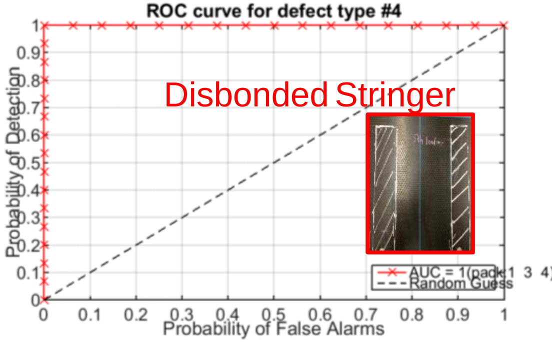




Perfect detection



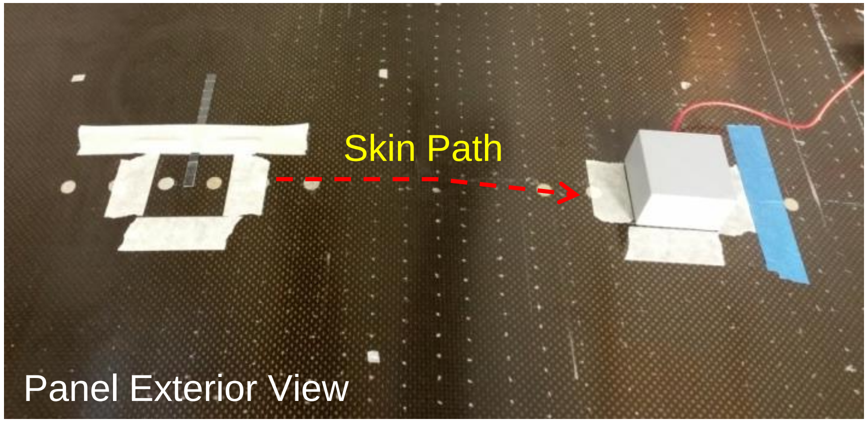
Perfect detection

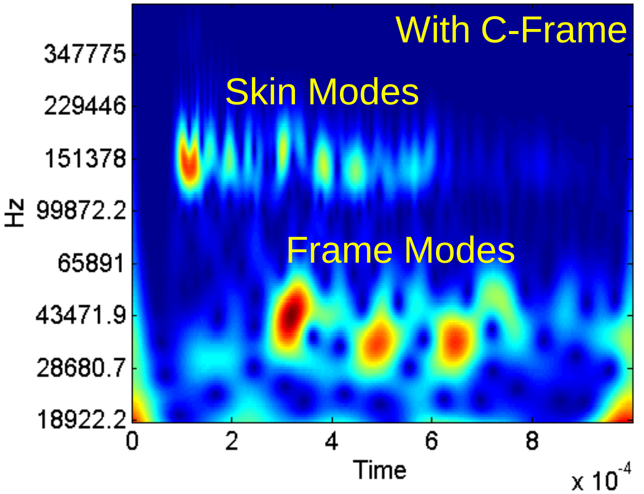


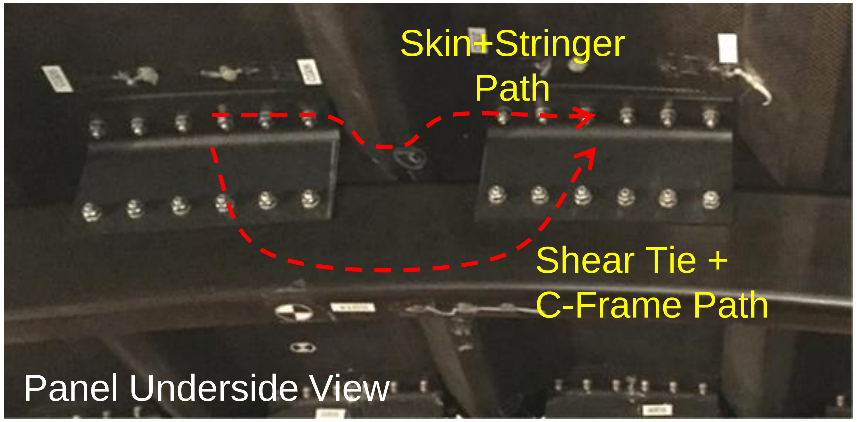
Perfect detection

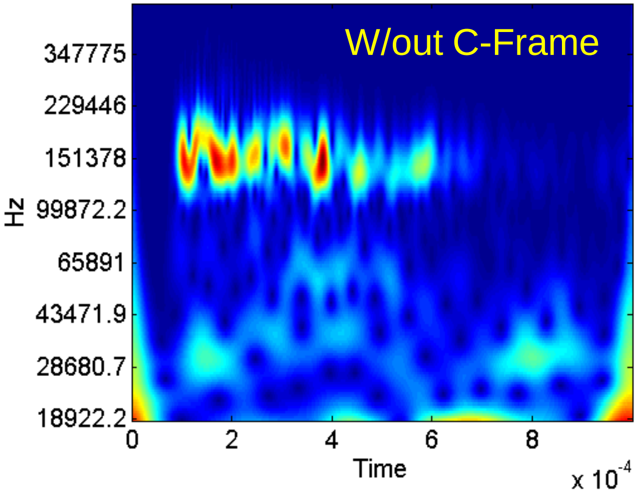
Mini Impactor on Built-up Panel

- Excitation and measurement (R15 contact transducer) on exterior skin-side
- S0 waves through skin path move faster (~150 kHz);
- A0 waves through C-frame path move slower (~50 kHz);
- Specimen with C-frame removed has only skin modes content



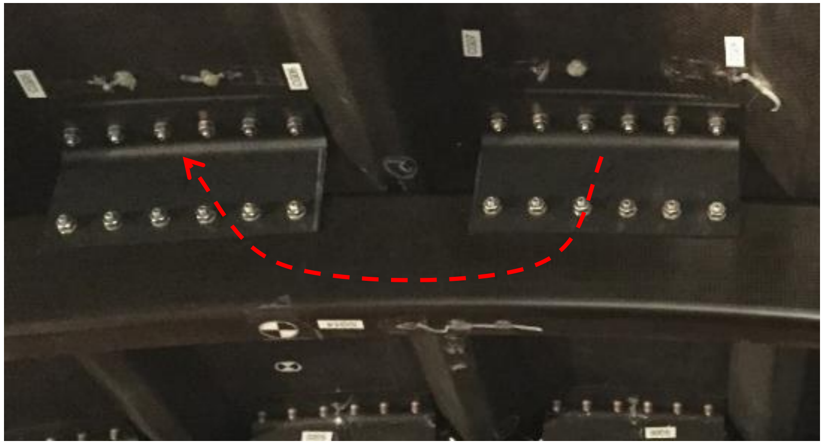


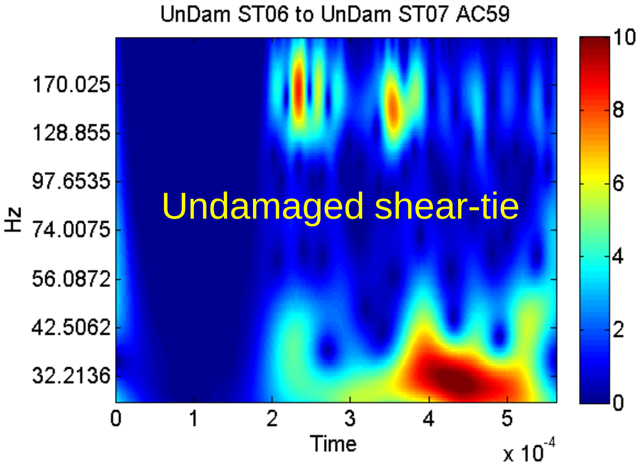


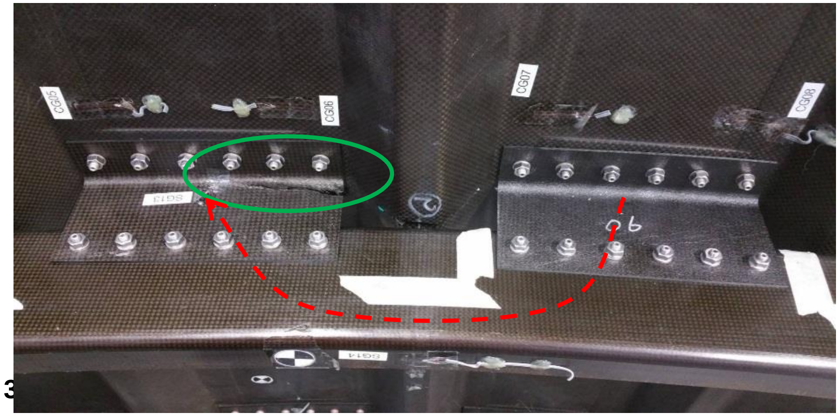


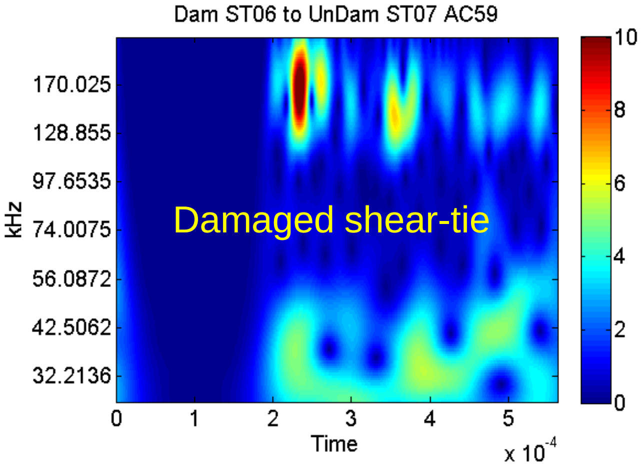
Mini Impactor on Built-up Panel

- Internal shear tie damage detection using mini-impactor excitation





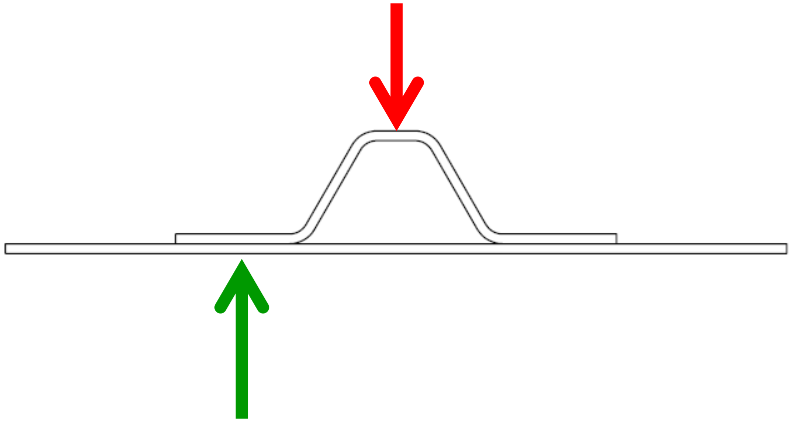




Residual Strength Estimation: Validation

- Three new stringer panels fabricated
  - T800/3900-2 uni-directional tape plies. Skin thickness = 3.175mm
  - Panel dimensions: 1m x 1.3m
  - Five stringers with 0.26m spacing
  - Various impact energy levels

Impact Locations



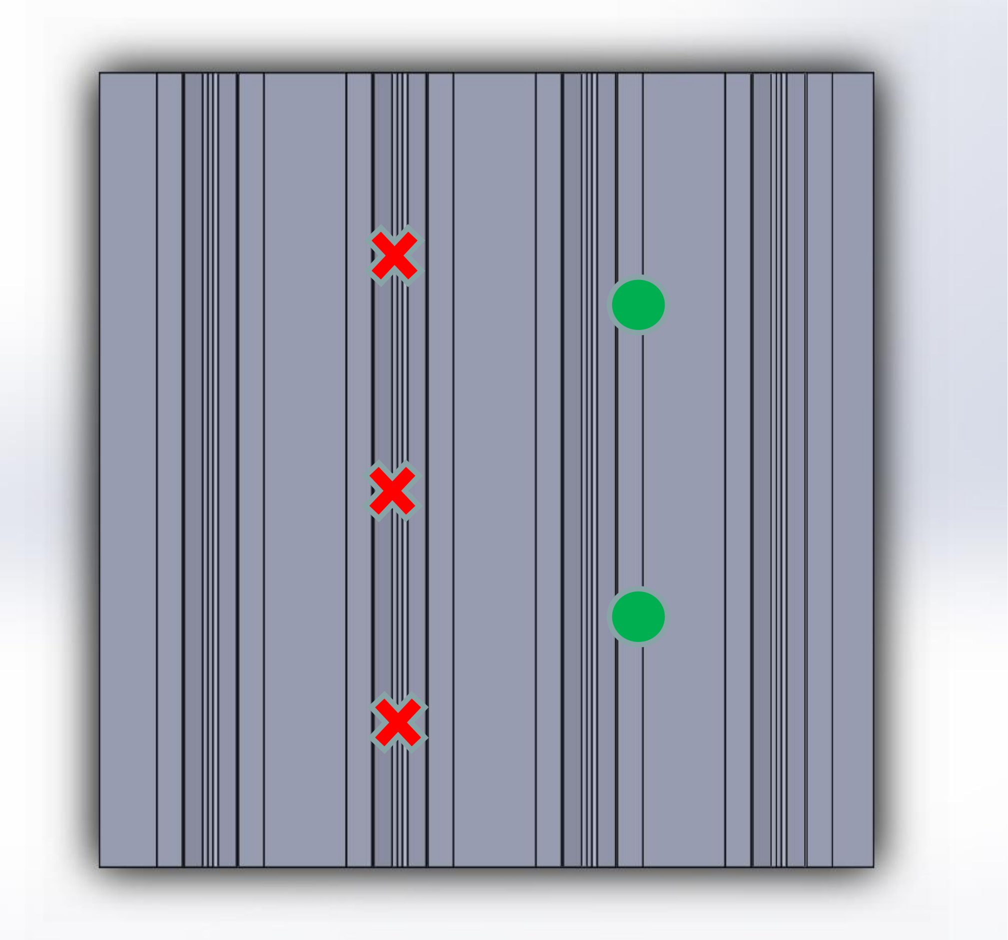
B (stringer cap)

A (stringer flange)

Residual Strength Estimation Plans: Flat Stringer Panel

Flat Stringer Panel Impact Plan

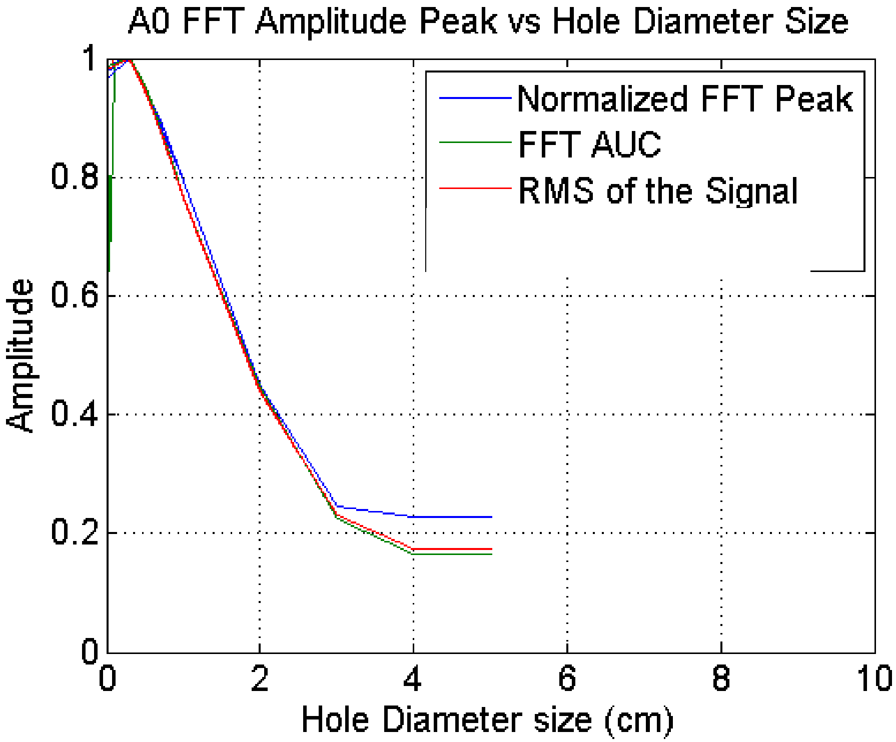
- Stringer cap impacted portion will be trimmed into 0.3m specimens for compression w/o buckling
- Stringer flange impacted portion will be trimmed into 0.48m specimens for compression w/ buckling



✖ **Stringer Cap Impact**

● **Skin&Stringer Flange Impact**

Residual Strength Estimation: Wave Scattering



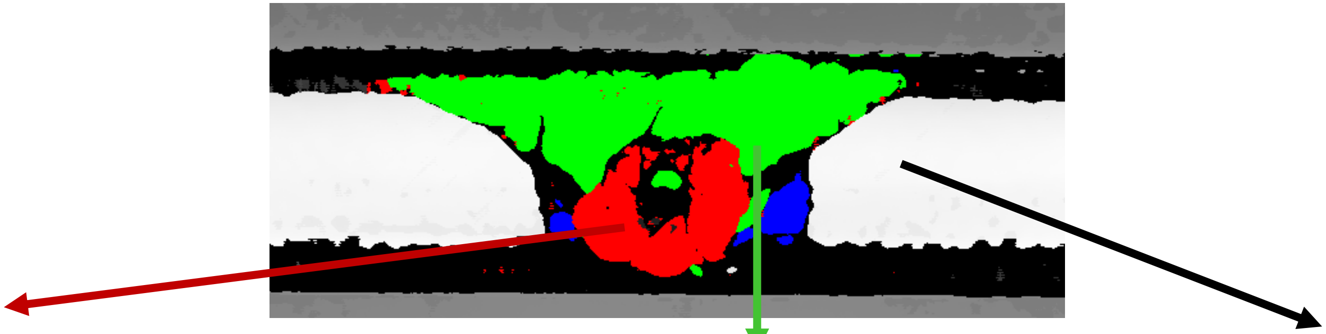
Empirically determine the exponential value e, and relate values to estimate residual strength

Wave_Amplitude= $(\text{Dam\_Size})^{-e}$ $\longrightarrow$ $\sigma_{crack} / \sigma_{pristine} = (L_0/\text{Dam\_Size})^m$ [Caprino]

Caprino, Giancarlo. "On the prediction of residual strength for notched laminates." ***Journal of Materials Science*** **18.8 (1983): 2269-2273.**

Looking forward

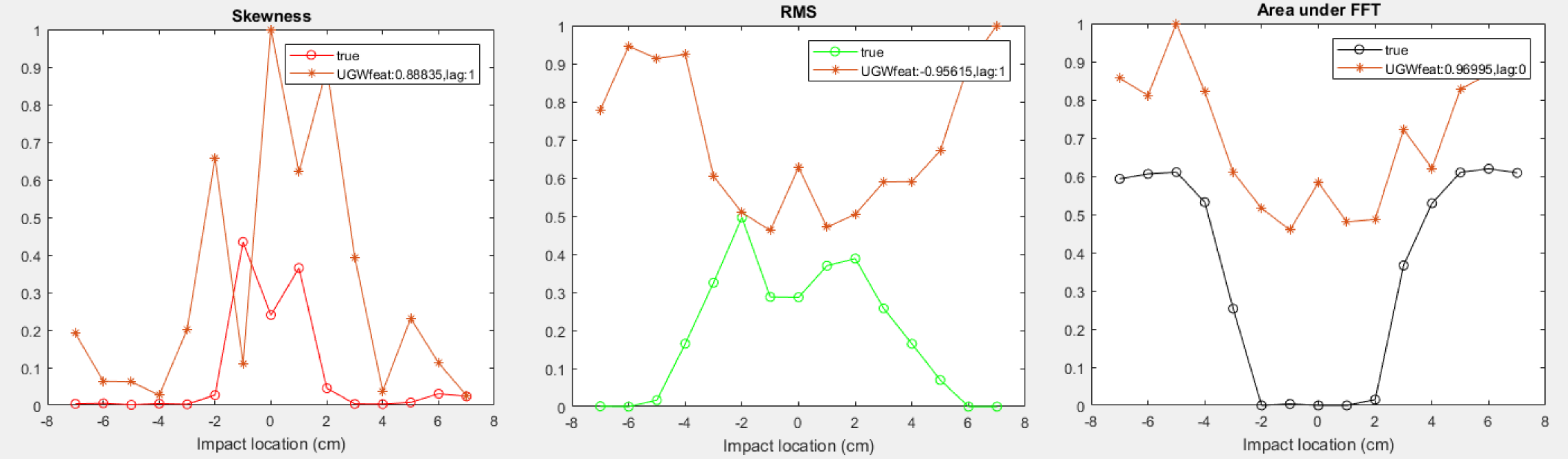
- Correlate the features with damage location and type: preliminary results of defect characterization (extension, severity, type) by UGW.



Skin Damage

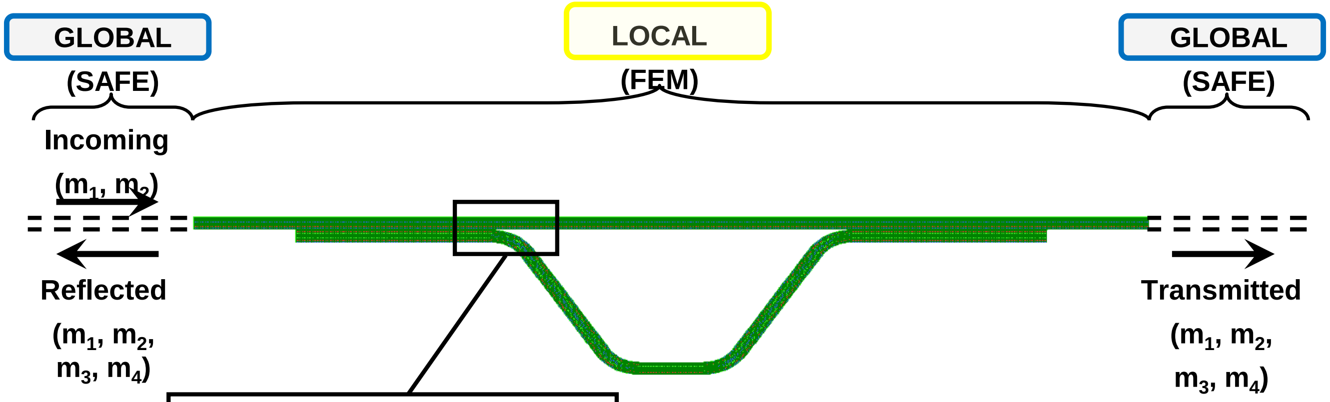
Disbond Damage

Undamaged



Looking forward

-
    - Further investigation on internal structural wave penetration. (Global Local modeling)



GLOBAL

(SAFE)

Incoming

(m$_1$, m$_2$)

Reflected

(m$_1$, m$_2$, m$_3$, m$_4$)

LOCAL

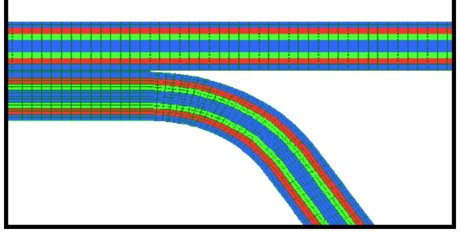
(FEM)

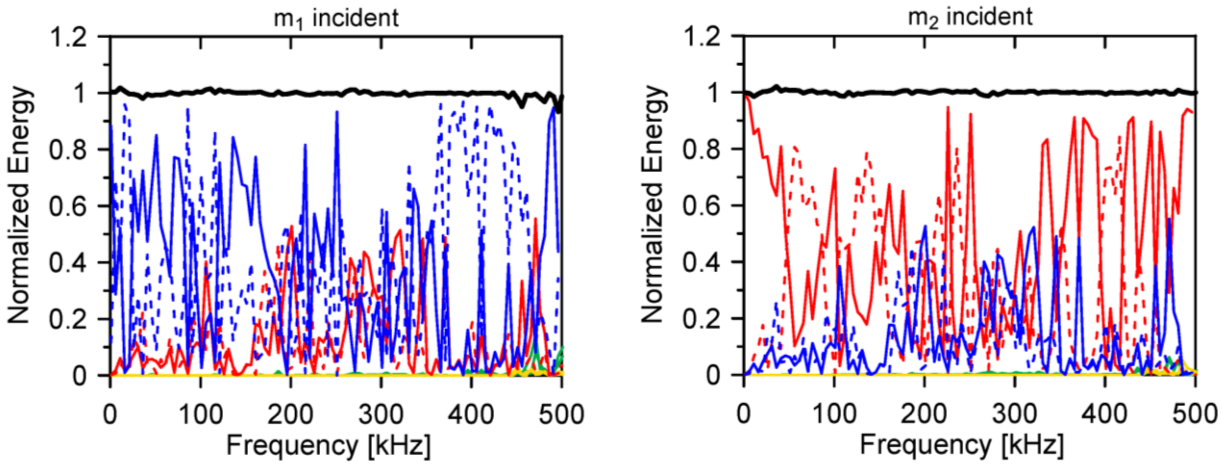
GLOBAL

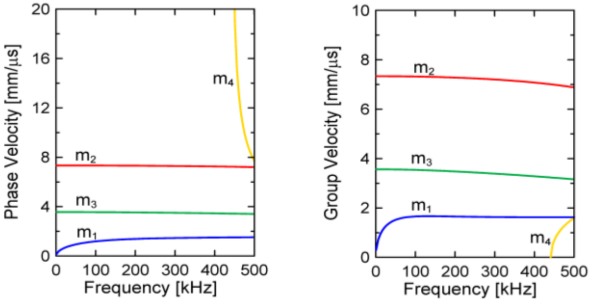
(SAFE)

Transmitted

(m$_1$, m$_2$, m$_3$, m$_4$)







Looking forward

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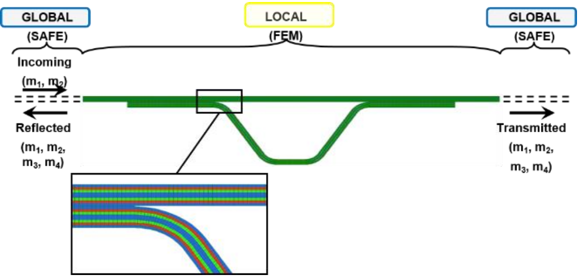

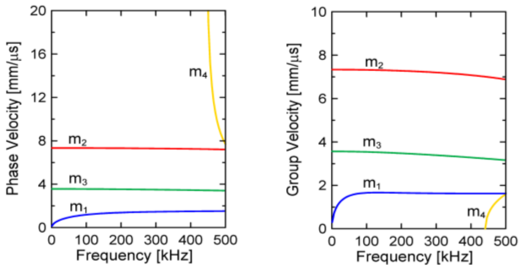

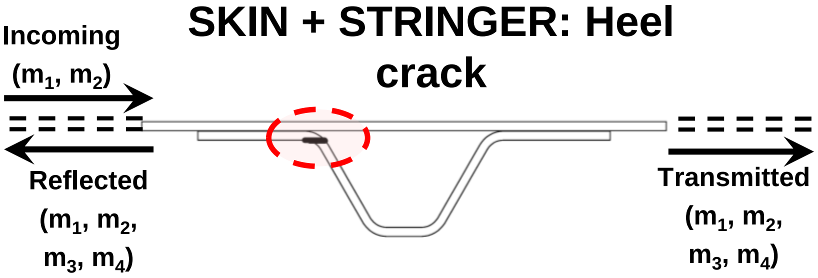

SKIN + STRINGER: Heel crack

Incoming (m_1, m_2)

Reflected (m_1, m_2, m_3, m_4)

Transmitted (m_1, m_2, m_3, m_4)