JOINT ADVANCED MATERIALS & STRUCTURES
CENTER OF EXCELLENCE

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

Francesco Lanza di Scalea

Professor, Dept. of Structural Engineering
University of California San Diego

2018 JAMS Technical Review
May 23-24, 2018

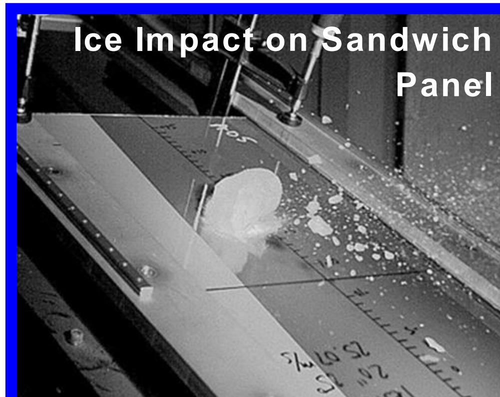
Long Beach Convention Center, Long Beach, CA

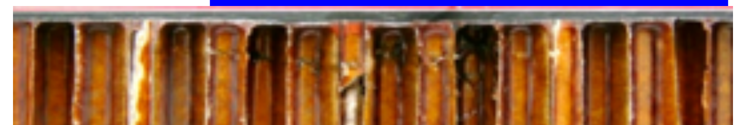
Participants

- **Principal Investigators & Researchers**
  - PI: Prof. Hyonny Kim, UCSD
  - Co-PI: Prof. Francesco Lanza di Scalea
  - Graduate Students
    - PhD: Eric Hyungsuk Kim, Margherita Capriotti, Ranting Cui
    - 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

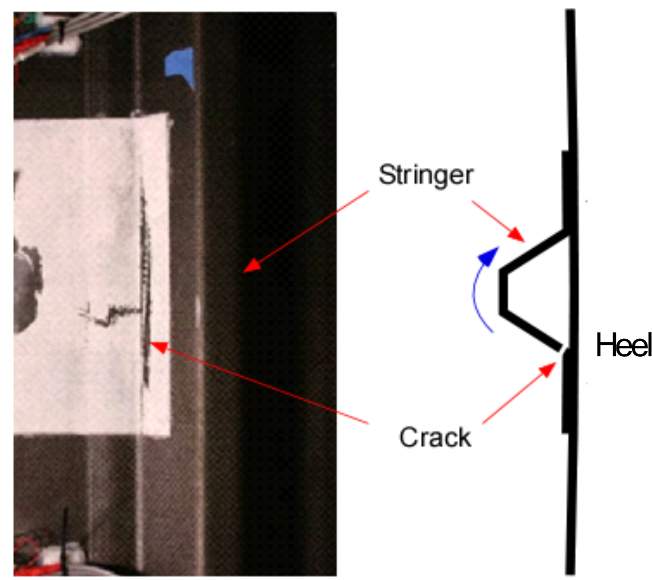
- High energy *blunt impact damage* (**BID**) of main interest
  - involves large contact area, multiple structural elements
    - GSE, FOD, railings/corners, hail ice, bird
  - internal damage (cracked shear tie, frame, stringer heel crack) can exist with ***little/no exterior visibility***
- Damage to internal members not visible by typical one-sided NDE (e.g., UT scan)
- External-only NDE needed to find such damage



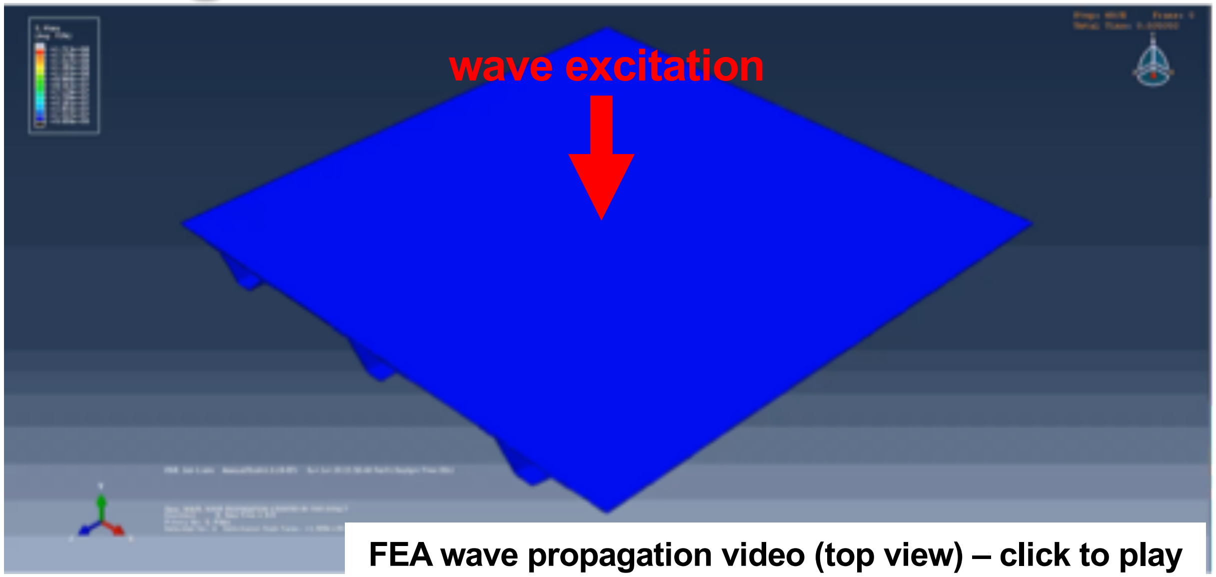


Sandwich Core Crush

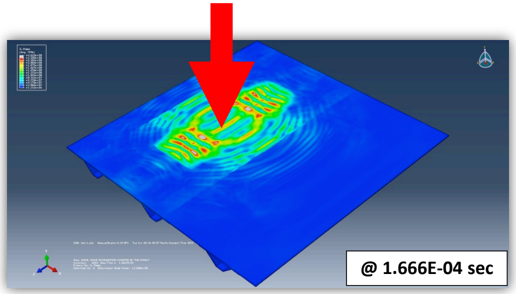
GSE Impact/Contact

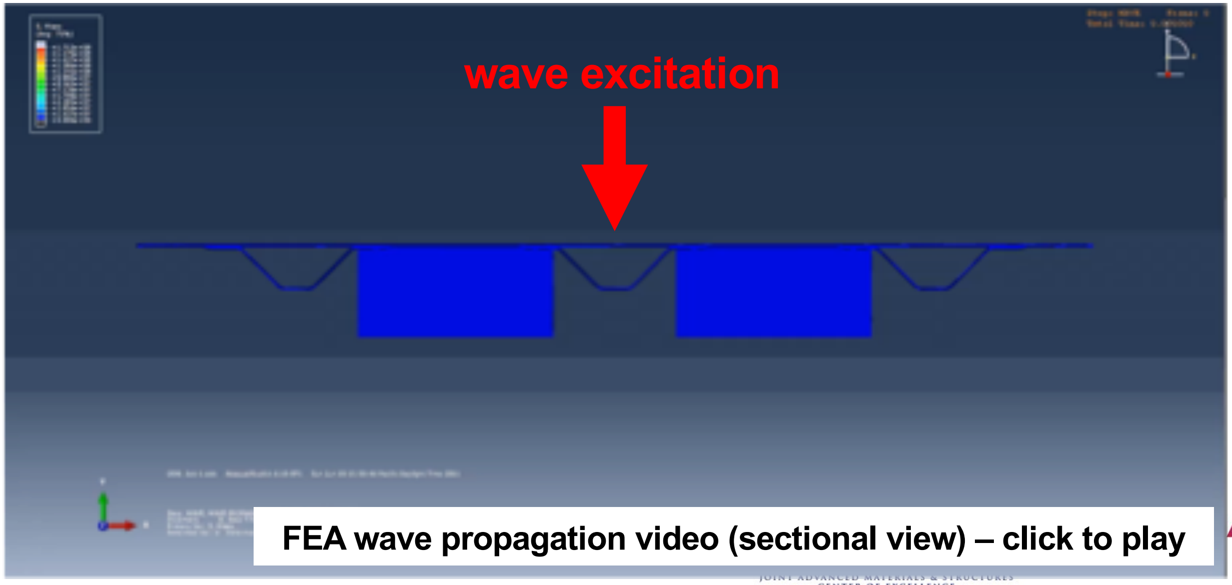


Ultrasonic Guided Waves: structure is a natural "waveguide"



FEA wave propagation video (top view) – click to play





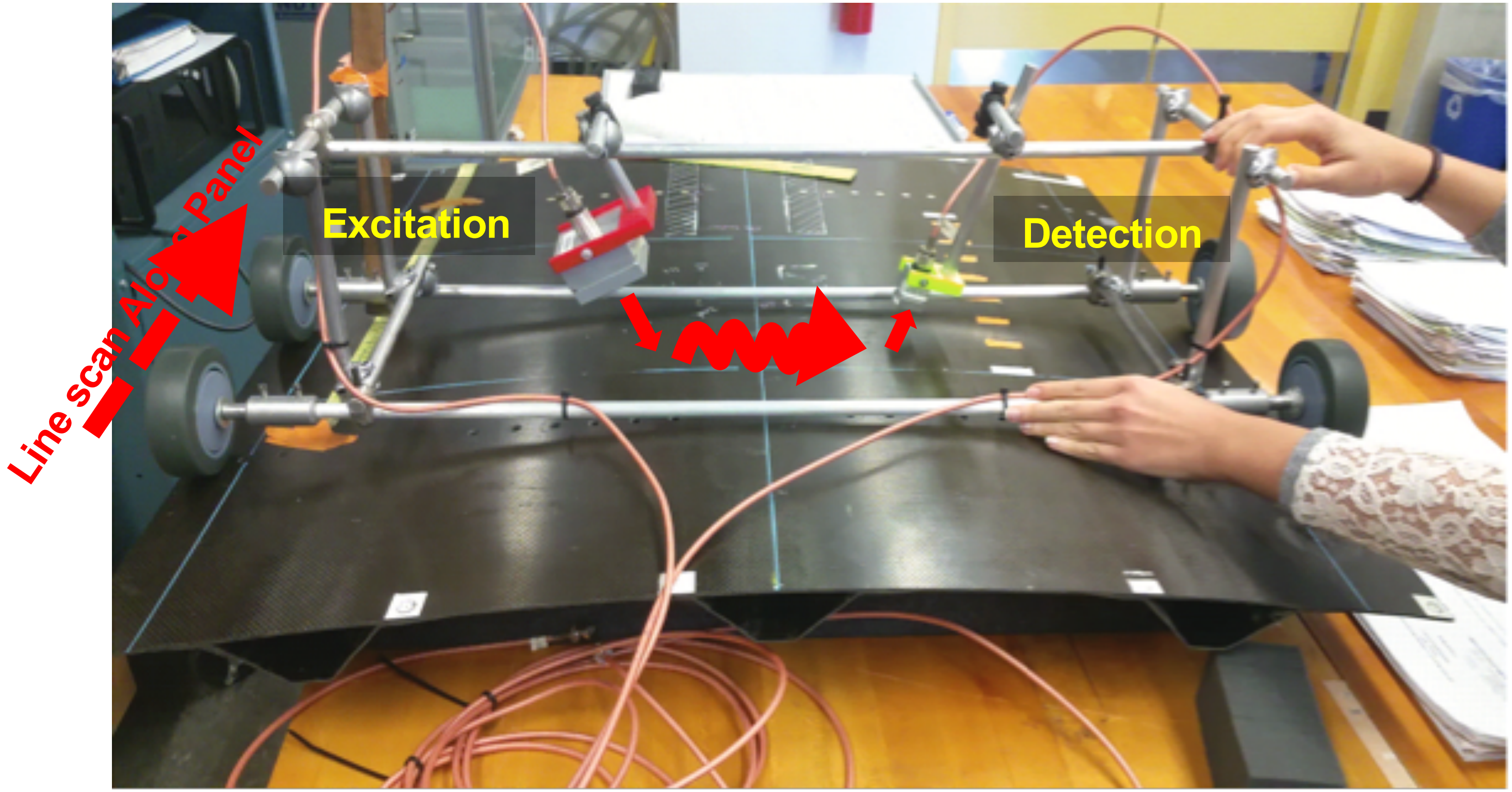
FEA wave propagation video (sectional view) – click to play

A Center of Excellence AMTAS Advanced Materials in Transport Aircraft Structures

JOINT ADVANCED MATERIALS & STRUCTURES CENTER OF EXCELLENCE

Non-Contact NDE Scanning Prototype

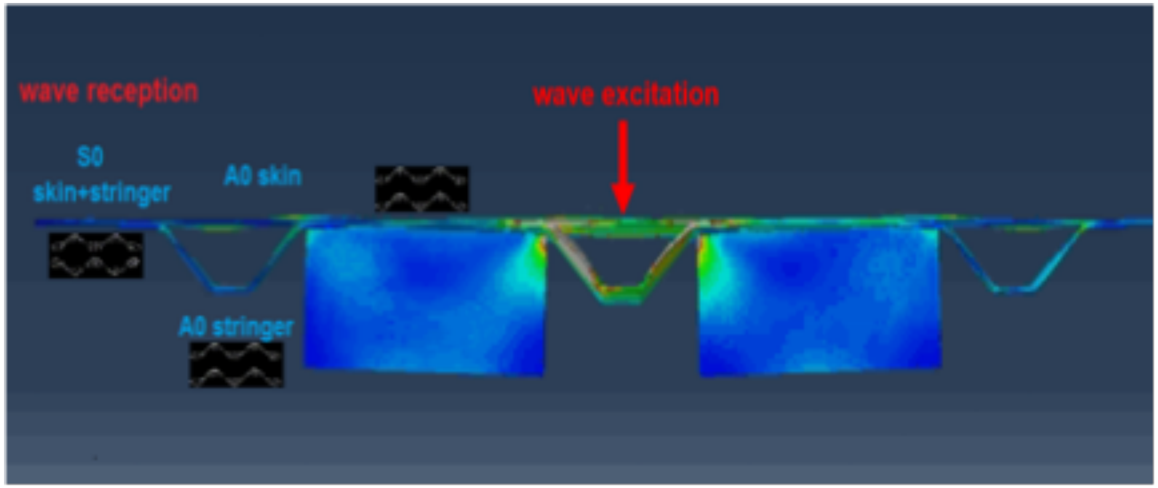
- Line scan approach with non-contact sensors on moving carriage
- Air-coupled piezocomposite transducers (170 kHz)



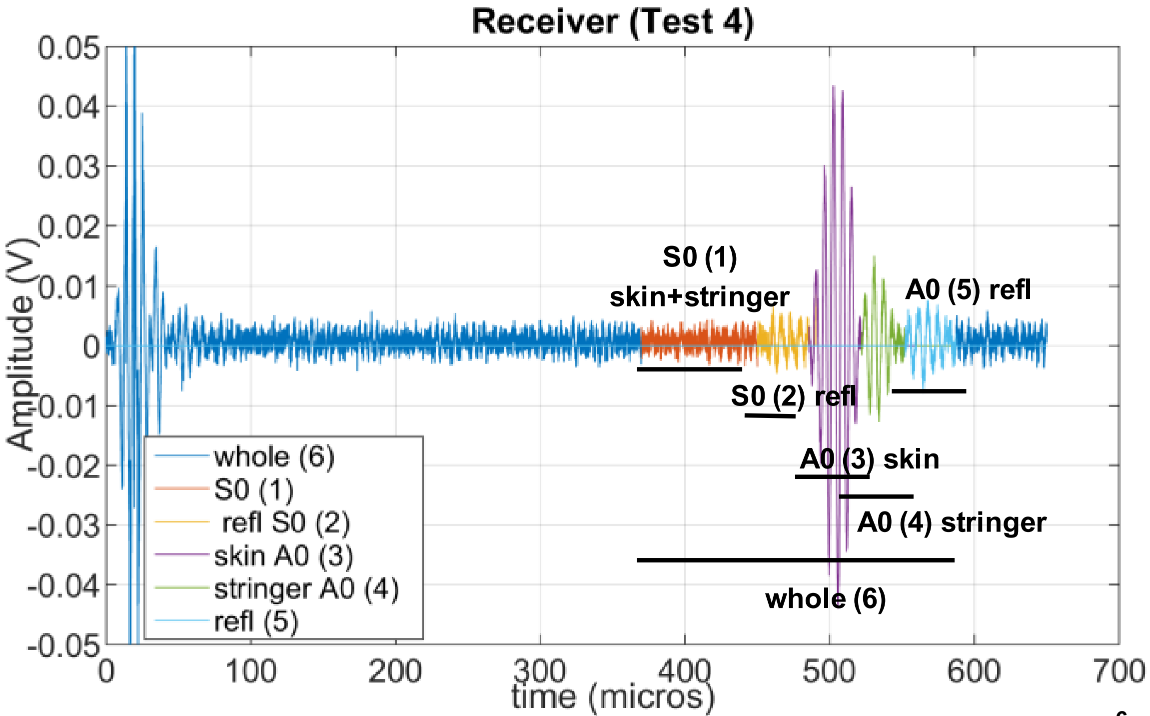
CECAM
JAMS JOINT ADVANCED MATERIALS & STRUCTURES CENTER OF EXCELLENCE
A Center of Excellence AMTAS Advanced Materials in Transport Aircraft Structures

Non-Contact NDE Scanning Prototype

- Typical Signal:
  - Multi-mode: A0 & S0 in Skin/Stringer
  - Time of Arrival computed from Group Velocity obtained from analysis



Gating in 6 different exploitable packets to isolate different modes

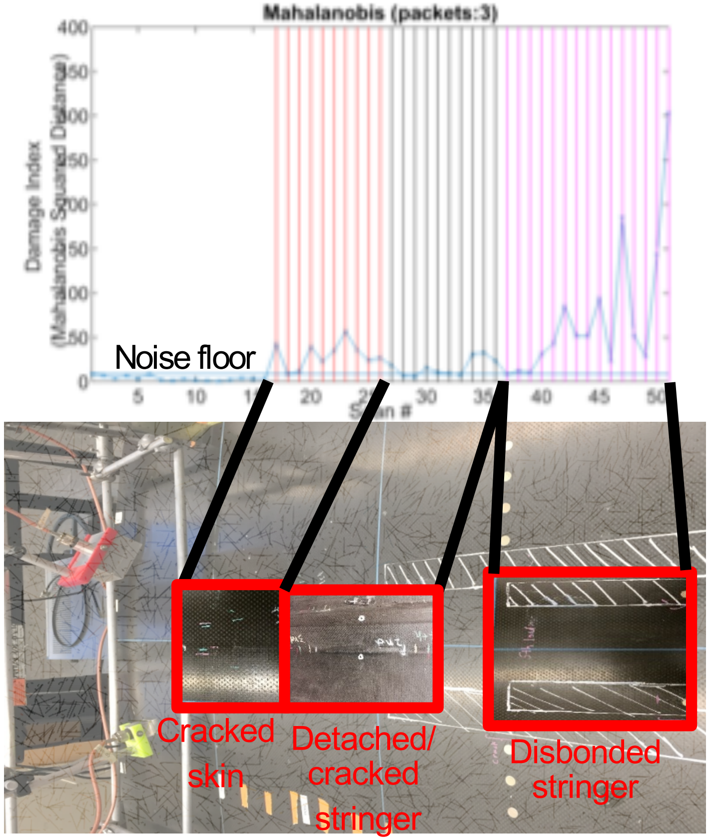


Statistical (Outlier) Analysis

Non-Contact NDE Scanning Prototype

Statistical Analysis Results:

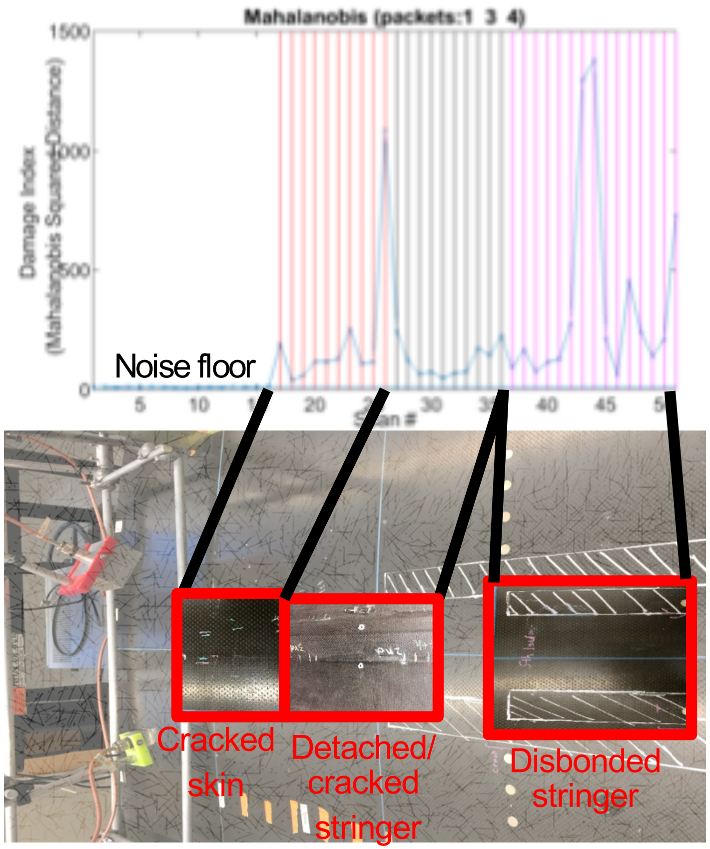
(Skin modes only)



Non-Contact NDE Scanning Prototype

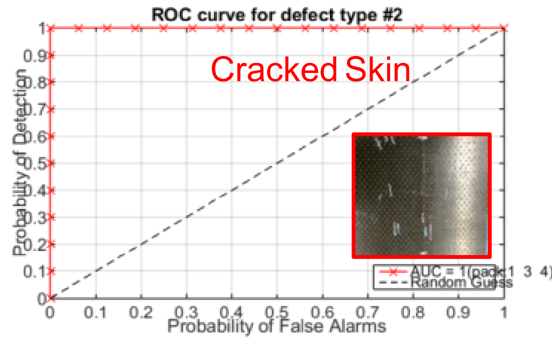
Outlier Analysis Results:

(Skin + Stringer modes)

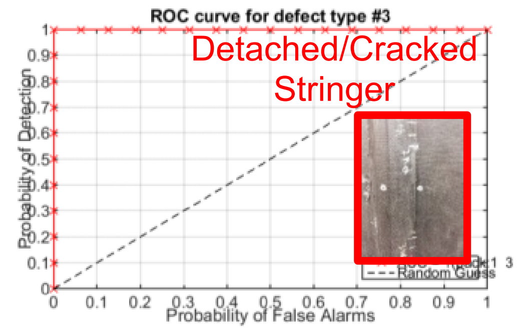


ROC curves

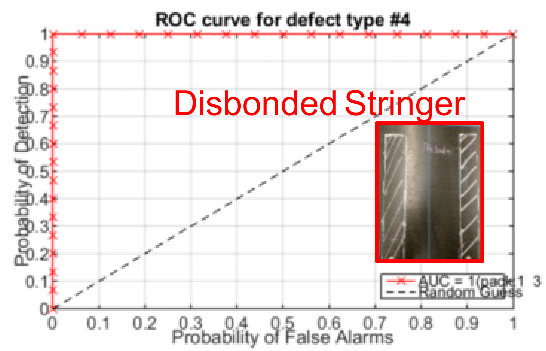
for performance assessment



Perfect detection



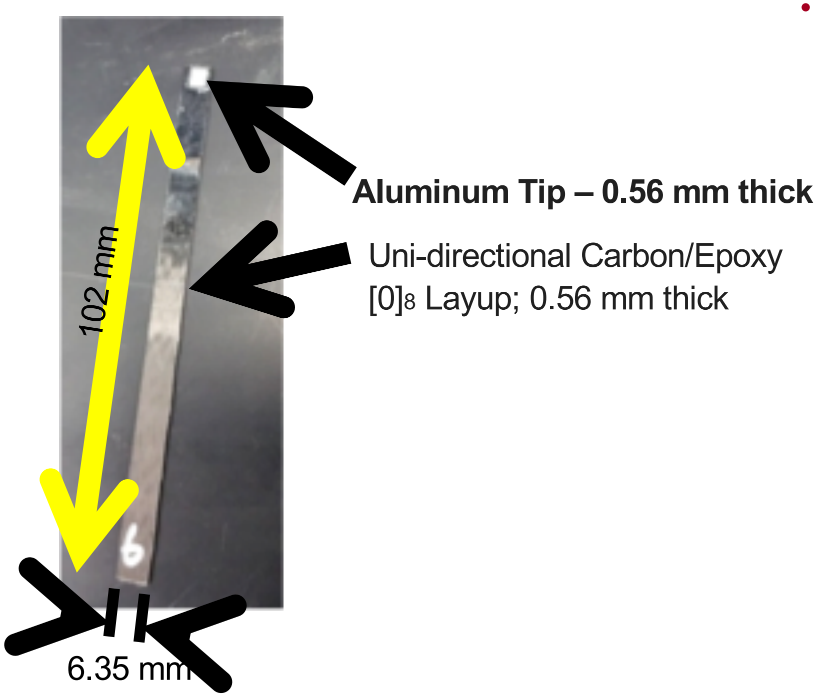
Perfect detection



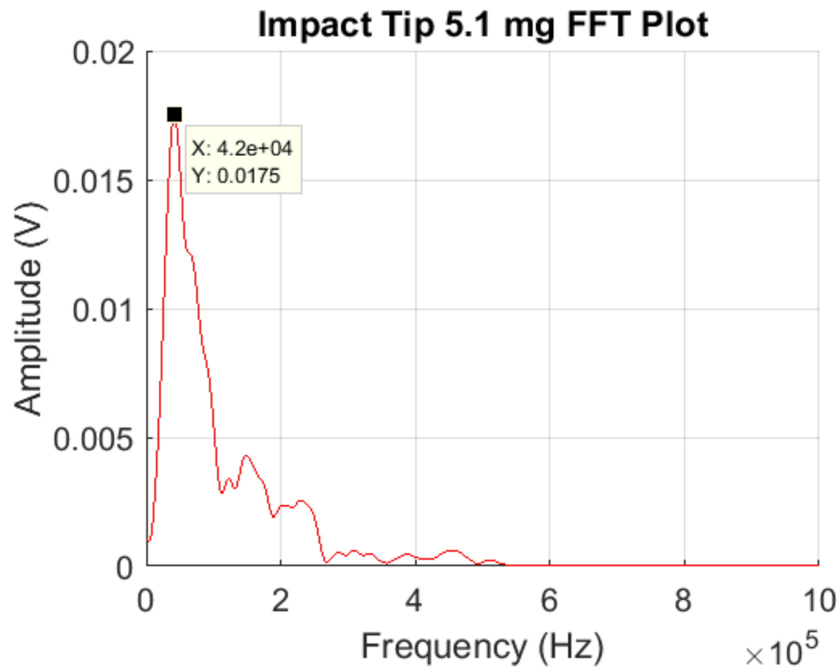
Perfect detection

CECAM JAMS JOINT ADVANCED MATERIALS & STRUCTURES CENTER OF EXCELLENCE AMTAS Advanced Materials in Transport Aircraft Structures

Mini-Impactor (probes interior + portable)

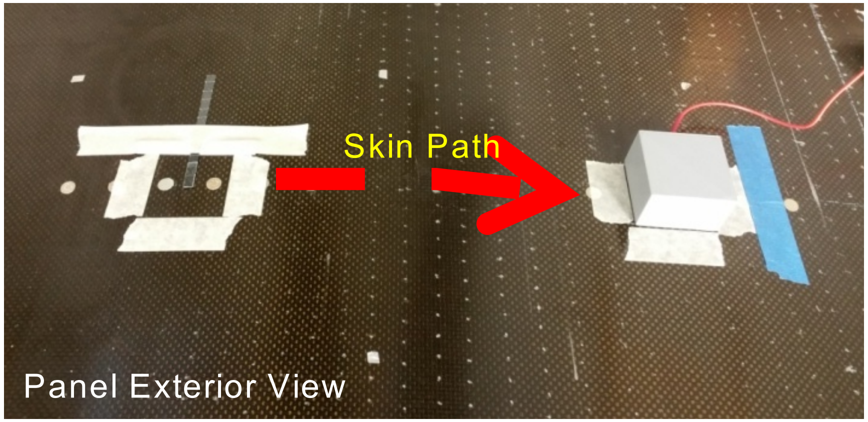


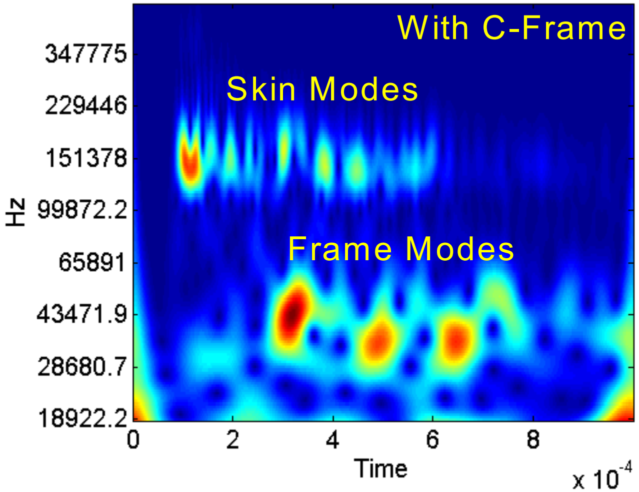
- Frequency range up to 500 kHz and peak intensity at 42 kHz

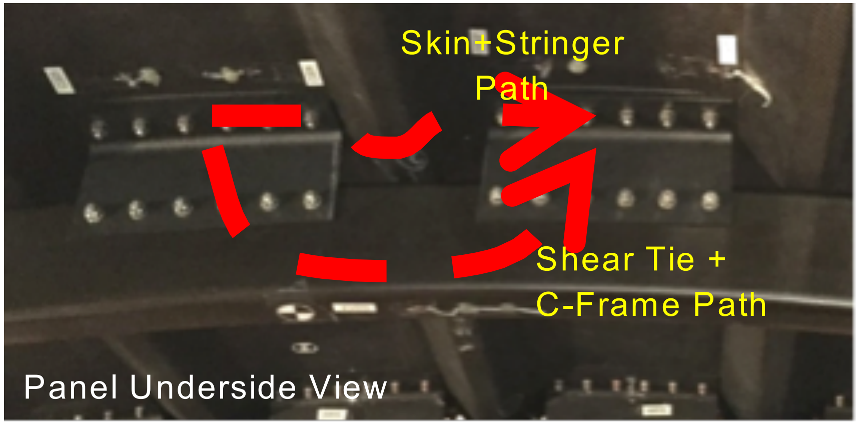


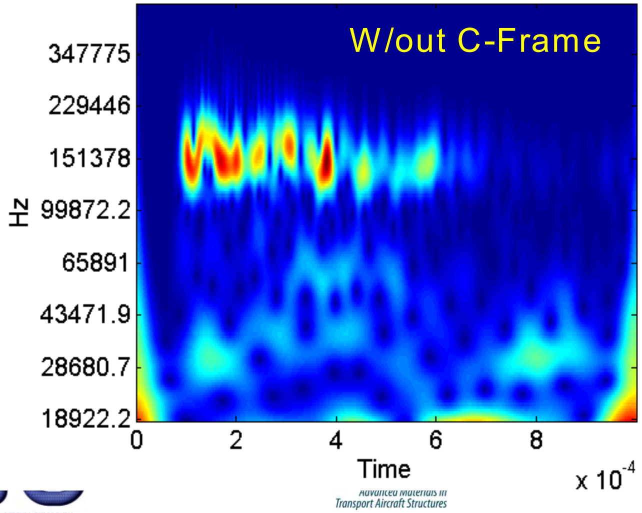
Mini Impactor on Built-up Panel

- 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







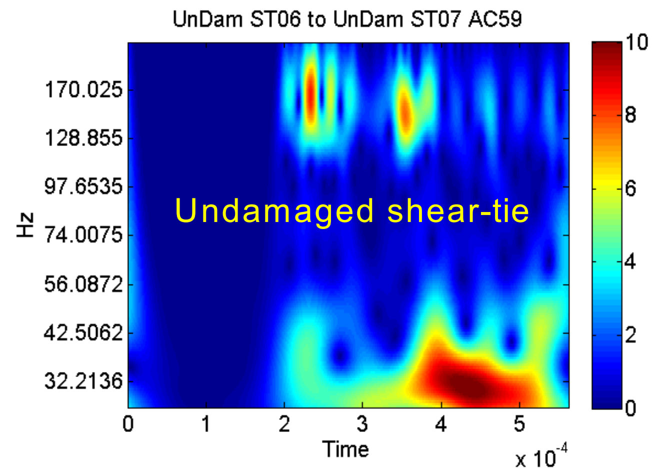


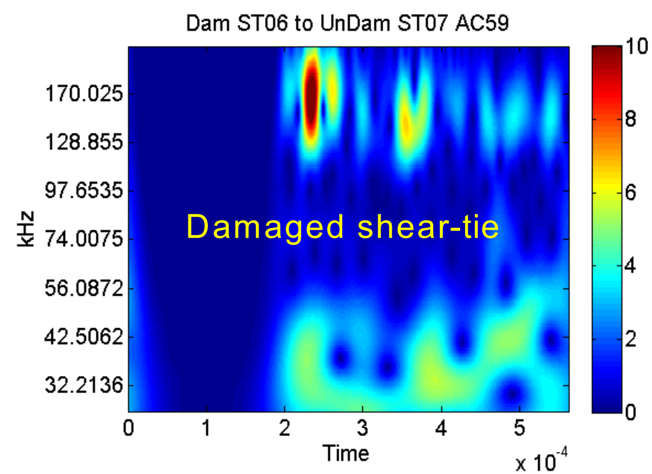
JOINT ADVANCED MATERIALS & STRUCTURES CENTER OF EXCELLENCE

Advanced Materials in Transport Aircraft Structures

Mini Impactor on Built-up Panel

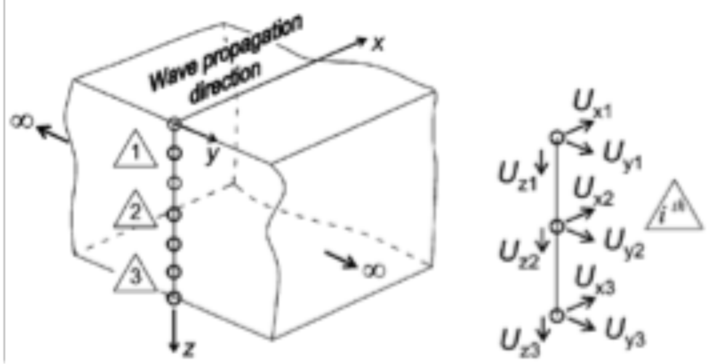
- Internal shear tie damage detection using mini-impactor excitation





GUIDED WAVE MODELING: S.A.F.E.

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



$[\mathbf{A} - \xi\mathbf{B}]_{2M}\mathbf{Q} = \mathbf{0},$ **Unforced solution** → **Dispersion curves & mode shapes**

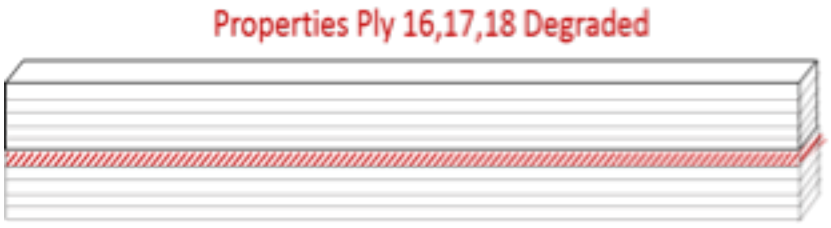
$$U(x_R) = -\frac{1}{2\pi}\sum_{m=1}^{2M}\frac{(\xi^m U_L^m)^T\, F_n\, U_R^m}{D_m}\int_{-\infty}^{\infty}\frac{1}{(\xi-\xi^m)}e^{i\xi(x_R-x_S)}d\xi$$

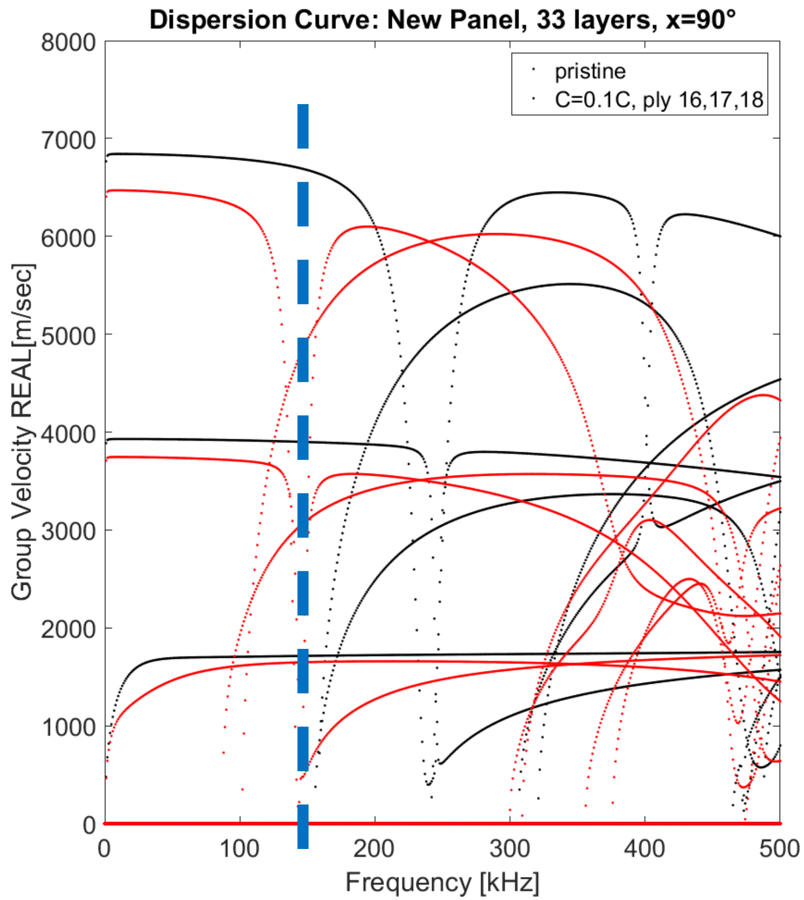
Forced solution

S.A.F.E. Results: CFRP skin + stringer

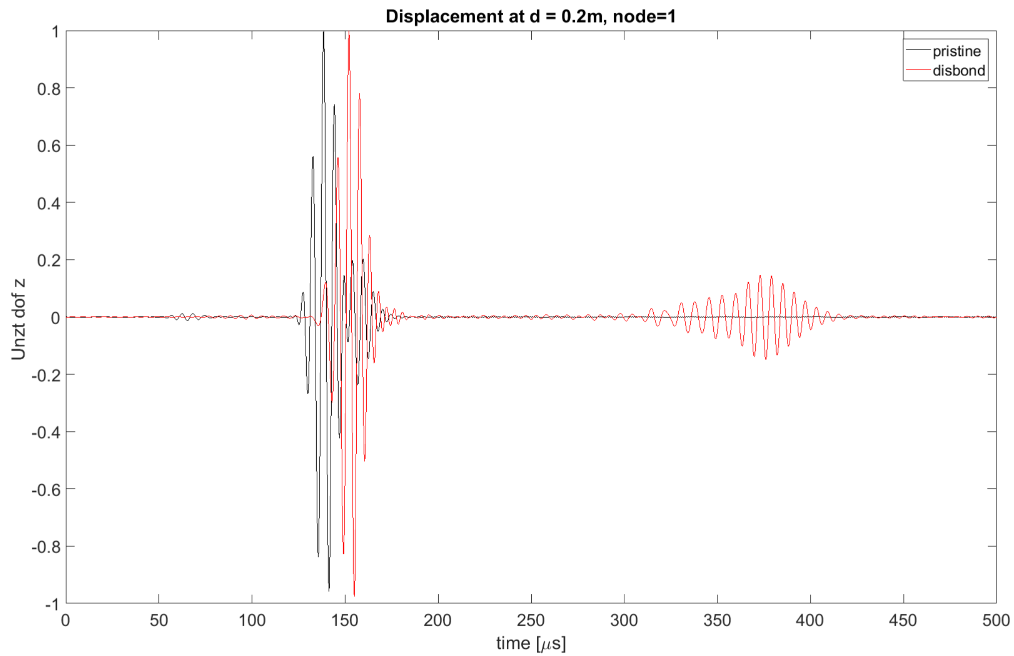
Stiffened Panel: Stringer Disbond Damage

- Wave propagation direction: 90° (across the stringer)
- Layup: 33 plies (Skin & Stringer)
- Lamina Properties: T800/3900-2 Unidirectional Tape





Laminate Properties: C reduced to 0.1 C for Plies 16, 17, 18



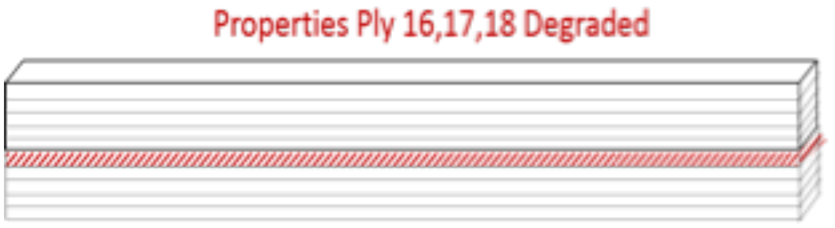
JOINT ADVANCED MATERIALS & STRUCTURES CENTER OF EXCELLENCE

Advanced Materials in Transport Aircraft Structures

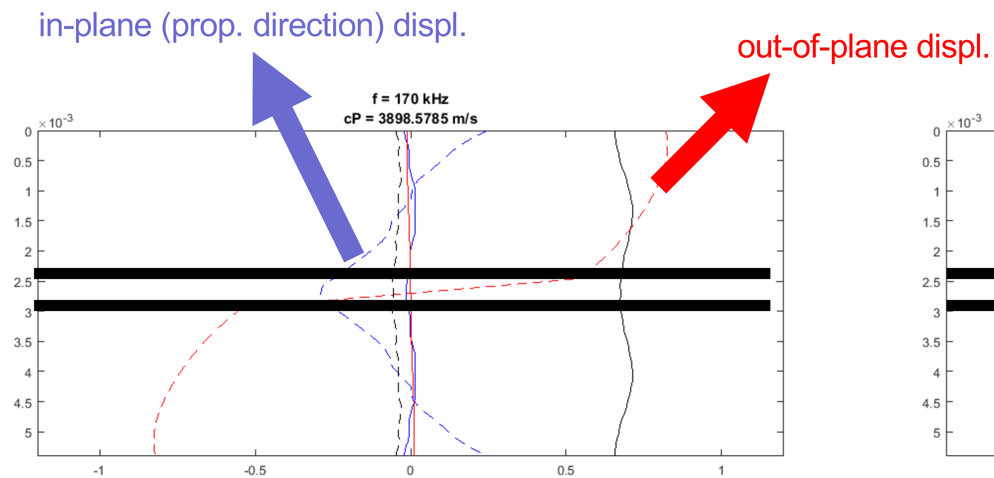
S.A.F.E. Results: CFRP skin+stringer

Stiffened Panel: Stringer Disbond Damage

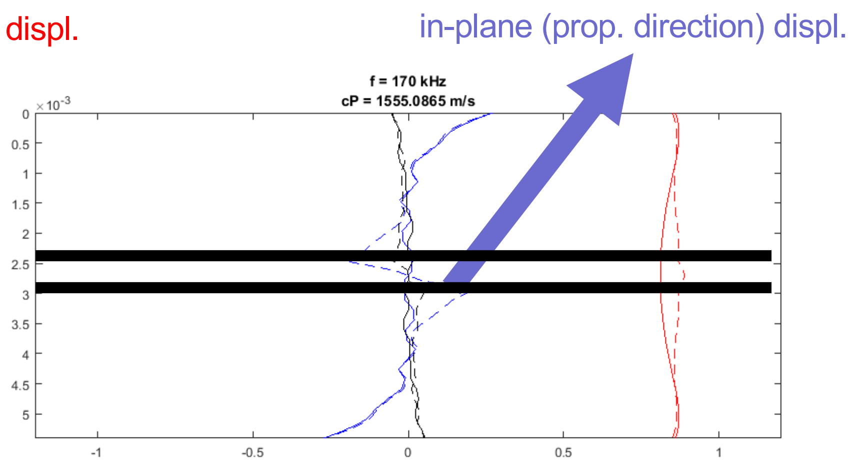
- Wave propagation direction: 90° (across the stringer)
- Layup: 33 plies (Skin & Stringer)
- Lamina Properties: T800/3900-2 Unidirectional Tape



Laminate Properties: C reduced to 0.1 C for Ply 16, 17, 18



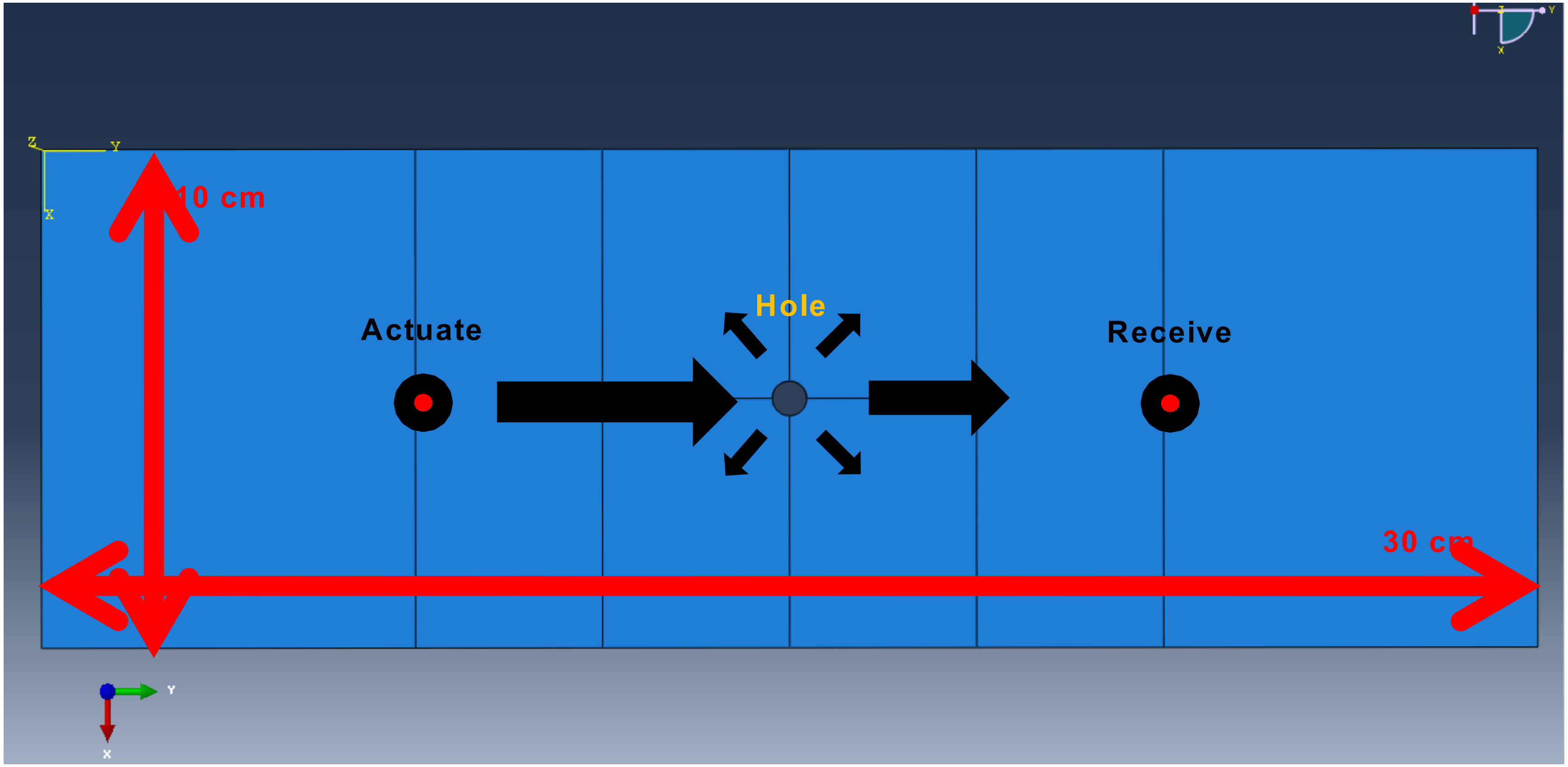
S0 modeshape



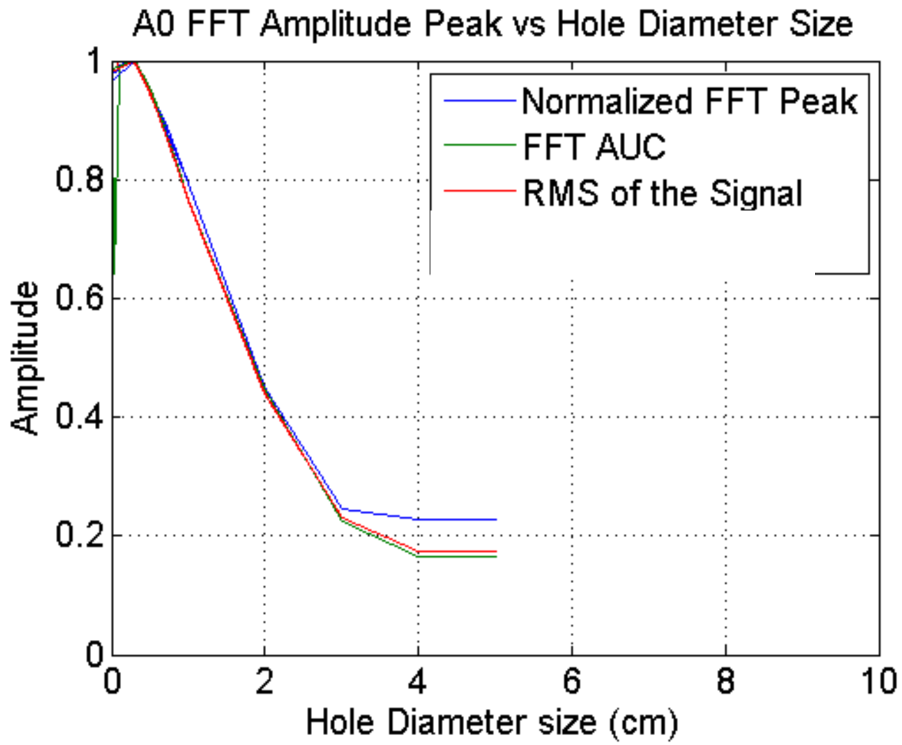
A0 modeshape

Residual Strength Estimation: Wave Scattering

- Simple beam with through holes from 0.05 mm to 50 mm dia
- Mesh size = 1mm, Time step = 5e-8 sec, Exc = 2.5 cycle toneburst at 150 kHz



Residual Strength Estimation: Wave Scattering



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

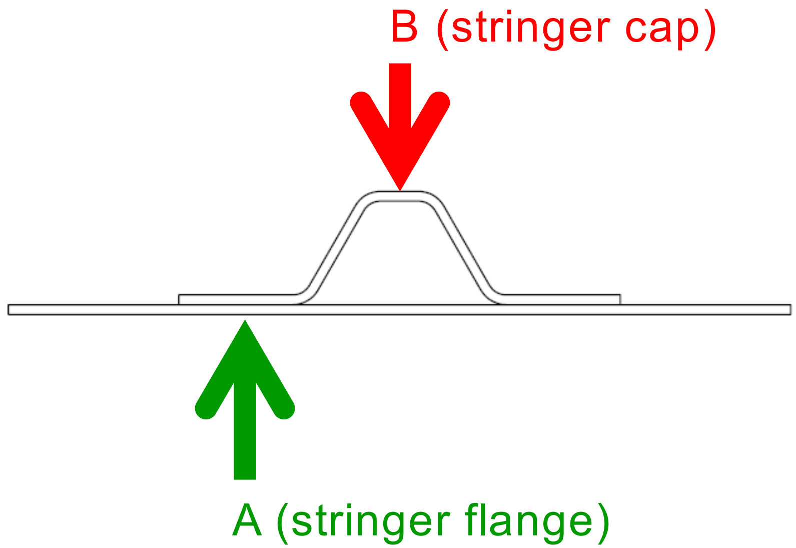
Wave_Amplitude= $(\text{Dam\_Size})^{-e}$ → $\sigma_{crack} / \sigma_{pristine} = (L_0/\text{Dam\_Size})^m$ [Caprino]

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

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



CECAM

JAMS
JOINT ADVANCED MATERIALS & STRUCTURES CENTER OF EXCELLENCE

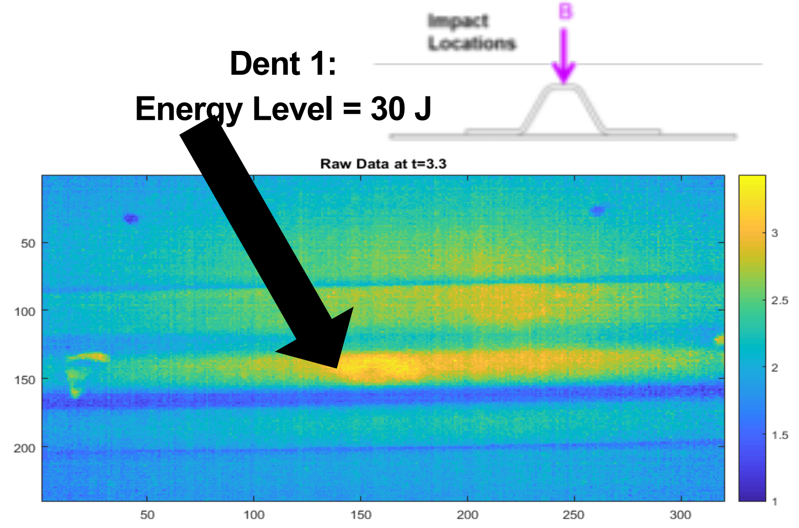
A Center of Excellence
AMTAS
Advanced Materials in Transport Aircraft Structures

Thermography for Independent Damage Survey

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

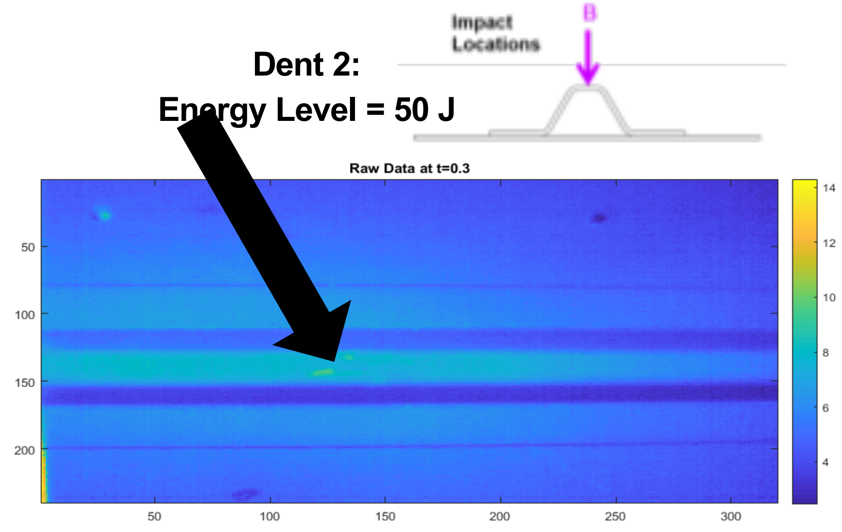
Dent 1:

Energy Level = 30 J



Dent 2:

Energy Level = 50 J



Ongoing/Future Work

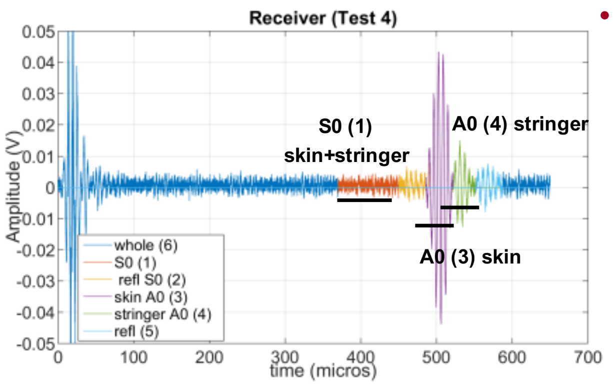
- Package mini-impactor into scanning system to probe interior structure for damage (shear ties and C-frames)
- Continue S.A.F.E. modeling of guided waves to select specific mode-frequency combinations highly sensitive to specific damage
- Conduct additional FE analyses of wave scattering through relevant damage types/severity for residual strength estimation from the guided wave measurements
- Validate residual strength predictions from wave measurements through failure tests of impacted panels

EXTRA SLIDES

Statistical Analysis

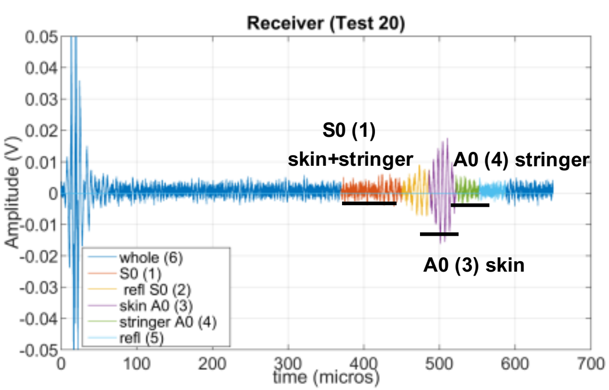
- Outlier Analysis:
  - Multivariate
  - Multi-mode

Super-Vector for mode compounding



Baseline Signal
(six possible time gates)

Test Signal
(six possible time gates)



Feature Super-Vector

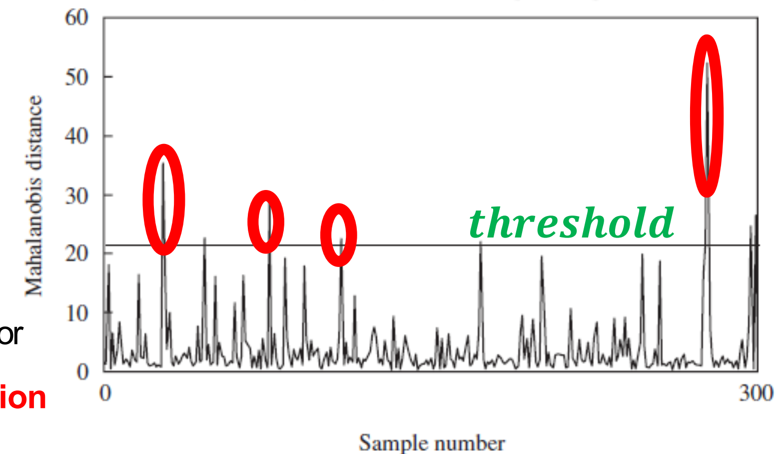
$$x = \left\{ \begin{matrix} \begin{bmatrix} Max\ Ampl \\ Max\ Ind \\ Variance \\ Kurtosis \\ \dots \end{bmatrix}_{m1} \\ \begin{bmatrix} Max\ Ampl \\ Max\ Ind \\ Variance \\ Kurtosis \\ \dots \end{bmatrix}_{m2} \\ \begin{bmatrix} Max\ Ampl \\ Max\ Ind \\ Variance \\ Kurtosis \\ \dots \end{bmatrix}_{mN}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

Known Undamaged Region:

Baseline Vector
Average, Covariance
$\bar{x}, C$

Test Vector
x
Any Location

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



$$If\ DI > threshold \Rightarrow \text{DEFECT}$$

New Stringer Panel Response Study

- **Green's Function Approach**
  - To extract structural behavior/response
  - To apply inversion methods for
    - **damage and structure characterization**
    - **residual strength estimation**

Semi Analytical Finite Element (SAFE) Method

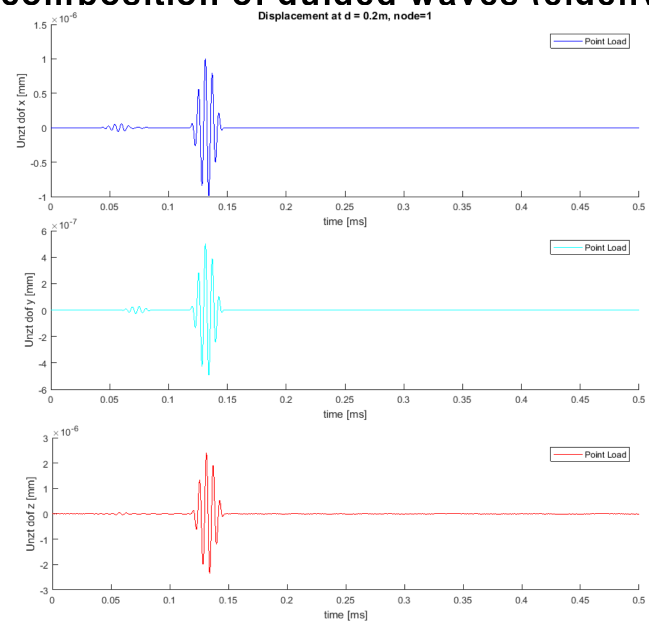
- **FE discretization and problem formulation (material & geometry)**
- **Normal mode decomposition of guided waves (eigenvalue**
- ***Analytical soluti*** **e**

Forced Solution: arbitrary force (in space and tim

$$\underbrace{\hat{F} = \int_{-\infty}^{\infty} F(x) e^{-i\xi x} dx, \qquad \hat{U} = \int_{-\infty}^{\infty} U(x) e^{-i\xi x} dx}$$

$$U(x_R) = -\frac{1}{2\pi} \sum_{m=1}^{2M} \frac{(\xi^m U_L^m)^T F_n U_R^m}{D_m} \int_{-\infty}^{\infty} \frac{1}{(\xi - \xi^m)} e^{i\xi(x_R - x_S)} d\xi$$

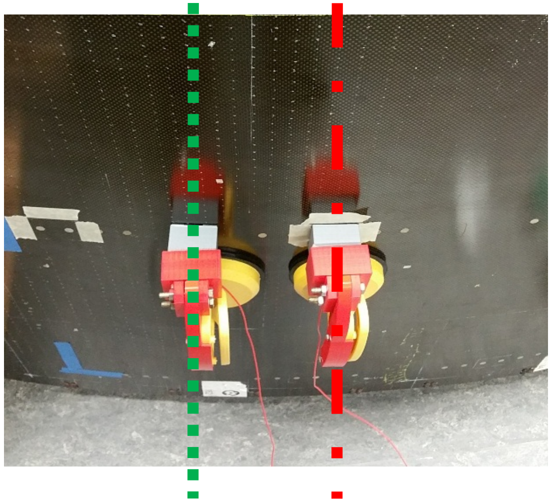
$$U(x_R, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} U(x_R) e^{i\omega t} d\omega$$

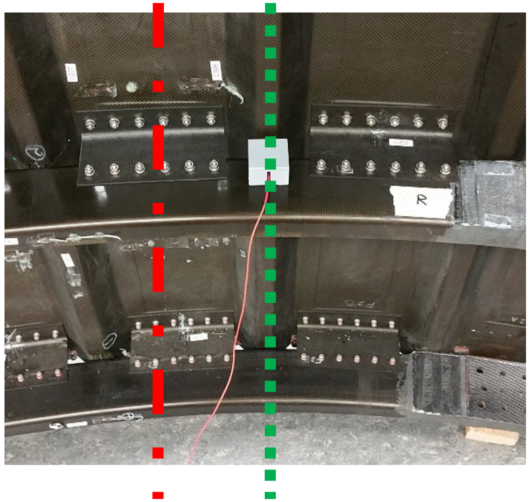


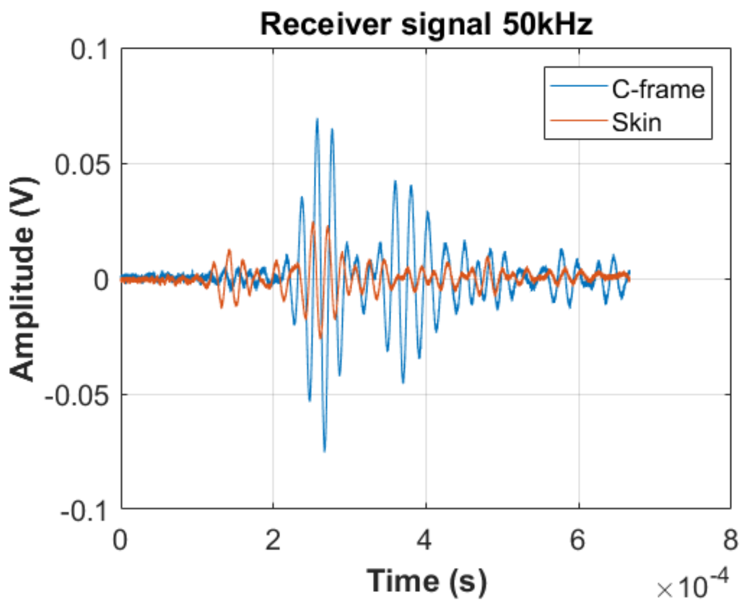
[Marzani A., "Time-transient response for ultrasonic guided waves propagating in damped cylinders", (2008) International Journal of Solids and Structures, vol.45, pp. 6347-6368.]

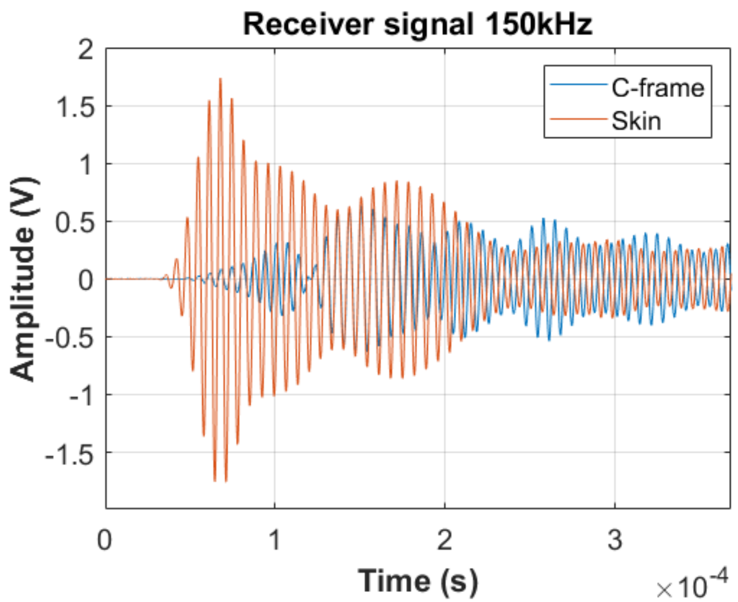
Panel Complexity Testing: External v. Internal UGW Transmission

- Wave transmission energy comparison between internal path (shear tie & C-frame) vs skin path shows 50 kHz wave energy is better transmitted internally compared to the exterior skin transmitted wave energy relative to 150 kHz







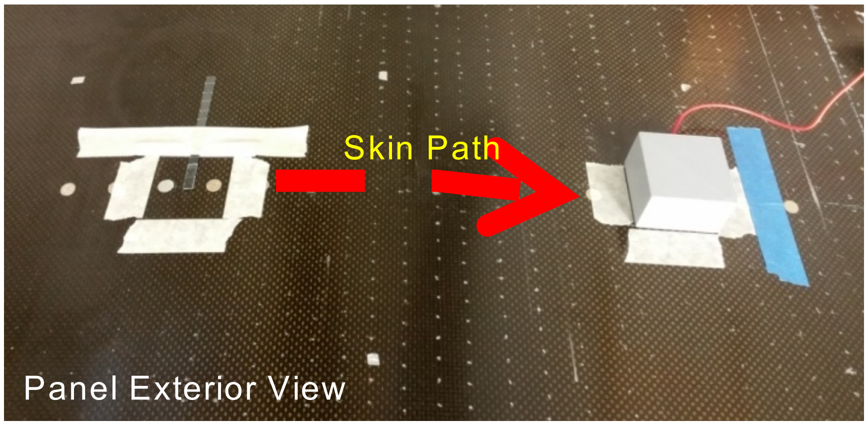


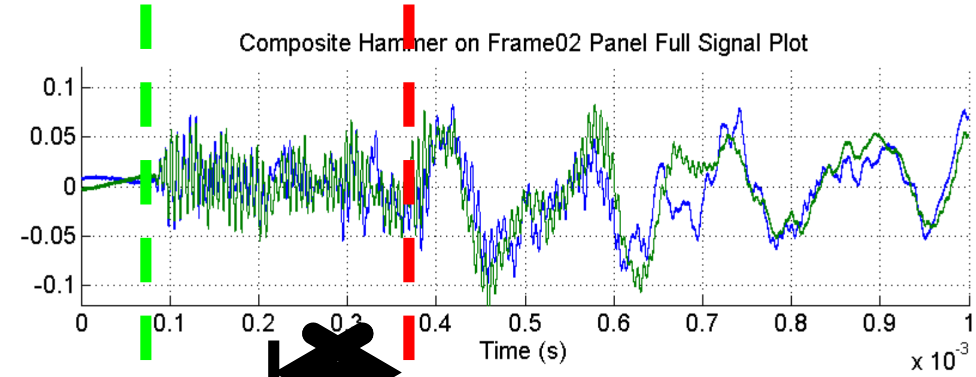
JOINT ADVANCED MATERIALS & STRUCTURES CENTER OF EXCELLENCE

Advanced Materials in Transport Aircraft Structures

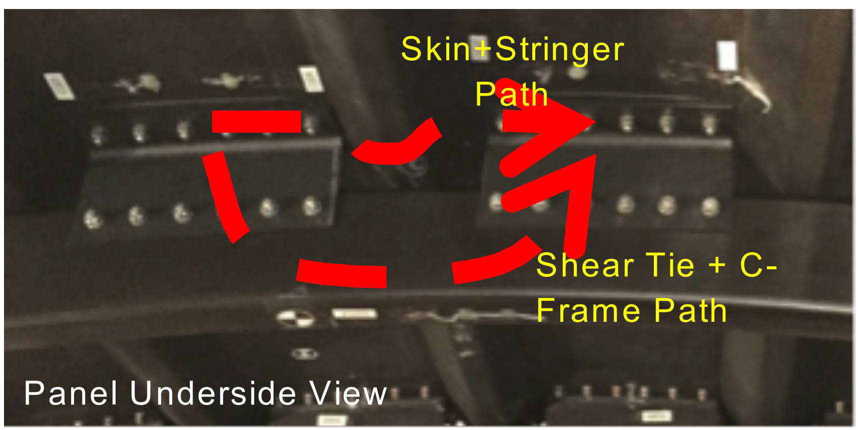
Mini Impactor on Composite Panel

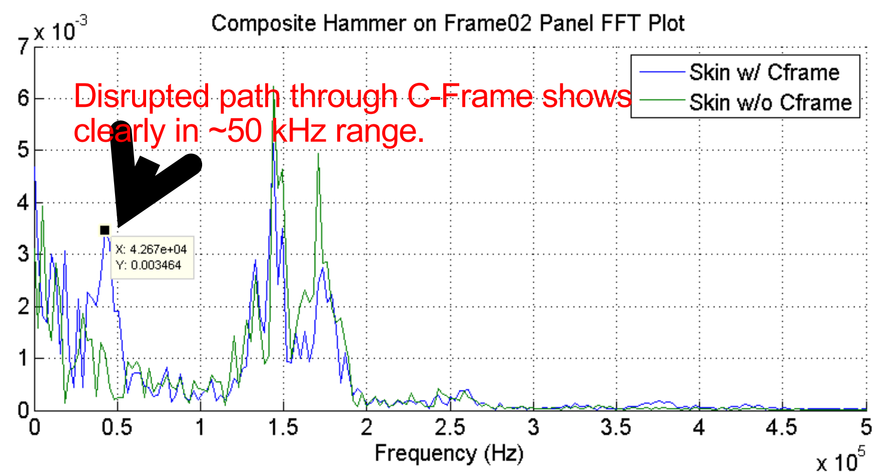
- Gating of time signal important for capturing different modes of interest – specifically those passing through frame.
- FFT shows clear sensitivity to disrupted path (C-frame detached at bolts to represent being fully cut)





Includes A0 modes through C-Frame path

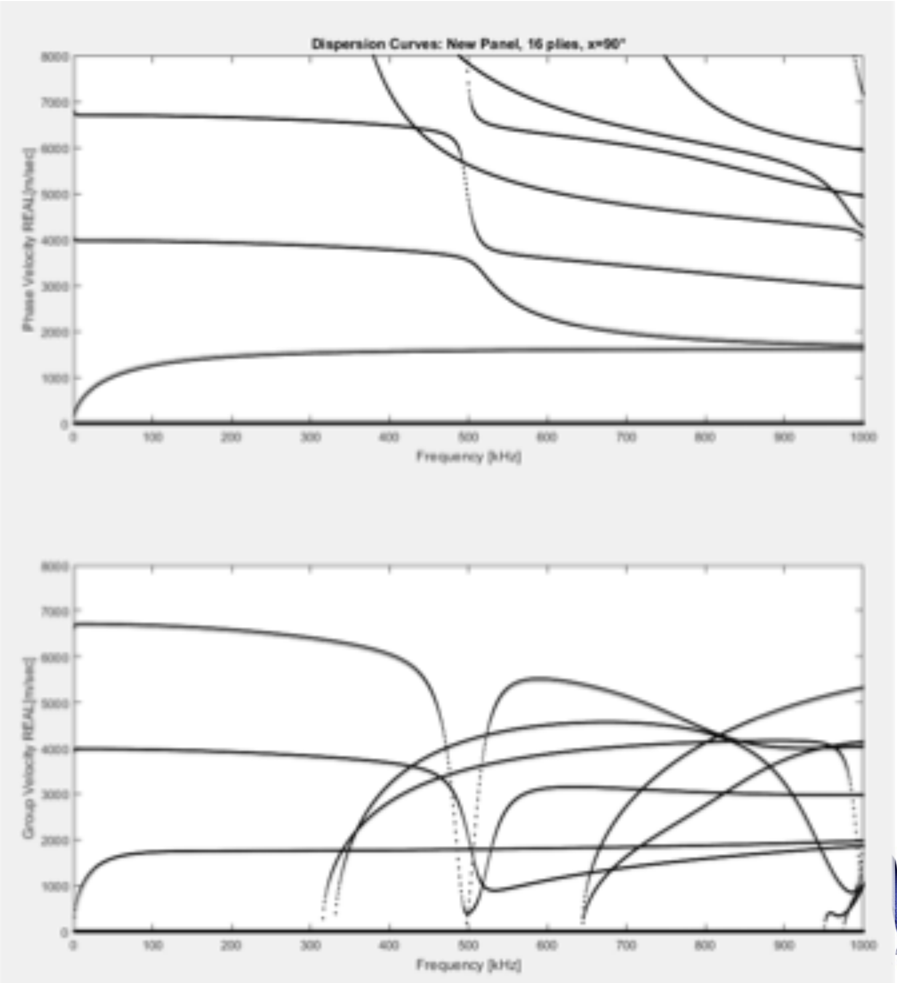


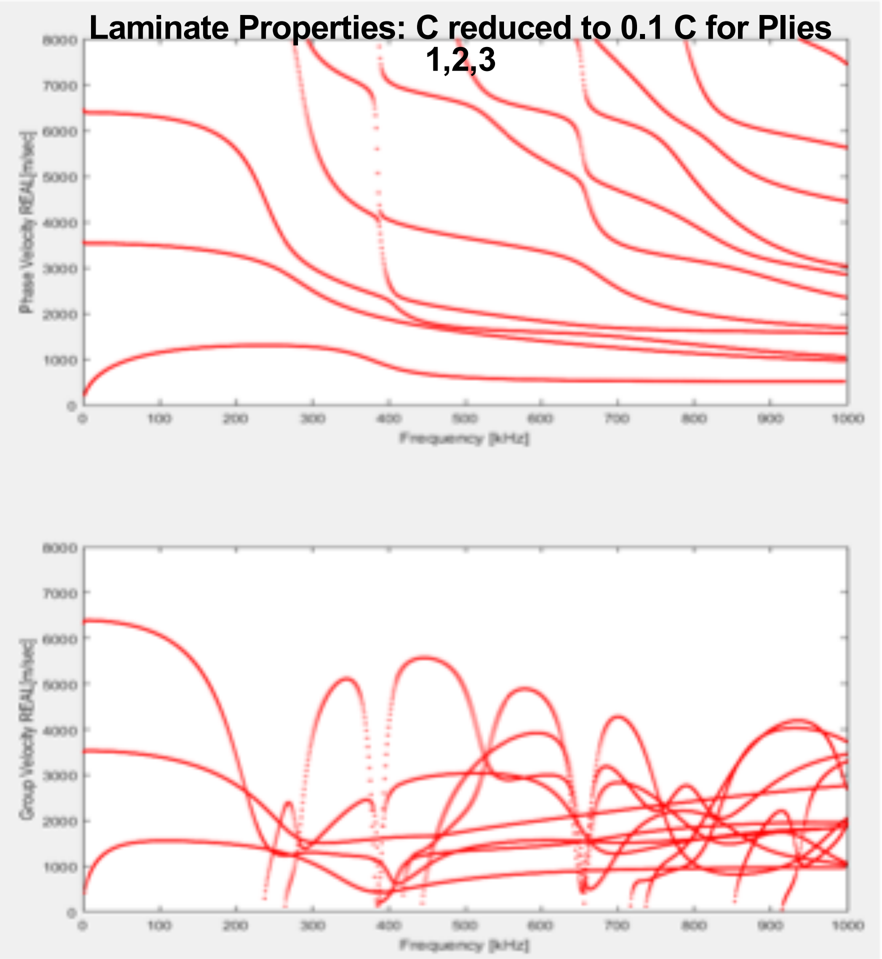


SAFE Results: CFRP skin

Stiffened Panel: Skin Surface Damage

- Wave propagation direction: 90° (across the stringer)
- Layup: 16 plies (Skin only)
- Lamina Properties: T800/3900-2 Unidirectional Tape



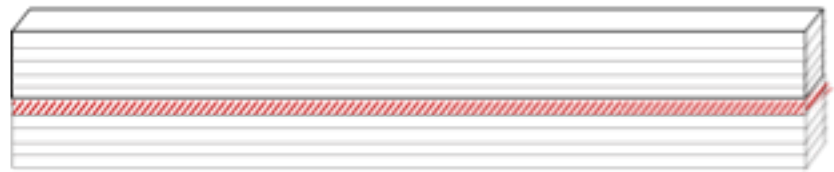


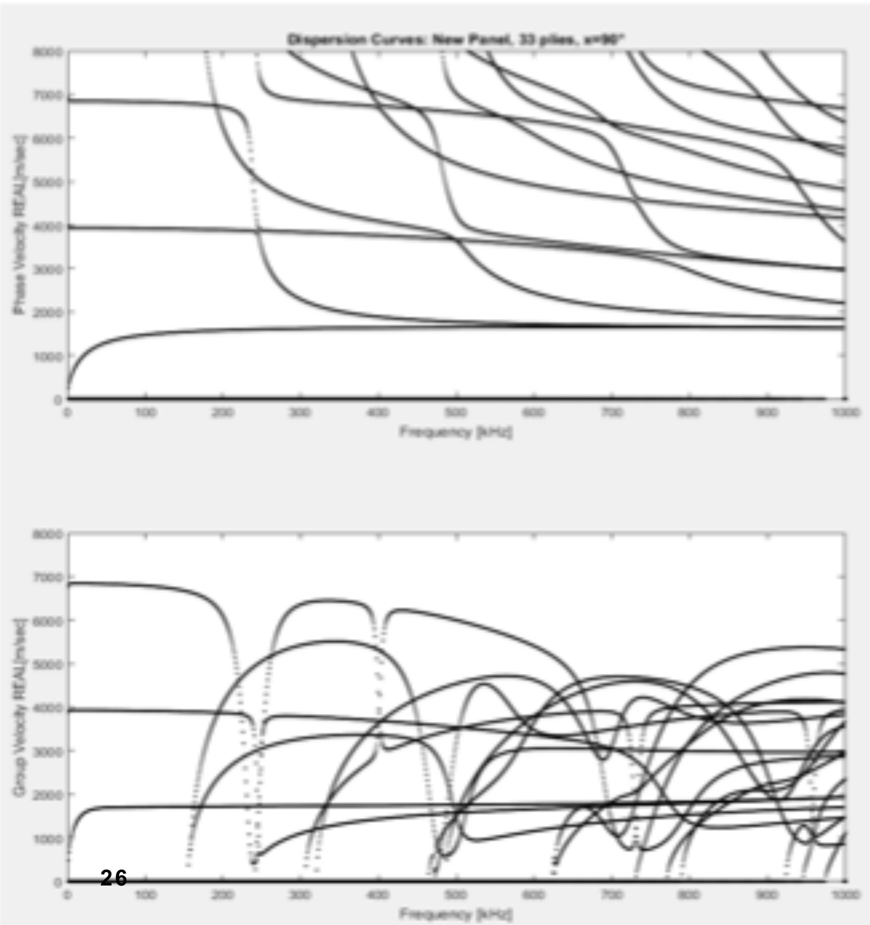
SAFE Results: CFRP skin+stringer

Stiffened Panel: Stringer Disbond Damage

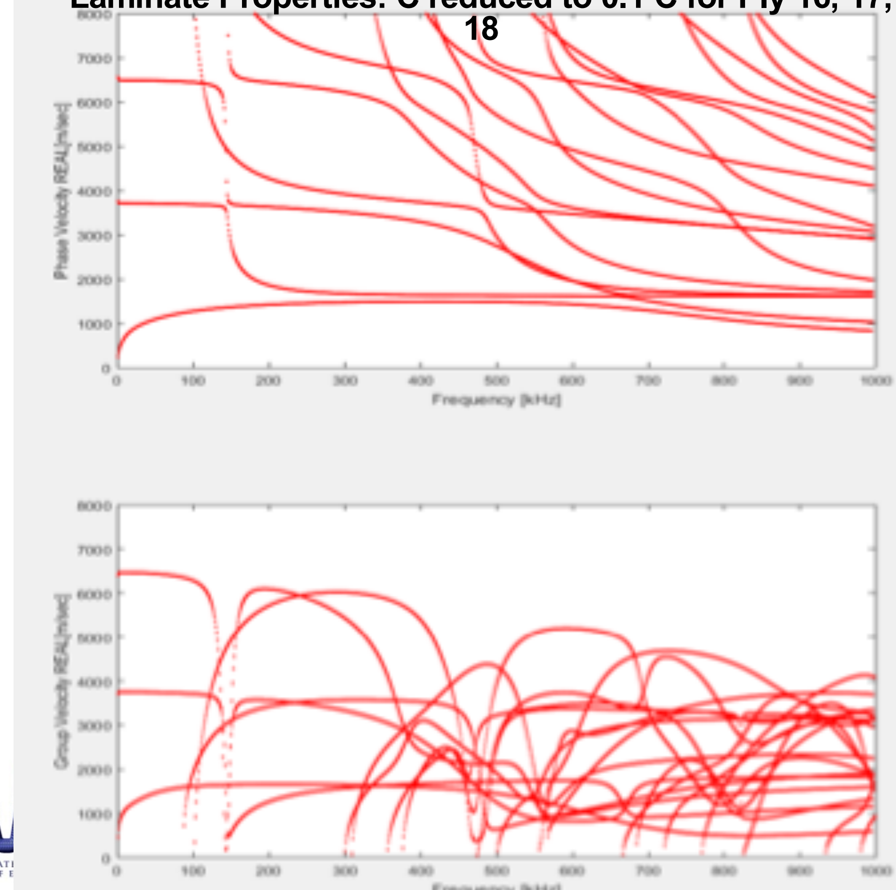
- Wave propagation direction: 90° (across the stringer)
- Layup: 33 plies (Skin & Stringer)
- Lamina Properties: T800/3900-2 Unidirectional Tape

Properties Ply 16,17,18 Degraded





Laminate Properties: C reduced to 0.1 C for Ply 16, 17, 18

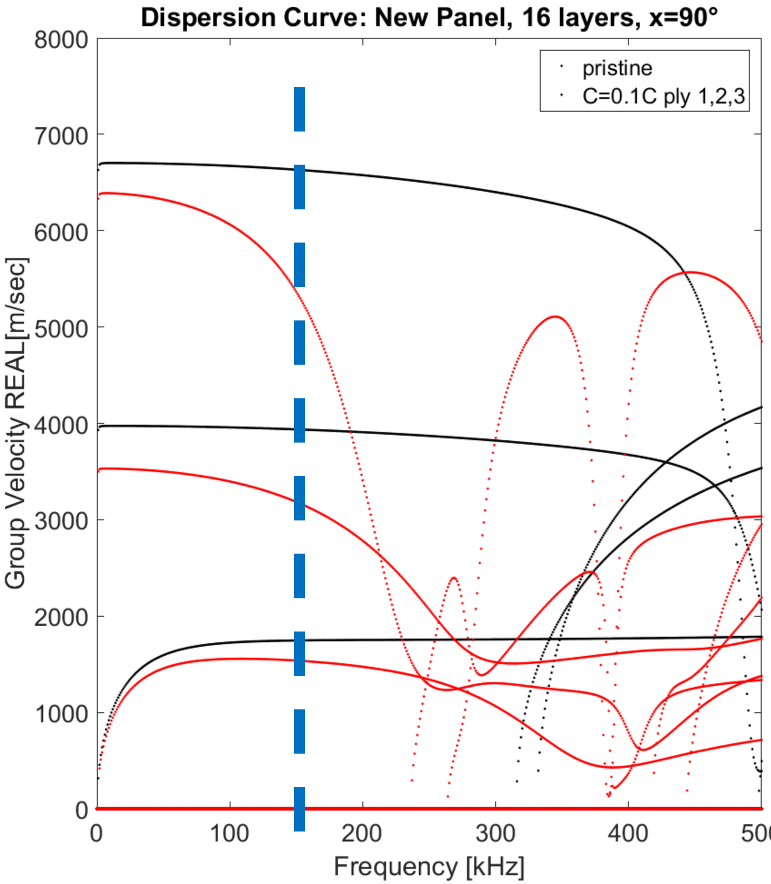


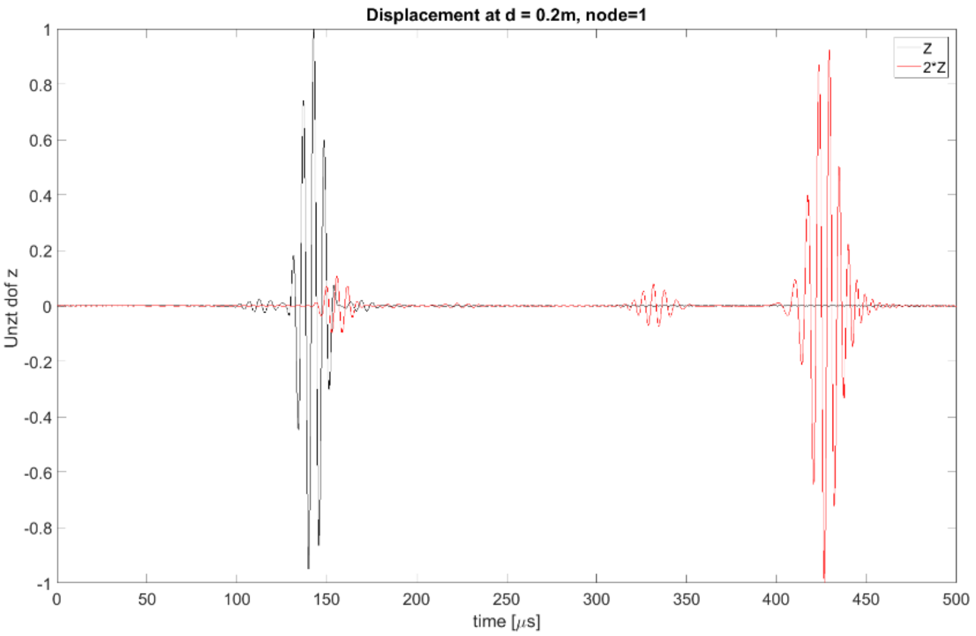
SAFE Results: CFRP skin

Stiffened Panel: Skin Surface Damage

- Wave propagation direction: 90° (across the stringer)
- Layup: 16 plies (Skin only)
- Lamina Properties: T800/3900-2 Unidirectional Tape

Properties Ply 1,2,3 Degraded



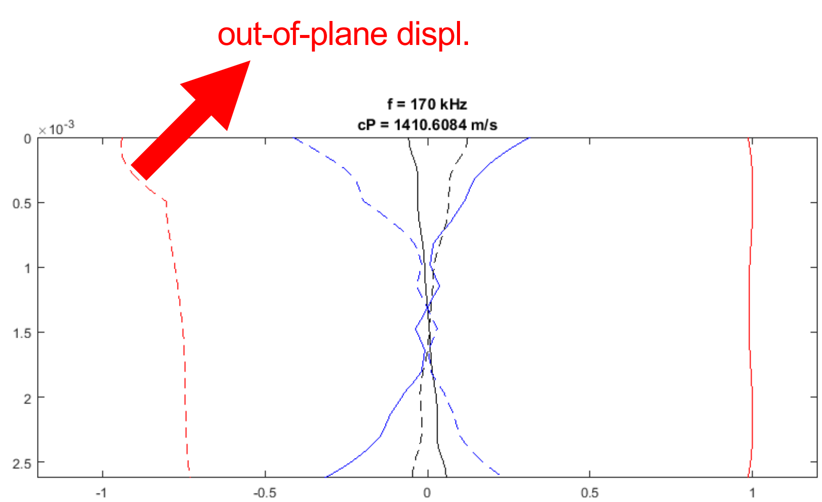


SAFE Results: CFRP skin

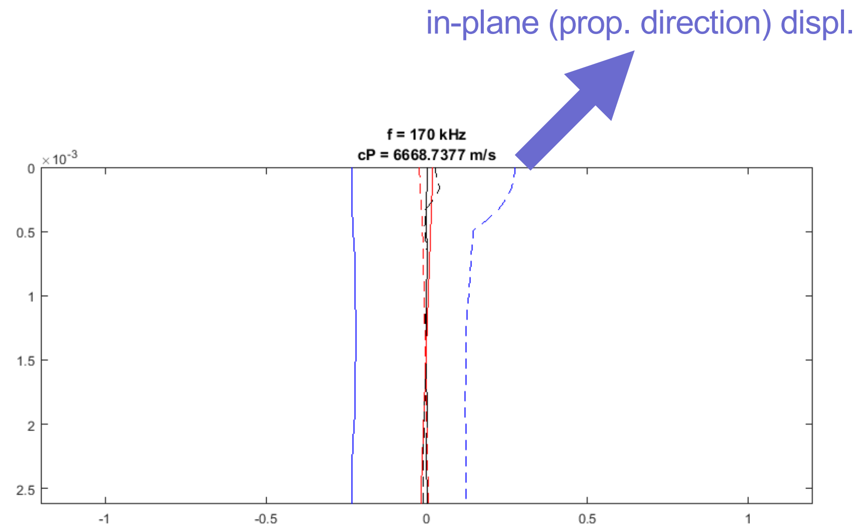
Stiffened Panel: Skin Surface Damage

- Wave propagation direction: 90° (across the stringer)
- Layup: 16 plies (Skin only)
- Lamina Properties: T800/3900-2 Unidirectional Tape

Laminate Properties: C reduced to 0.1 C for Ply 1,2,3



A0 modeshape

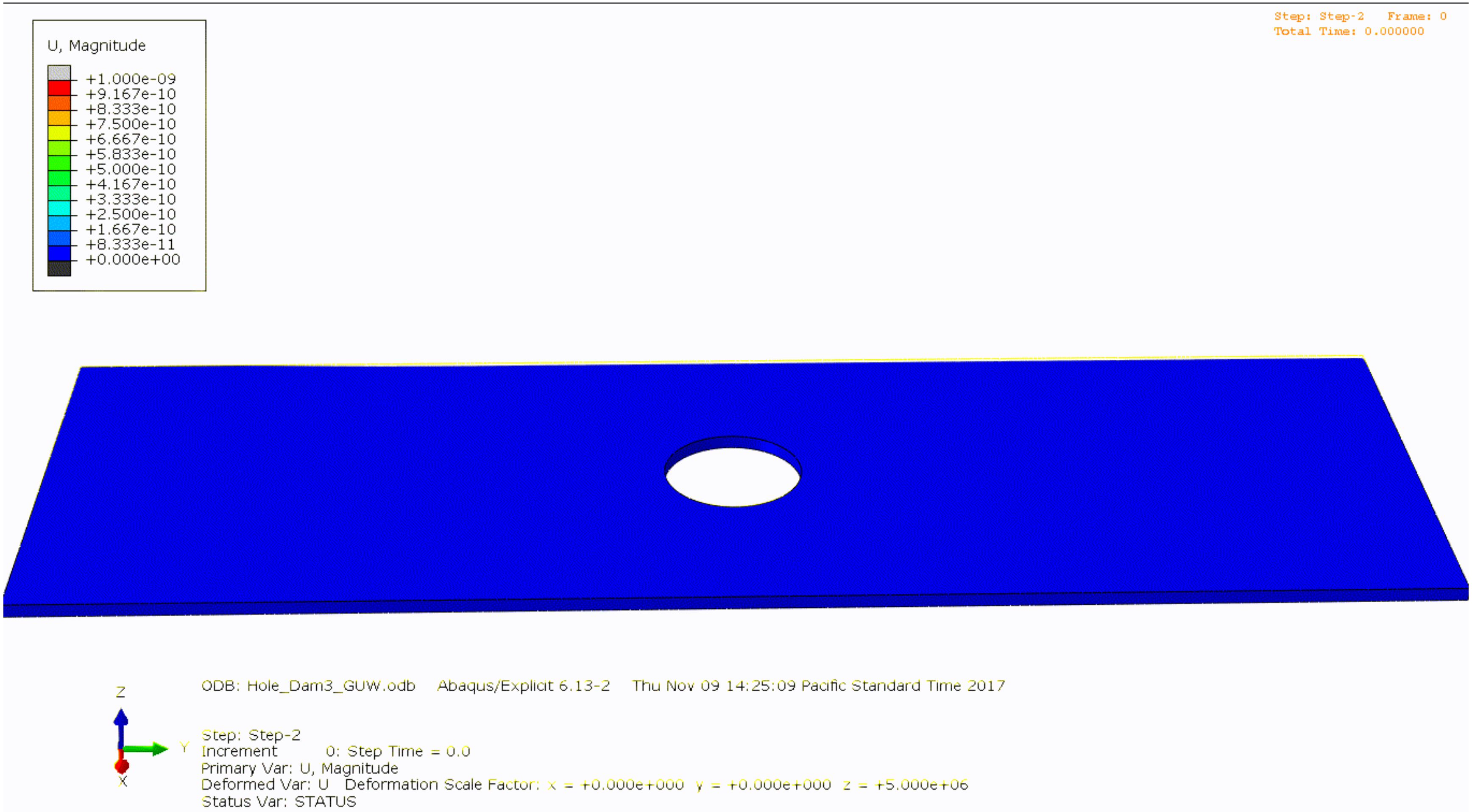


S0 modeshape

CECAM JAMS AMTAS

Residual Strength Estimation: Wave Attenuation Based

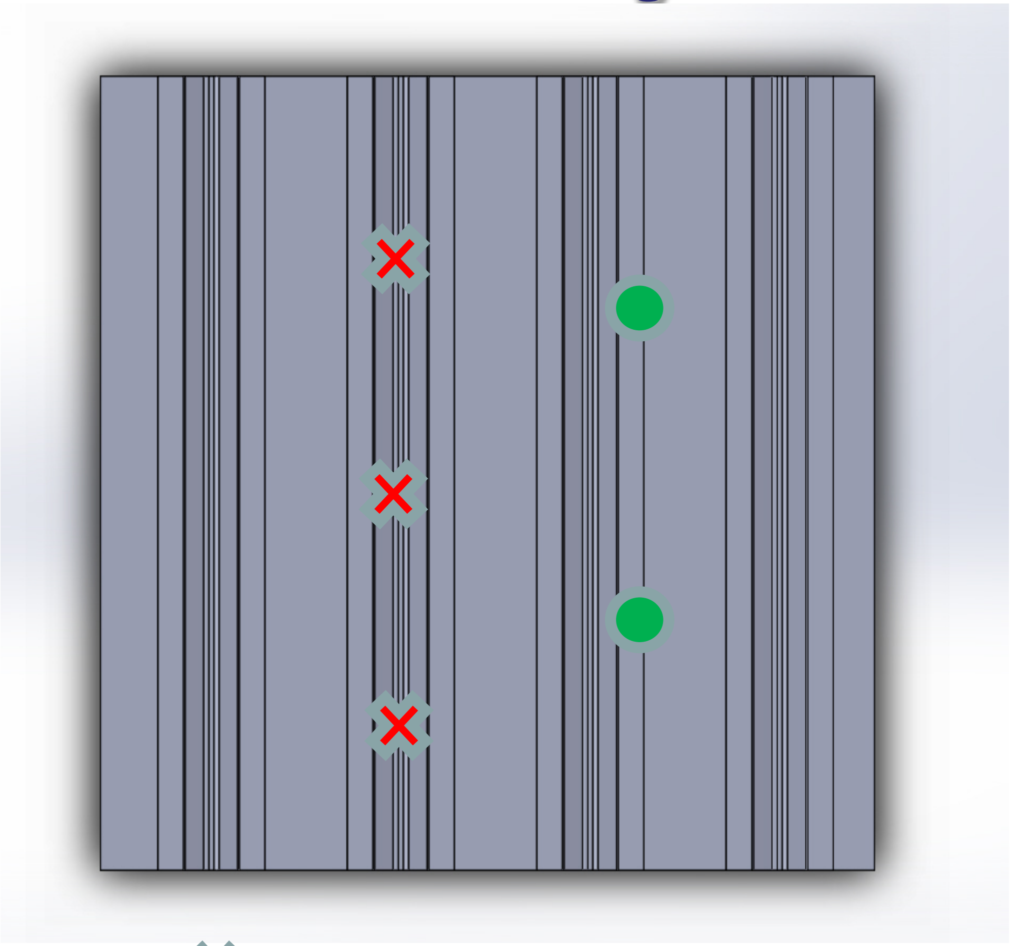
- Amplified out-of-plane displacement to observe A0 wave mode propagation around the hole notch
- Notch diameter = 30 mm



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