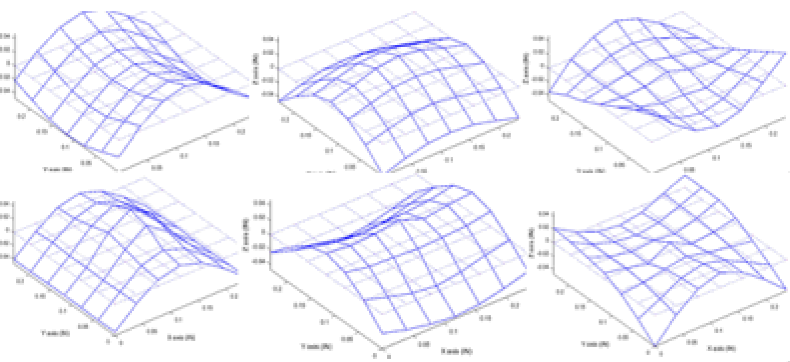

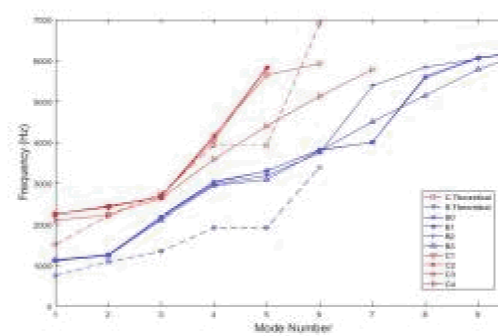

An NDE Approach to Composite Material Impact

Damage Initiation and Growth Process

David G. Moore, Tim M. Briggs and Mike D. Jev

MIDN Mathew ‘Matt’ Kautzman and Paige Furlong, USI

SAND2018-7936C

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Background

- Develop a testing/inspection strategy to efficiently survey a composite structure for the full life-cycle.
- Introduce damage into a composite sample under a known load condition, inspect the samples with traditional NDI techniques.
- Determine the relationship between damage, dynamic frequency response, mode shape, and damping of a carbon fiber composite material and the use of inspection techniques.

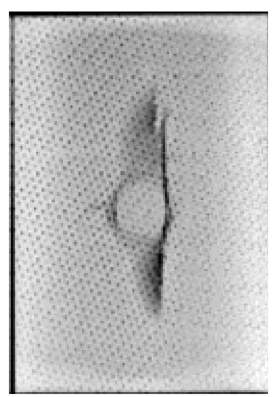
Why use composites?

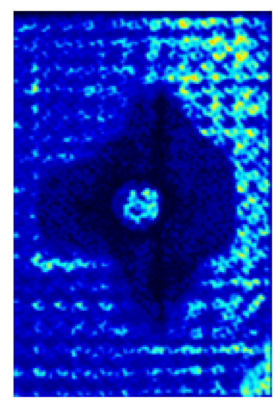
- Typical Composites
  - Glass
  - Carbon
  - Aramid
  - Epoxy

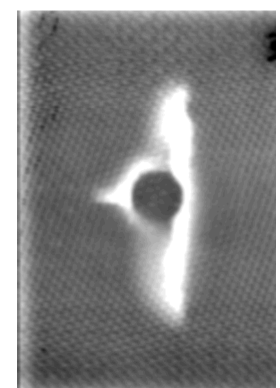
Fiberglass. 2016. *Fins'nTales*. Web.

Kevlar Rope. 2016. *China's Senior Supplier*. Web.

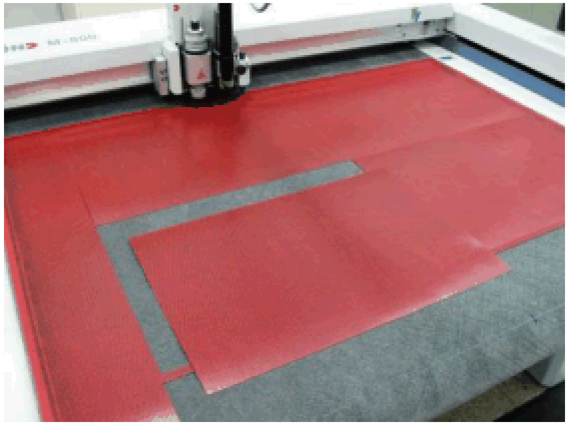
- Benefits: high strength to weight ratio, fatigue resistance
- Challenges: transverse loading deficient, subsurface damage, and delamination
- Damage detection techniques for composite structures
  - Visual
  - Optical
  - **Ultrasonic**
  - Acoustic
  - **Radiographic**
  - Thermal
  - **Modal Analysis**



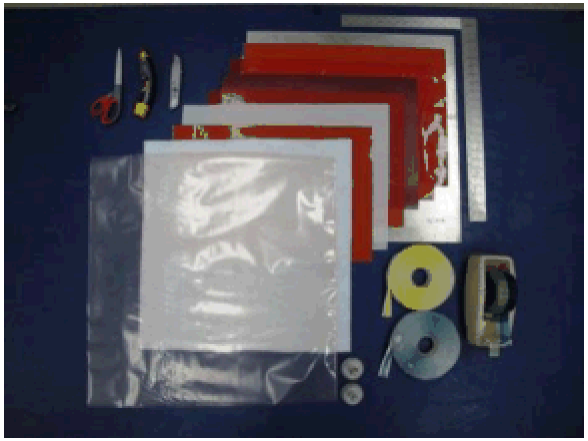




Specimen Fabrication

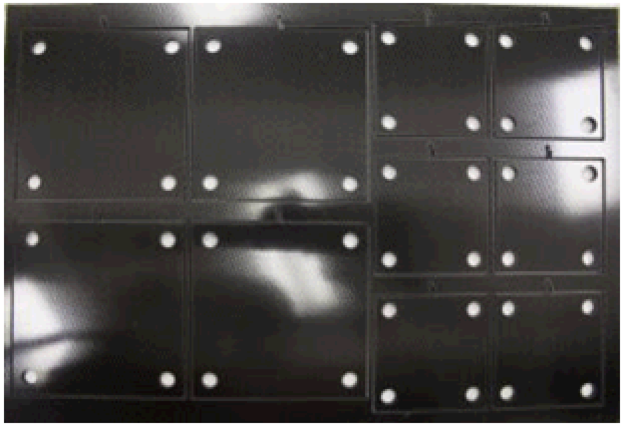


4-Axis CNC Ply Cutting



Layup Kits for Laminates

Panels Autoclave Cured

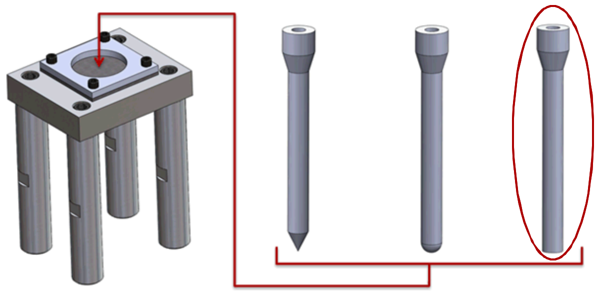


Specimens Cut From Laminate

Thickness (mm.)	Ply Count	Stack Sequence	Square Dimension (mm.)
4.2	12	[(0/90)6]s	152
8.4	24	[(0/90)12]s	152

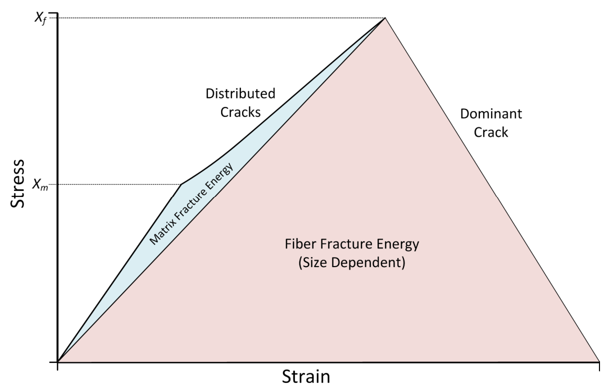
Boundary Conditions

- Existing orthotropic material models either do not consider damage or use a fully interactive damage criteria
- Our model divides material behavior into 3 sections:
  - Linear elastic
  - Distributed damage (hardening often associated with matrix cracking)
  - Localized damage (softening often associated fiber breakage)
- Damage initiates according to a partially-interactive strain based failure criteria

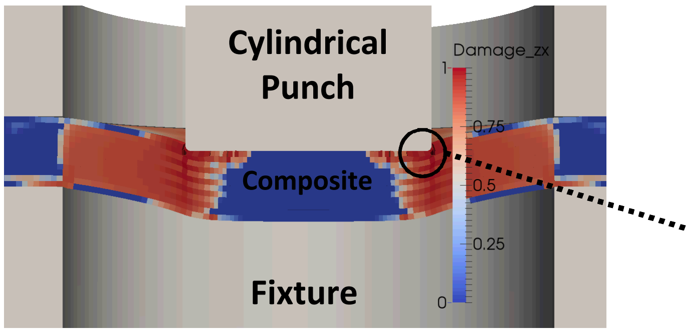


For this investigation, we are focusing on the flat cylindrical punch.

Indentation experimental fixture



Idealized Stress-strain response showing damage while loaded

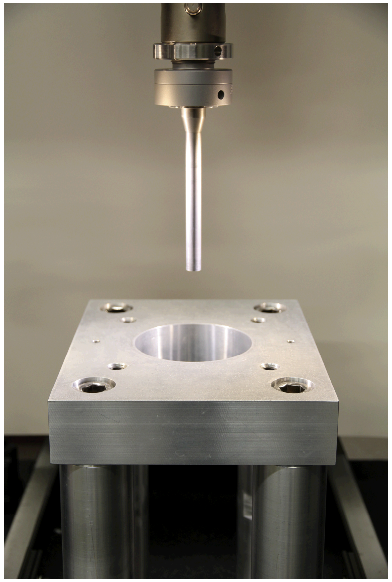


Cylindrical punch simulation example with out-of-plane shear damage

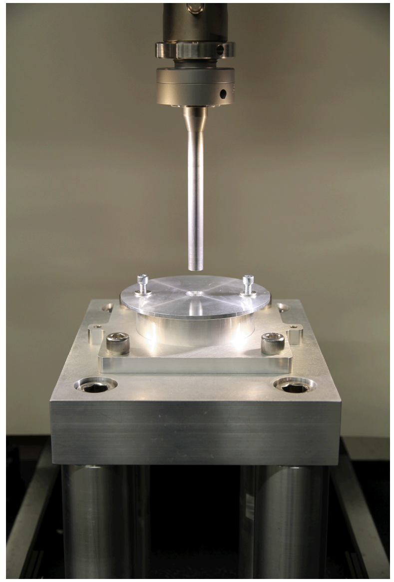
"This highly localized event may not be feasible to model with standard 3D finite elements due issues associated with mesh dependence and model size. Surface localization elements, such as CZEs, can possibly be used to better predict the localized out-of-plane shear failure."

Briggs, Timothy, Shawn Allen English, and Stacy Michelle Nelson. "Quasi-Static Indentation Analysis of Carbon-Fiber Laminates." (2015)

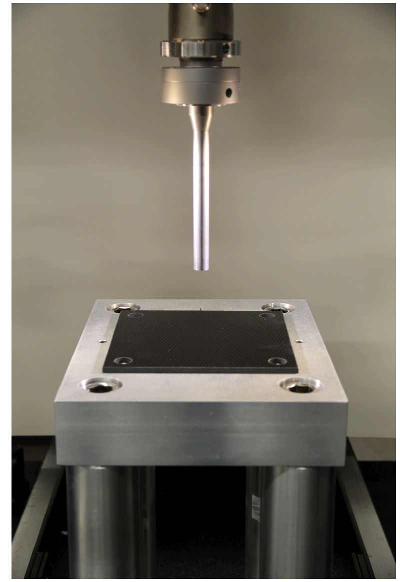
Test Configuration



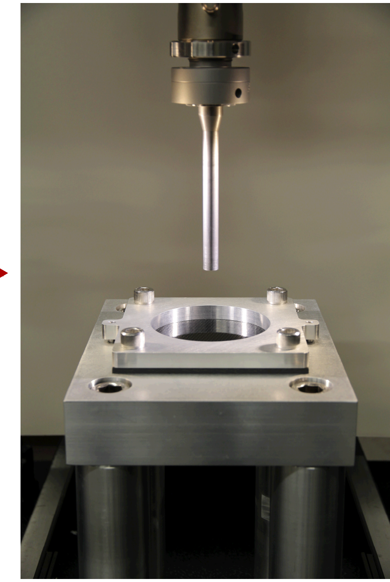
Mount Bottom Plate



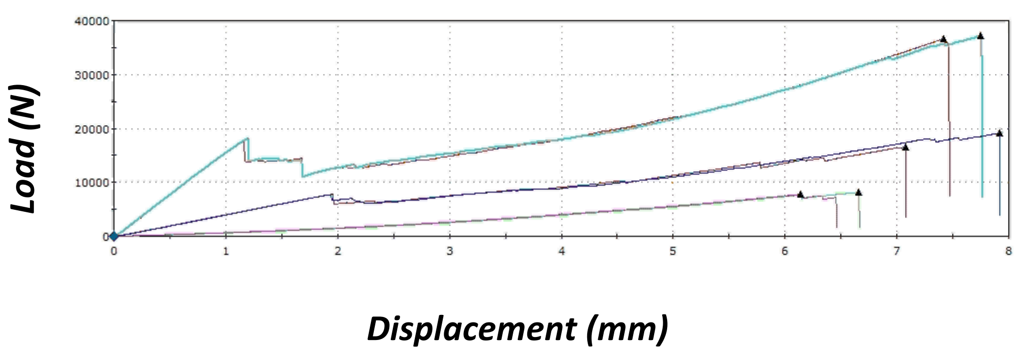
Alignment Bushing

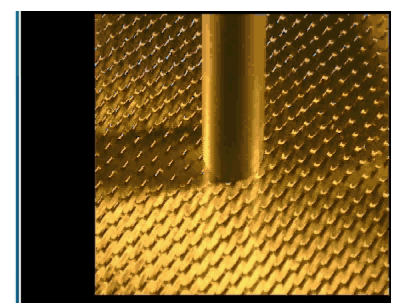


Mount Specimen



Clamp and Test

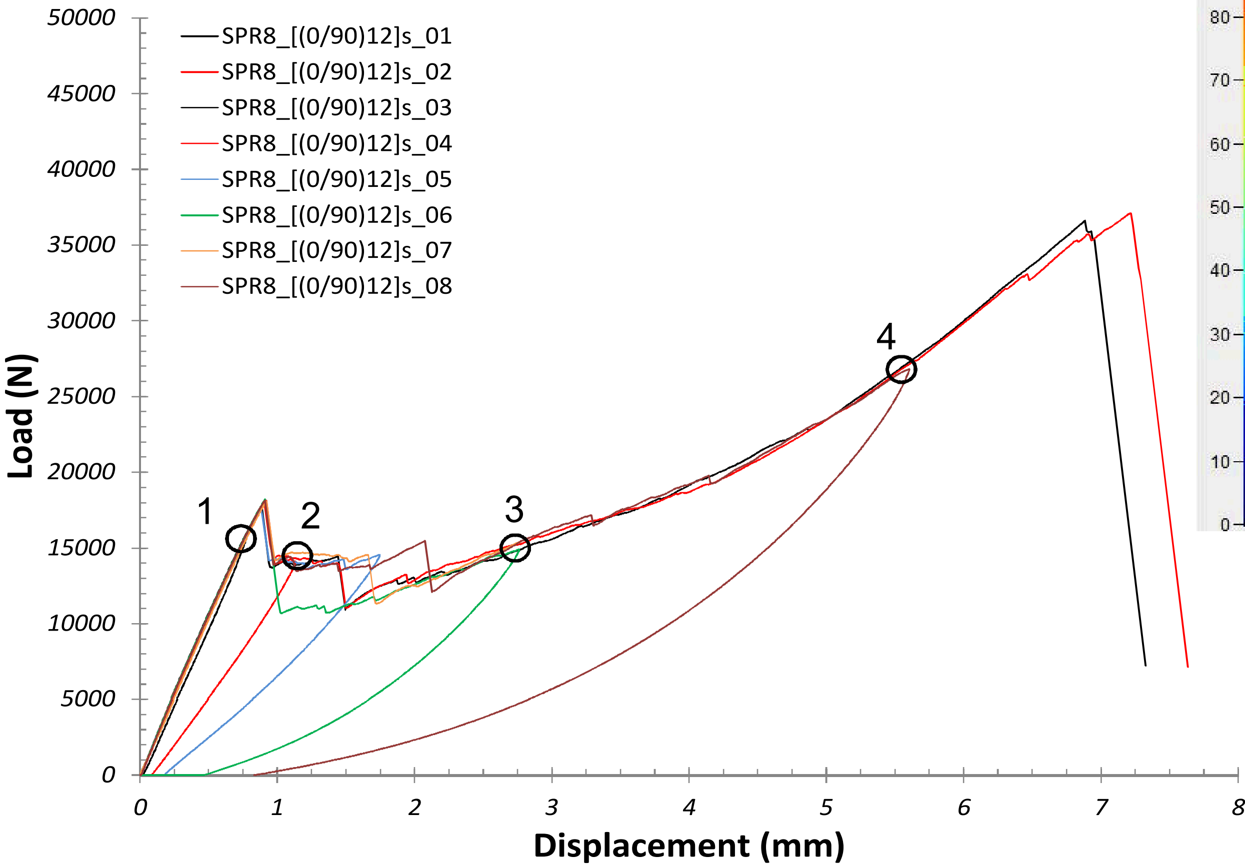


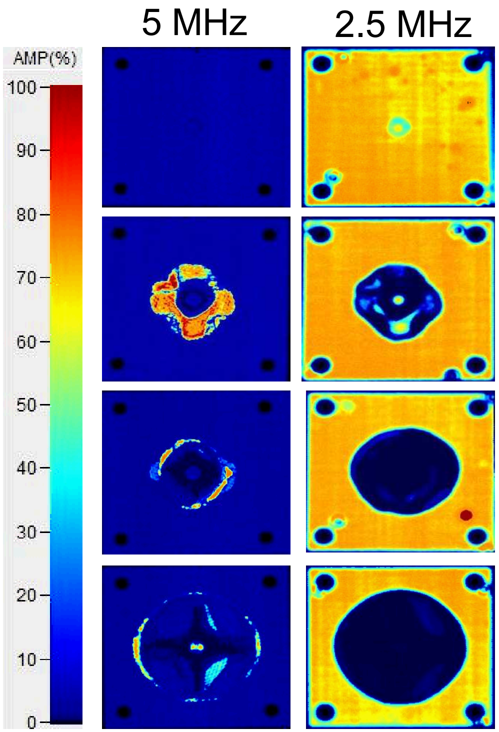


Specimen surfaces show little detail of damage

Damage and Growth

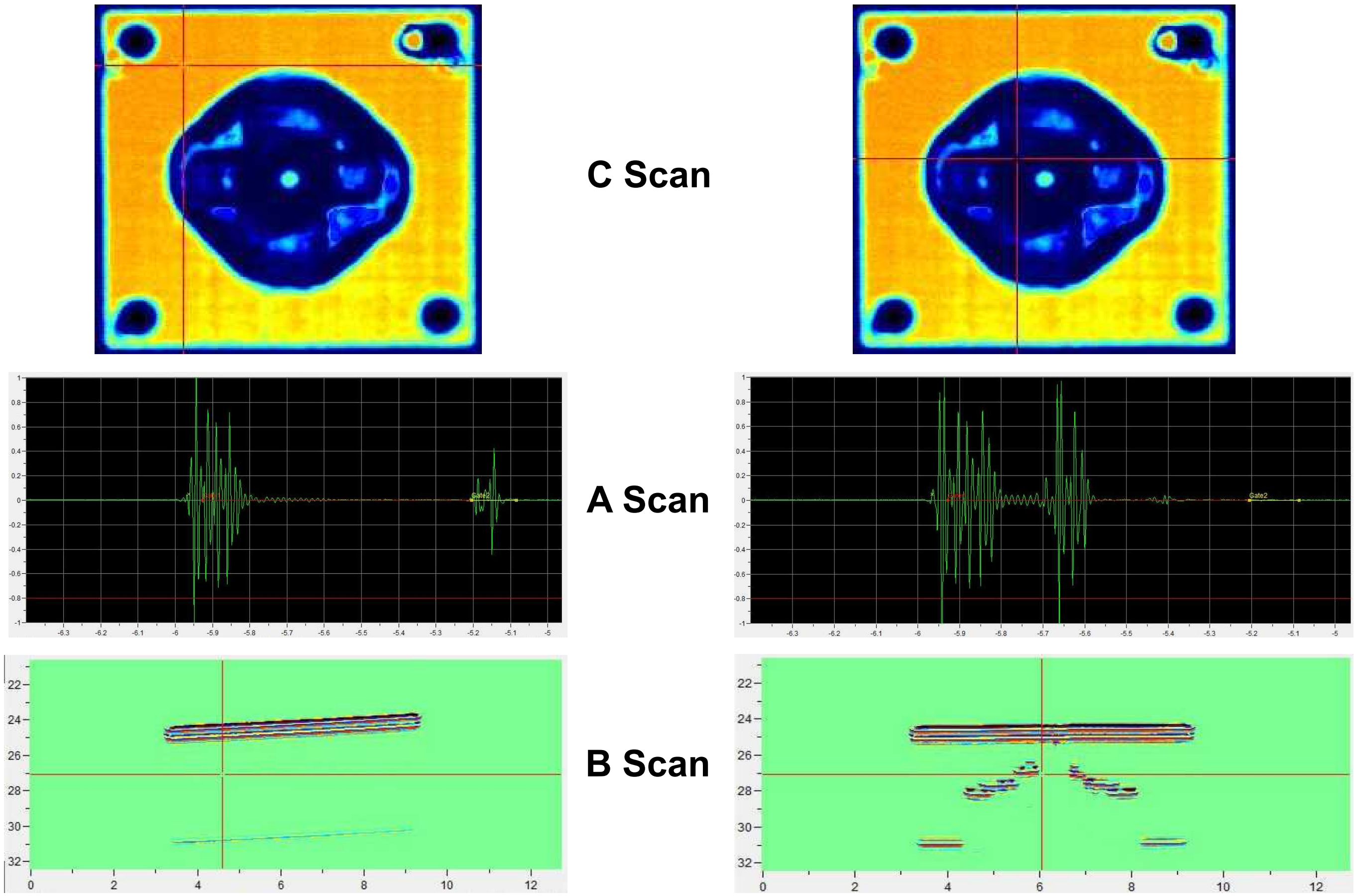
By systematically increasing the level of loading to regions of 'interest,' an understanding of the damage time sequence of events can be determined (24 Ply).

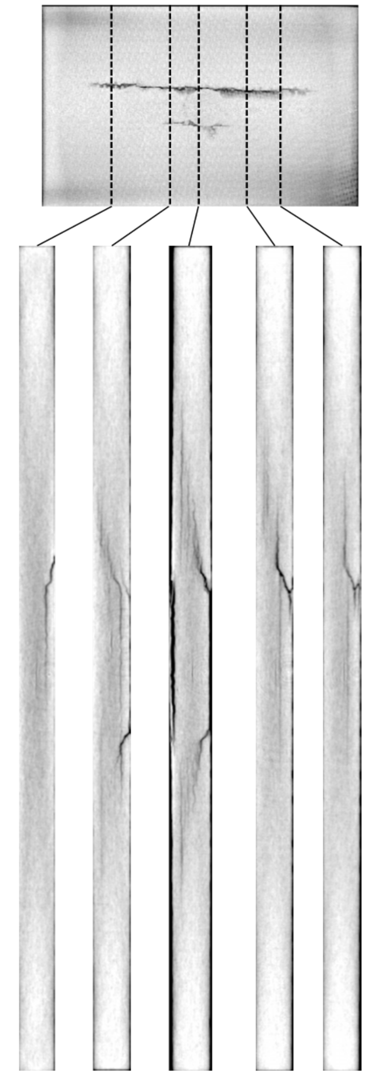




The nature and spatial variation of the damage is difficult to define using traditional ultrasonics.

Ultrasonics versus Computed Tomography

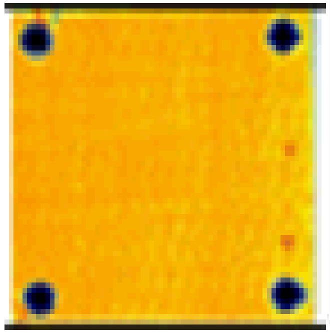




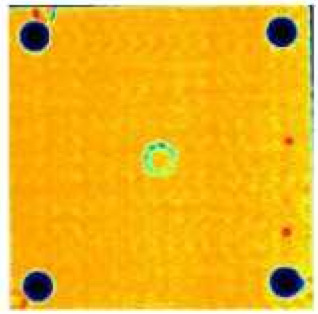
Although some spatial variation can be determined from signal attenuation, additional insight is gained by CT inspection.

Damage Quantification

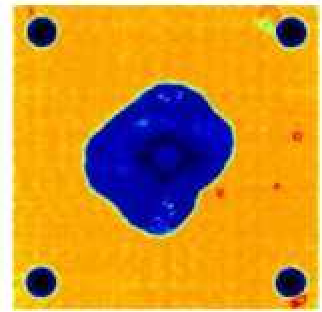
12-Ply



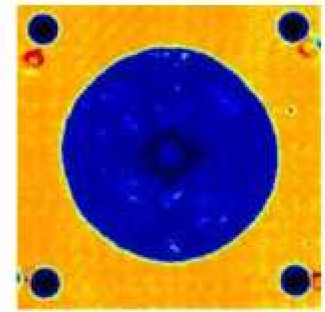
B0



B1



B2

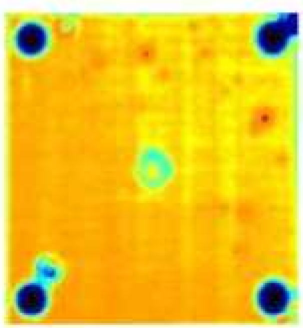


B3

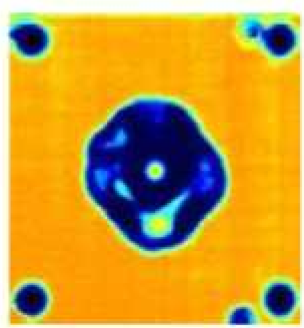
$$Q = \frac{A_{Damaged}}{A_{Total}}$$

Plate	B0	B1	B2	B3	C1	C2	C3	C4
$A_{damaged}$ (in^2)	0	0.262	6.07	14.5	0.427	6.67	12.5	16.3
Q (%)	0	1.60	37.0	89.0	2.61	40.8	76.2	100

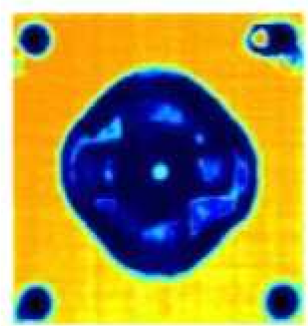
24-Ply



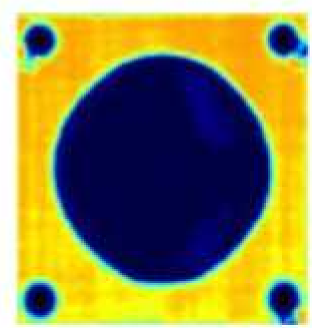
C1



C2



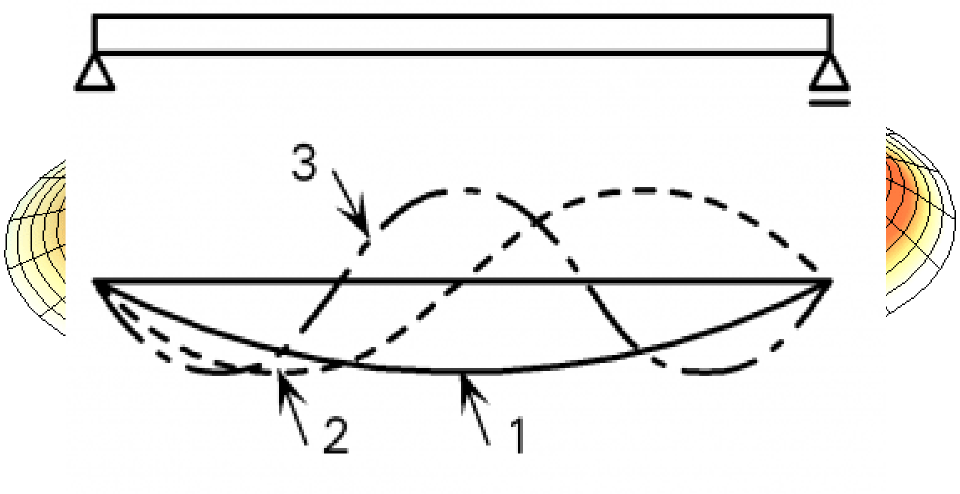
C3

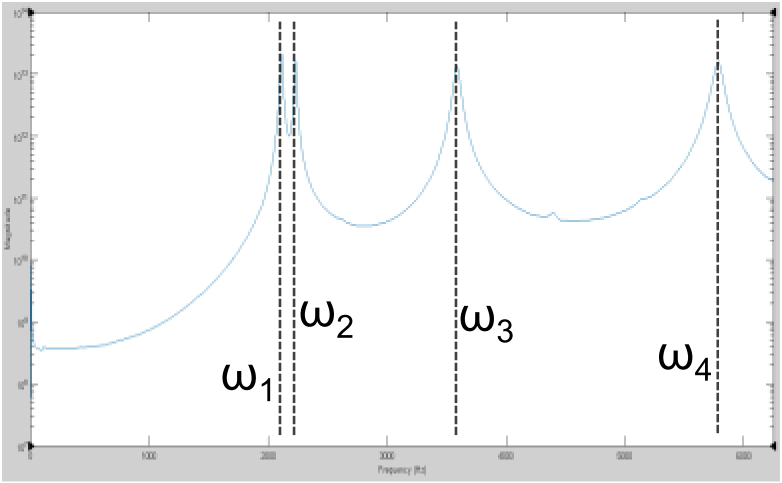


C4

Introduction—Mode Shapes

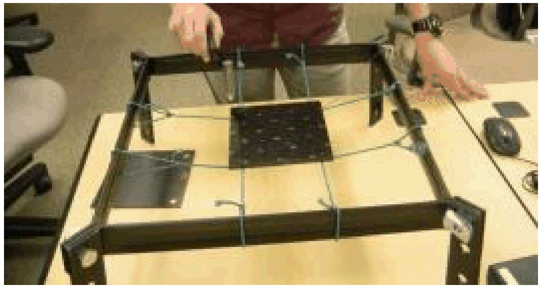
- Specific pattern of vibration that move sinusoidally at varying points
- All mode shapes are present at the same time, however are shown at different frequencies
- Each mode shape and correlating frequency depend on structure, material, and boundary conditions





Josić, Krešimir. *Mode Shape*. 2010. *CAN WE HEAR SHAPES?* Web.
Russell, Daniel A. *Circuluar Modes.* 1998. Pennsylvania State University, University Park. *Acoustics and Vibration Animations.* Web.
Coleman, Robert E. *Four Spring Modes*. N.d. Vibration Theory. *Signalysis: Delivering the Sound of Silence*. Web.

Experimental Approach

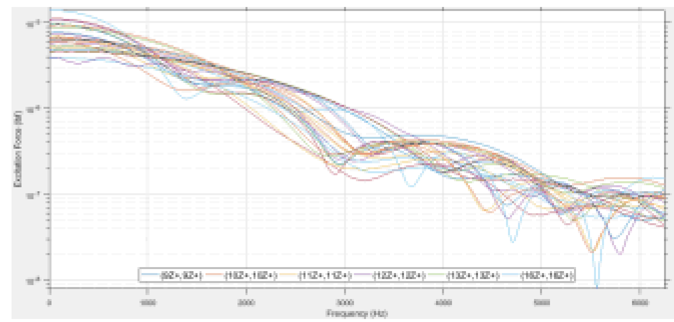


Grid System, Free Boundary Conditions

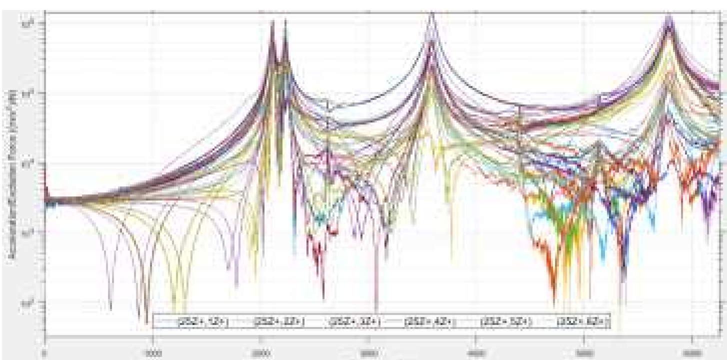
Mounted Accelerometer

Endevco 2250AM1 Accelerometer
Piezoelectric Quartz

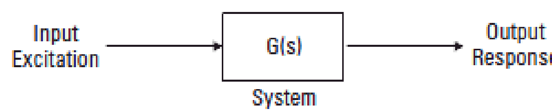
PCB 086C03 Modal Hammer



Modal Hammer Impulse Force



Frequency Response Measured Outputs



System Block Diagram

$$\text{Transfer Function} = \frac{\text{Output}}{\text{Input}}$$

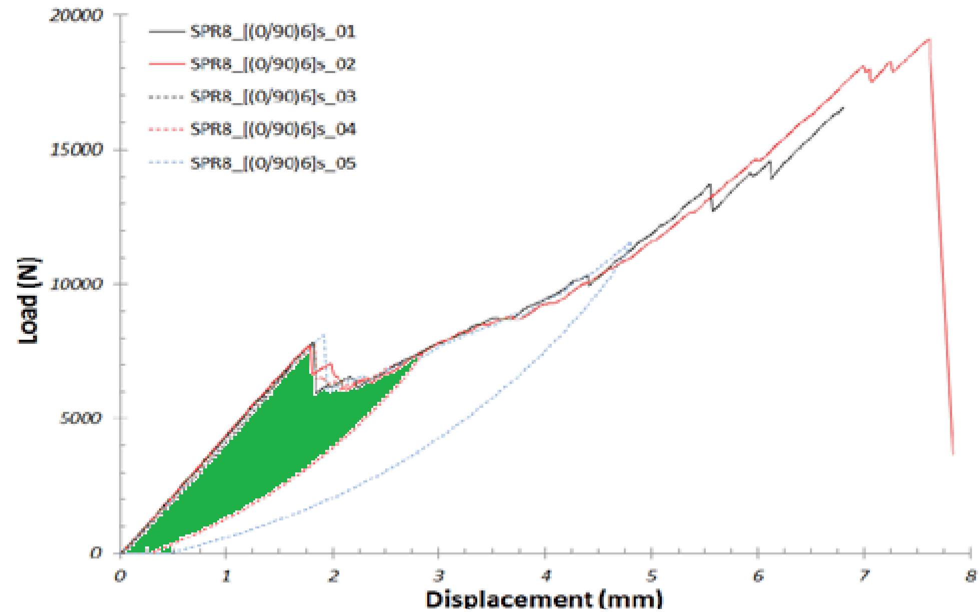
$$G(s) = \frac{Y(s)}{X(s)}$$

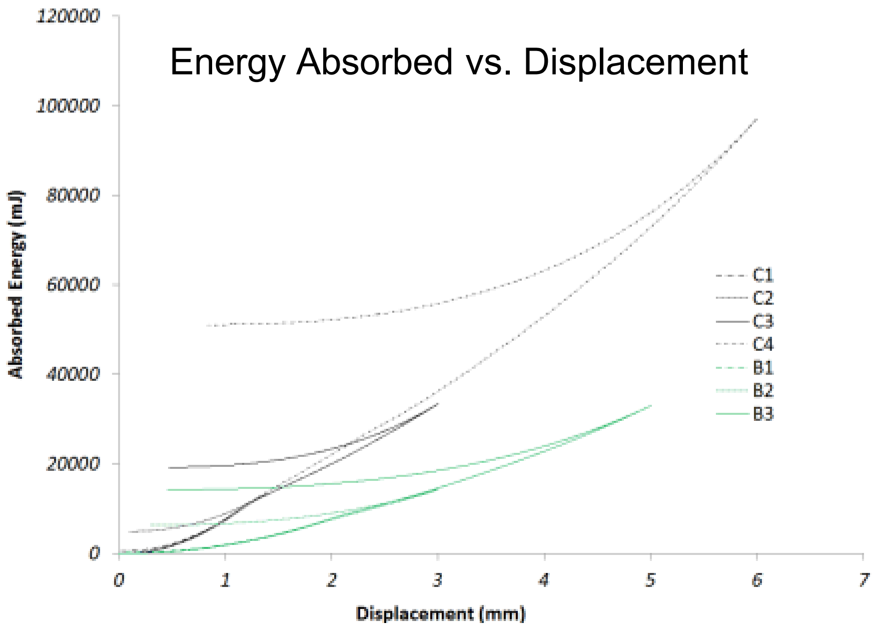
PCB 086C03 Modal Hammer. 2016. Dr. Ferenc Papai: Experimental Modal Analysis Equipment. *PCB Piezoelectronics*. Web.
"Agilent." *III-Vs Review* 17.5 (2004): 6. Web.

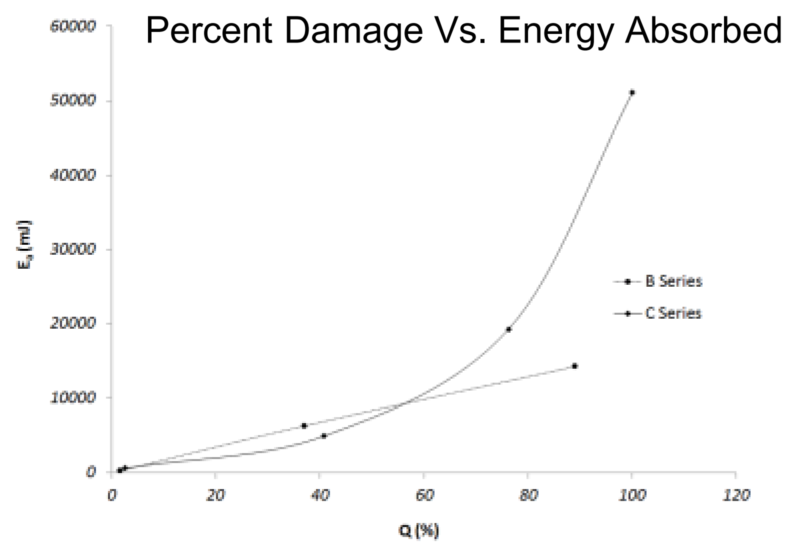
Energy Quantification

Absorbed Energy (E_A) defined as area under load displacement graph

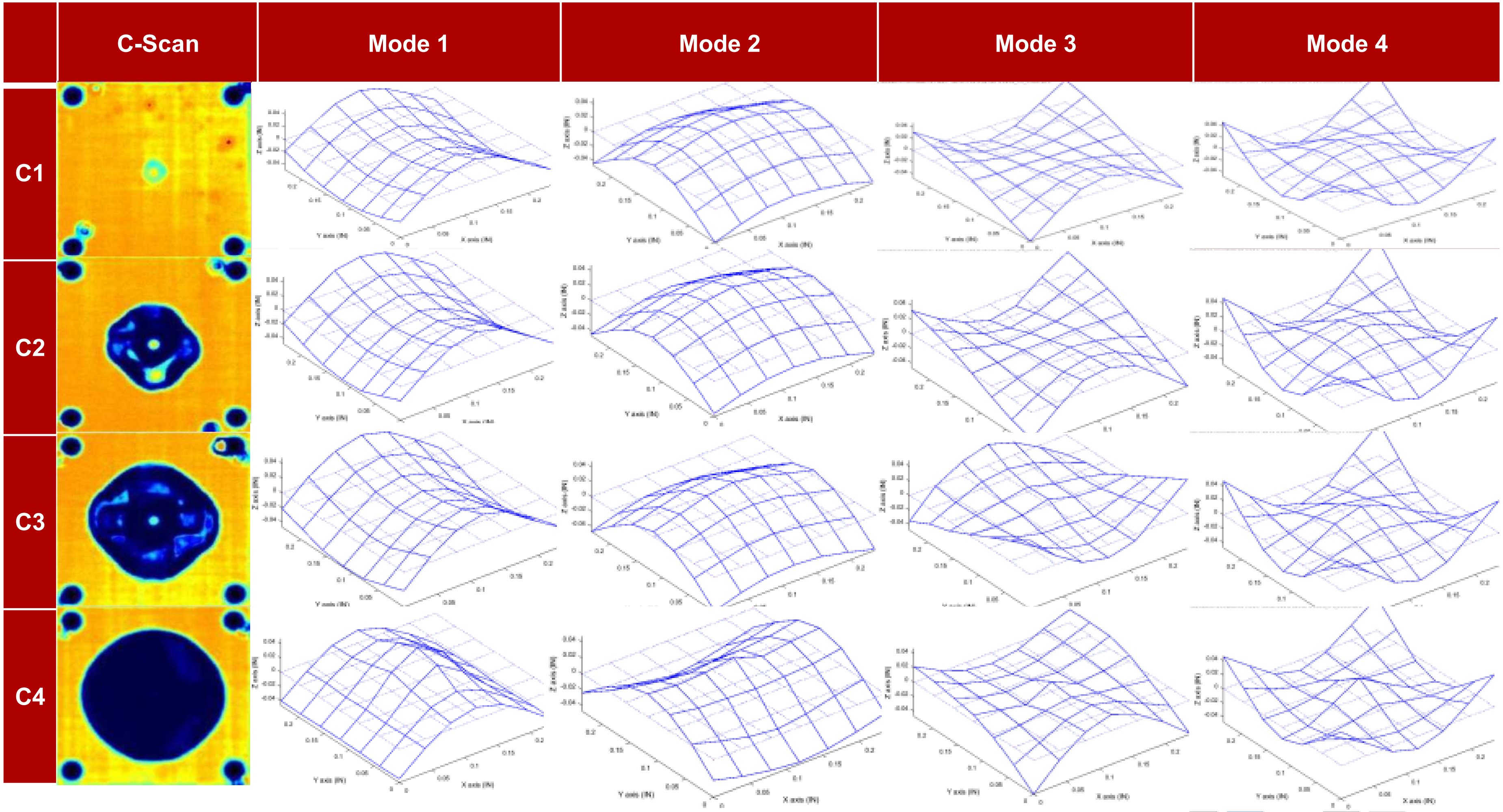
$$E_A = \int P d\delta$$





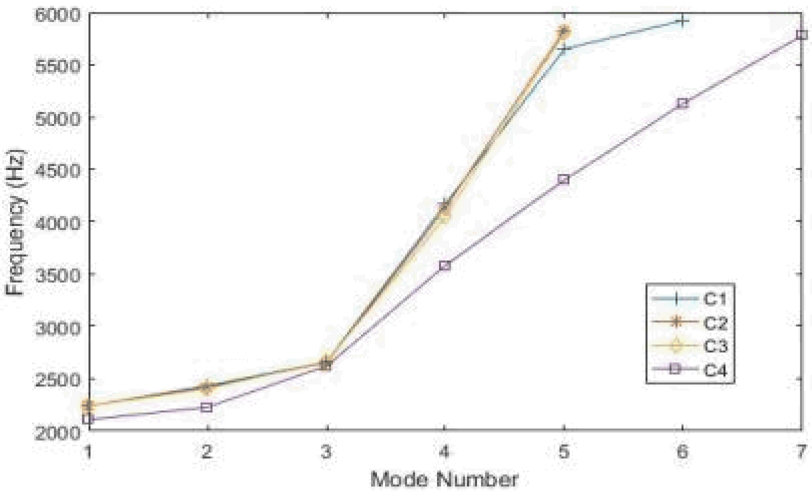


24 Ply Series Mode Shapes

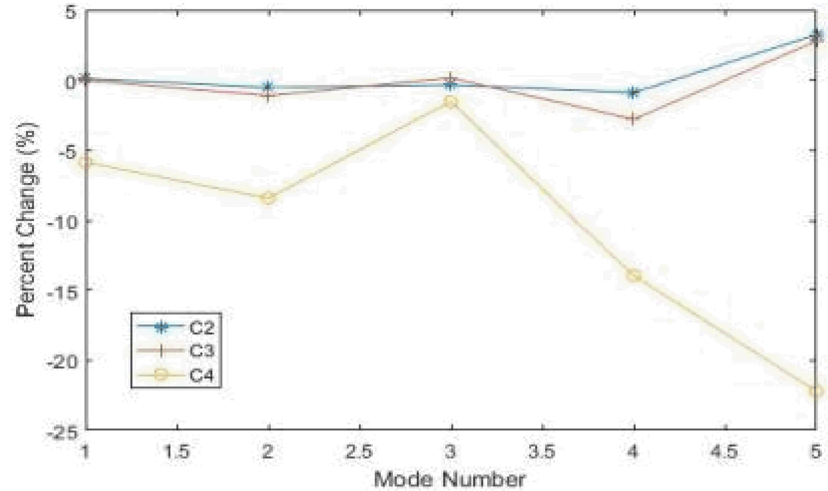


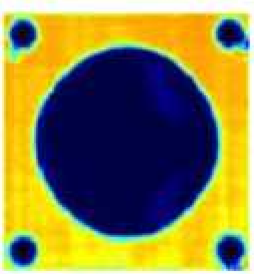
24 Ply Series Frequency

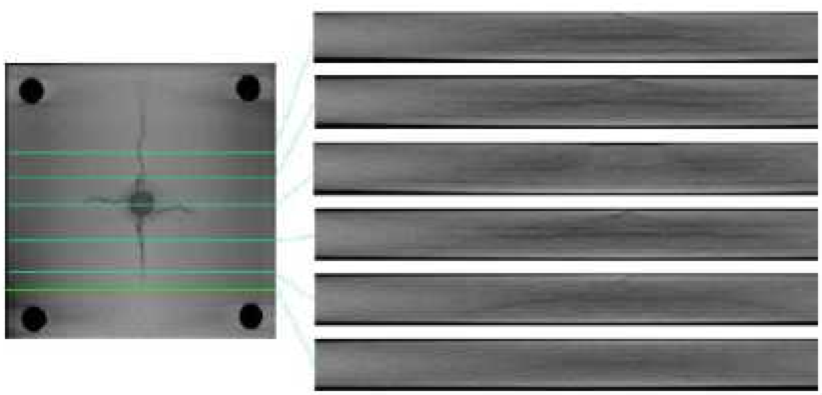
Frequency vs. Mode Number



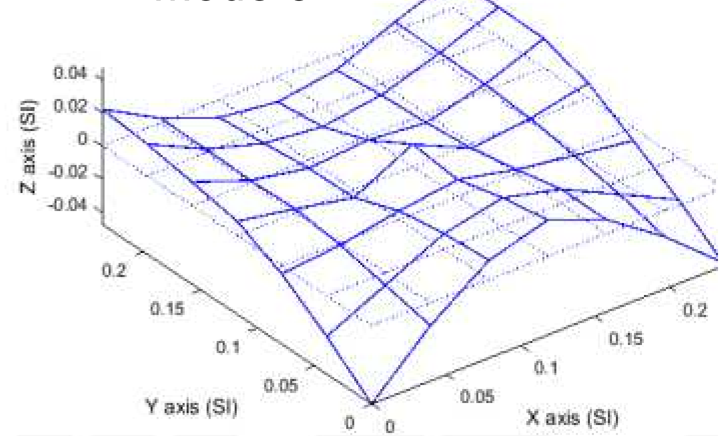
Percent Change of Frequency vs. Mode Number



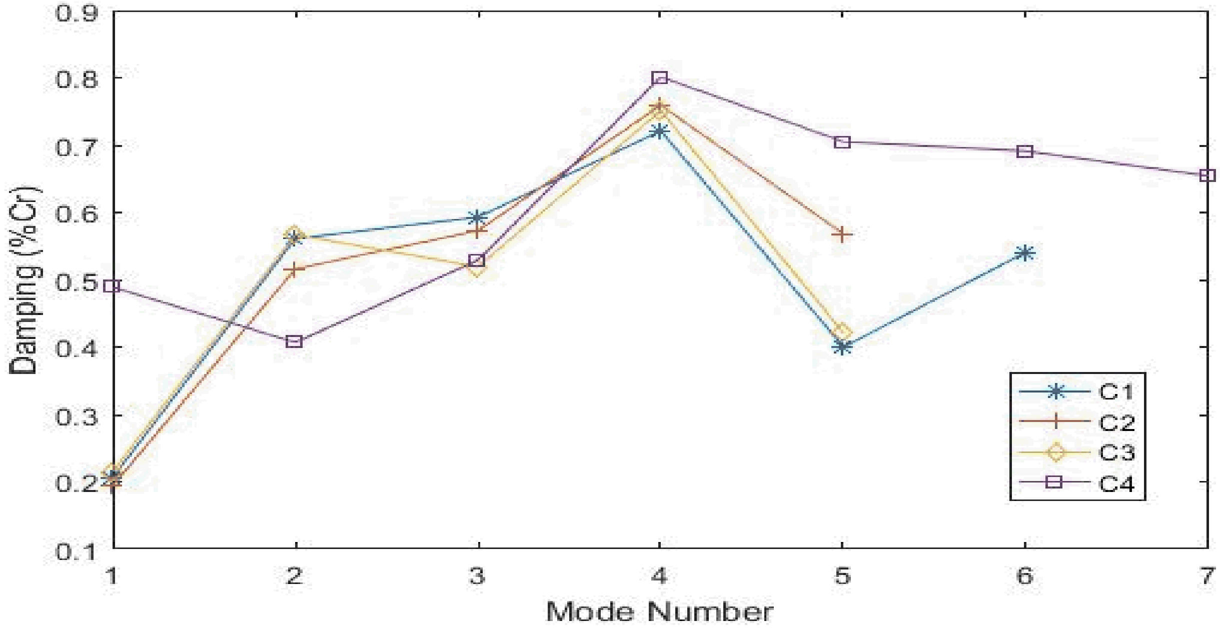




Mode 3

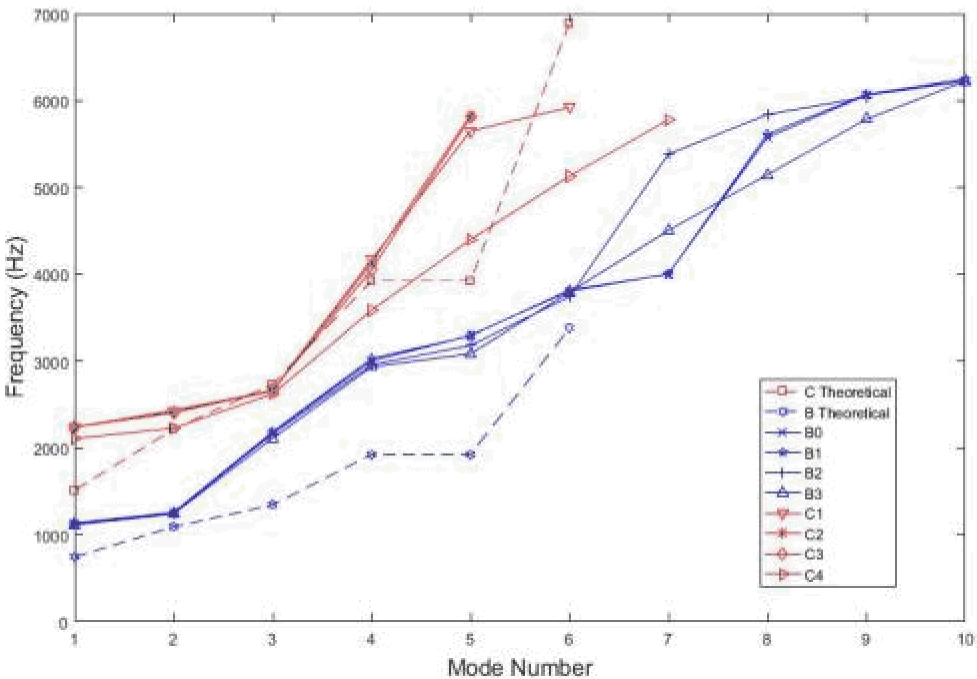


24 Ply Series Damping



- Critical damping has a similar increasing trend in magnitude for first 4 modes
  - This trend is consistent with the dynamic location of the mode shape and the potential for increasing frictional losses
- Damping magnitudes at mode 4 correlate with degree of damage
- All specimens show a decrease in damping from mode 4 to 5
  - However, mode shapes begin to differ at this transition

Comparison with Isotropic Theory



$$f_{ij} = \frac{\lambda_{ij}^2}{2\pi a^2}\sqrt{\frac{Eh^3}{12\gamma(1-\nu^2)}}$$

a = **length of plate**
b = **width of plate**
h = **thickness of plate**
E = **modulus of elasticity**
$\gamma = \mu h$ = **mass per unit area**
ν = **Poisson's ratio**
λ_{ij}^2 = **Dimensional Frequency Parameter**

- Increasing trend of frequency and mode number, as expected
- Mode 4 and 5 are orthogonal bending modes and are predicted to have the same frequency for isotropic plates
- Theory predicts relative trend with acceptable agreement, but any damage or anisotropy violate assumptions

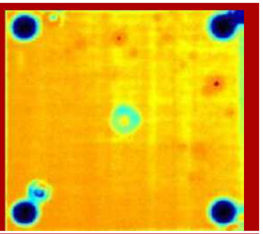
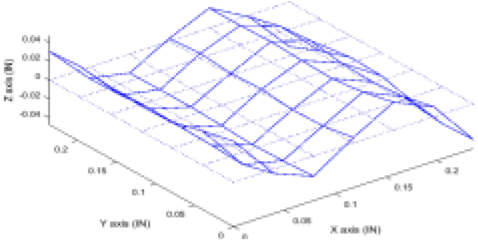
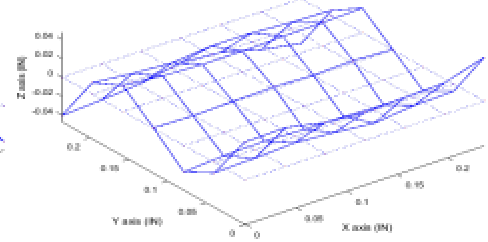
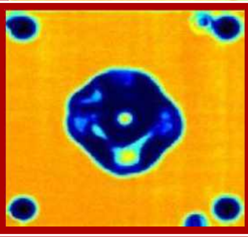
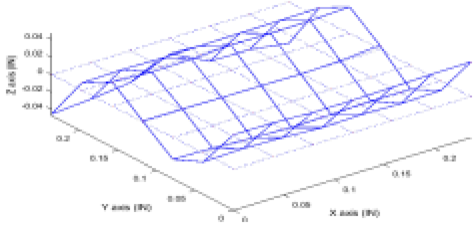
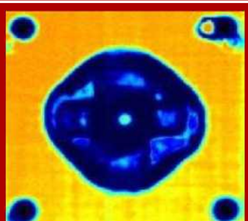
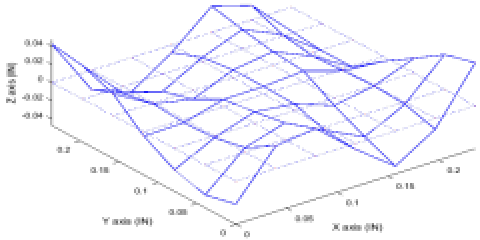
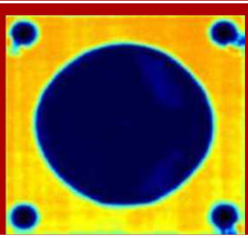
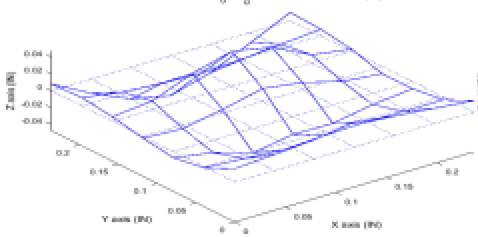
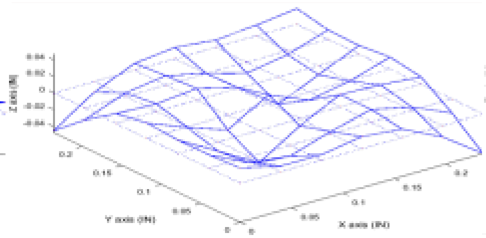
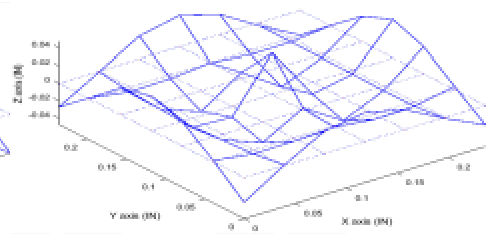
Conclusions

- Frequency of bending modes likely depends on spatial distribution and form of damage.
- If damage was centered at a dynamic point of the mode shape, notable variation in frequency occurs.
- If damage was centered at a node of the mode shape, little variation in frequency at that mode shape was noted.
- Mode shape change was the earliest indication of damage.

Future Research

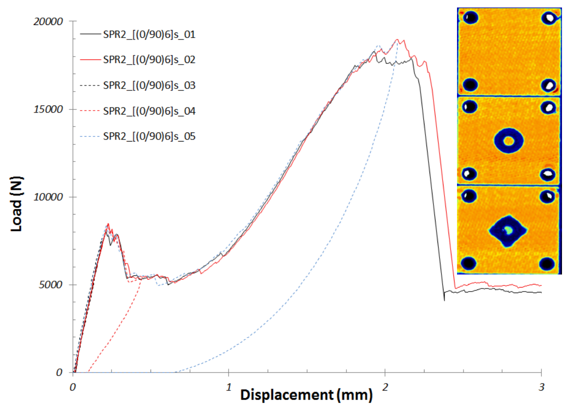
- Variable damage locations
- Variation in damage forms
- 3D damage correlation with:
  - Damping
  - Frequency
  - Mode shapes
- Relating these dynamic changes to damage mechanisms
- Development and validation of orthotropic damage models that capture structural dynamic effects
- Relating these effects to long-term performance and reliability of critical components

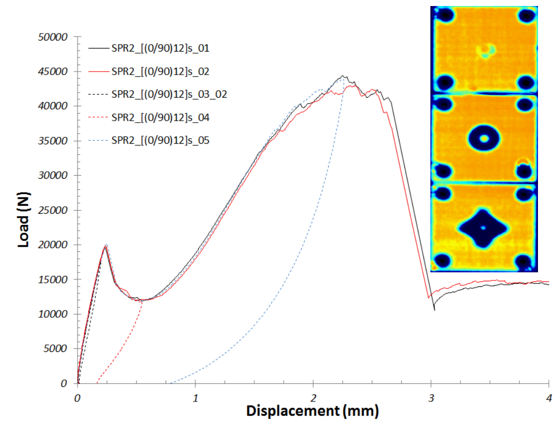
24 Ply Series Mode Shapes

		Mode 5	Mode 6	Mode 7
C1				
C2				
C3				
C4				

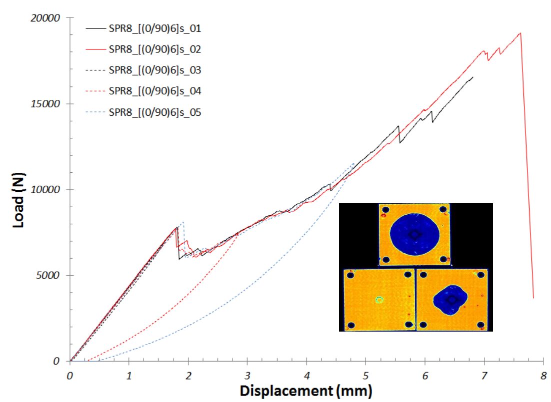
12 Ply

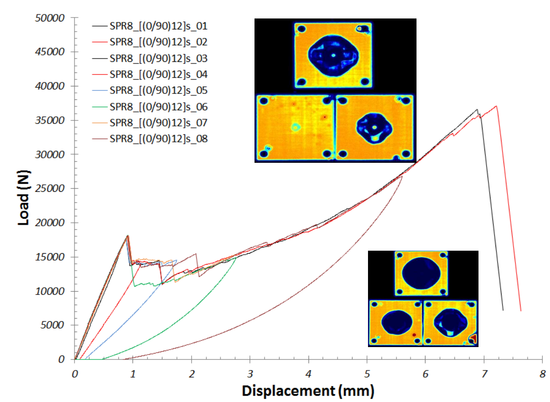
24 Ply





SPR 2





SPR 8