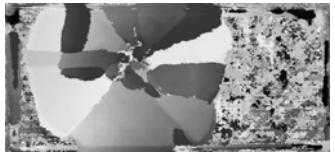
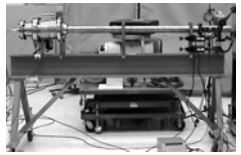
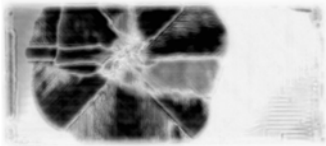
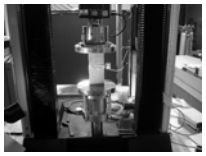





Ultrasonic Assessment and Model Validation of Damage in Carbon-fiber Based Composites

Rodrigo Cooper

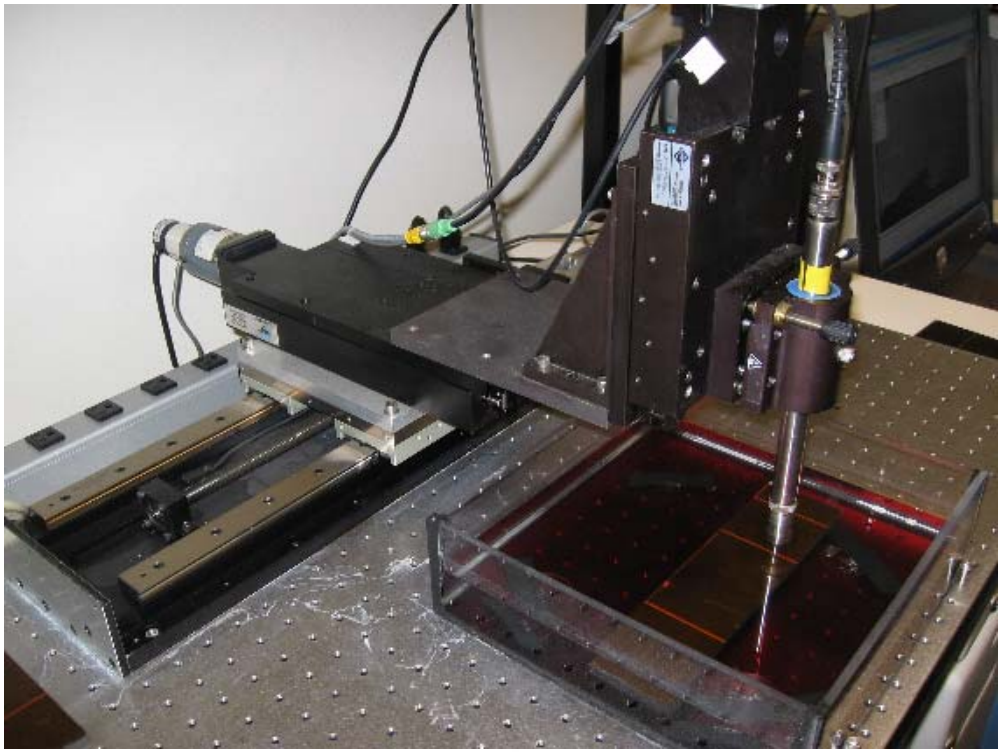
Manny Gonzales

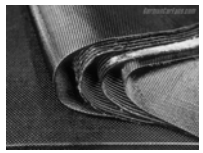
Gregory Graf

Mentors:

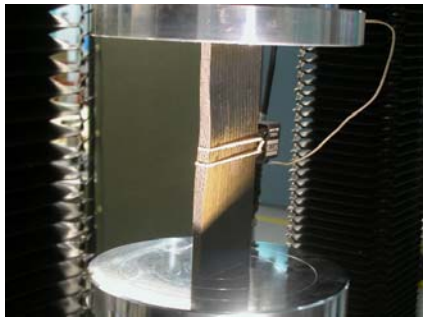
Thomas Claytor

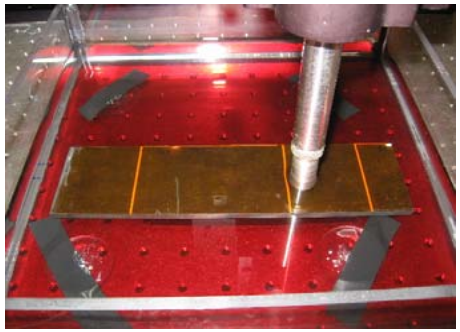
Brett Nadler

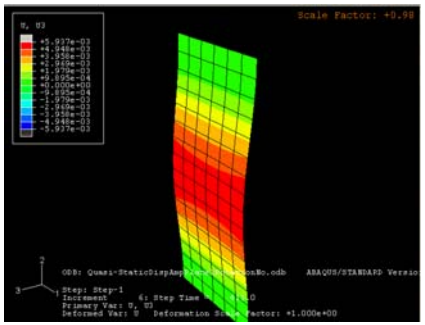




Introduction



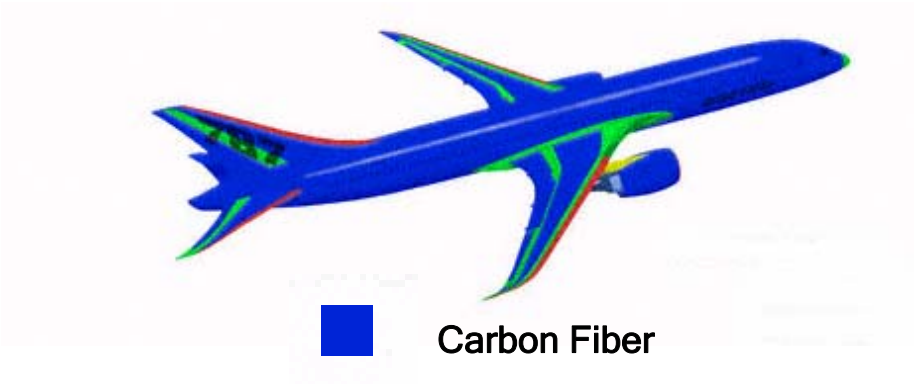




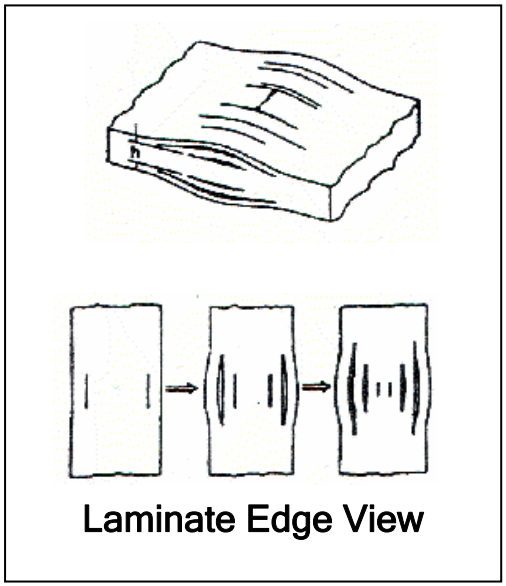
Coupon Creation → Compression → Ultrasonic Analysis → Finite Element Model → System Properties Confirmed → Impact Damage → Modal Analysis → 24inX24inX1/4in Carbon Composite Plate

Motivation

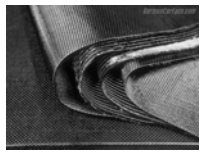
- Abundant use of materials
  - Lack of understanding of failure modes and material behavior
- High cost and downtime requirements of current NDE in the field
- Inaccessibility of critical components in the structure
- Identification of local damage prior to global failure



Nearly all the exterior surfaces of the 787 are composites

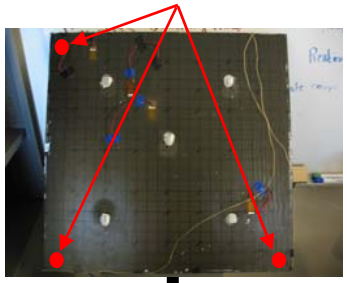


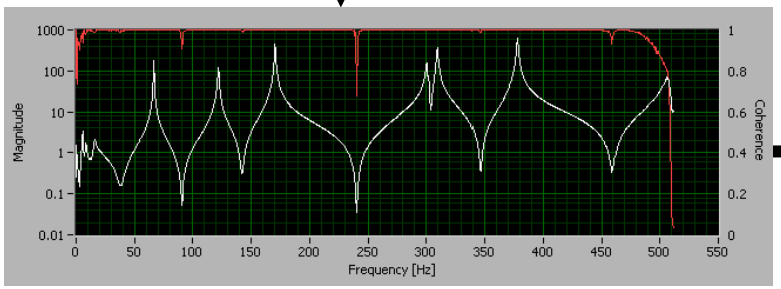
Delamination and Sub-laminate Stability

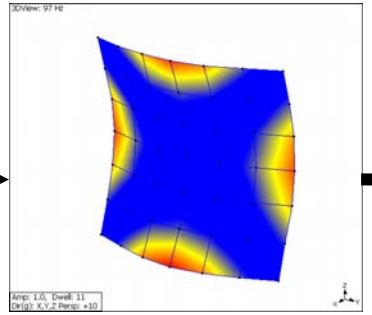


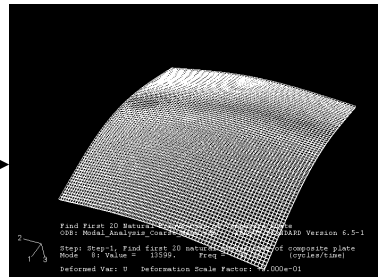
Modal analysis of a composite plate

Accelerometer Placement

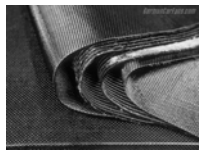








- Three fixed accelerometers
  - Ensure mode detection
- Roving Hammer
  - 3-inch spaced grid
  - 49 impact points
- ME'scope analysis
- Comparison to numerical simulation



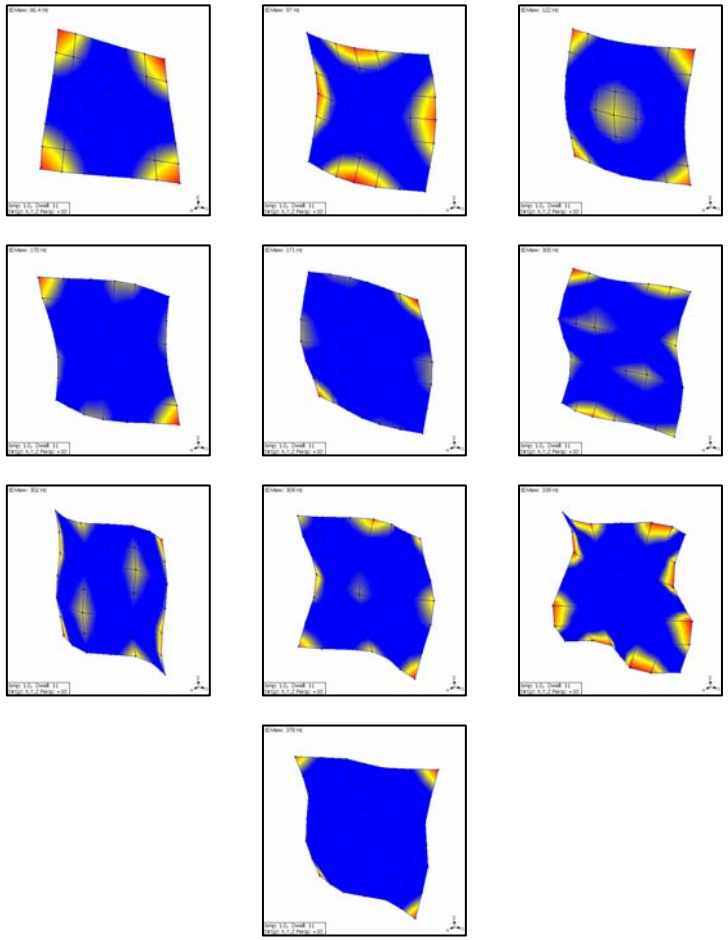
Experimental Frequency Response

1-3

4-6

7-9

10

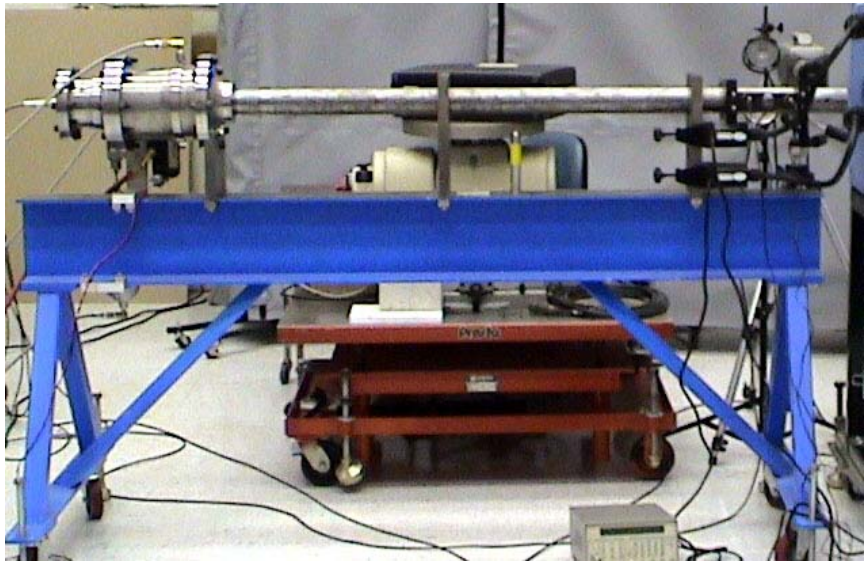


Modal Frequencies

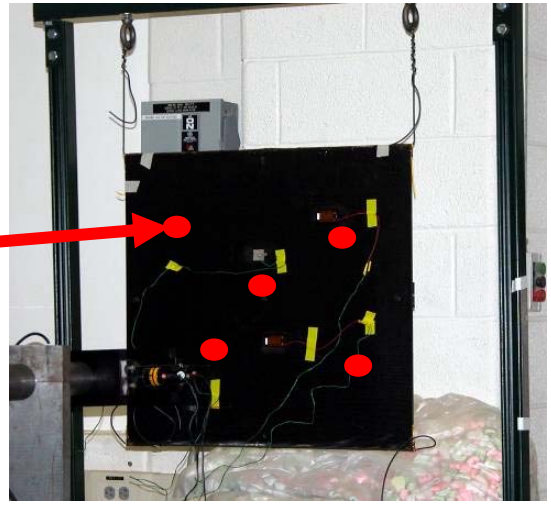
Mode 1	66Hz
Mode 2	97Hz
Mode 3	122Hz
Mode 4	170Hz
Mode 5	171Hz
Mode 6	300Hz
Mode 7	302Hz
Mode 8	309Hz
Mode 9	339Hz
Mode 10	378Hz

Damage Initiation Via Steel Projectile

- Projectile shot using gas gun
- Low impact velocity does not pierce plate
  - Initiates delamination
  - Damage not visibly perceptible

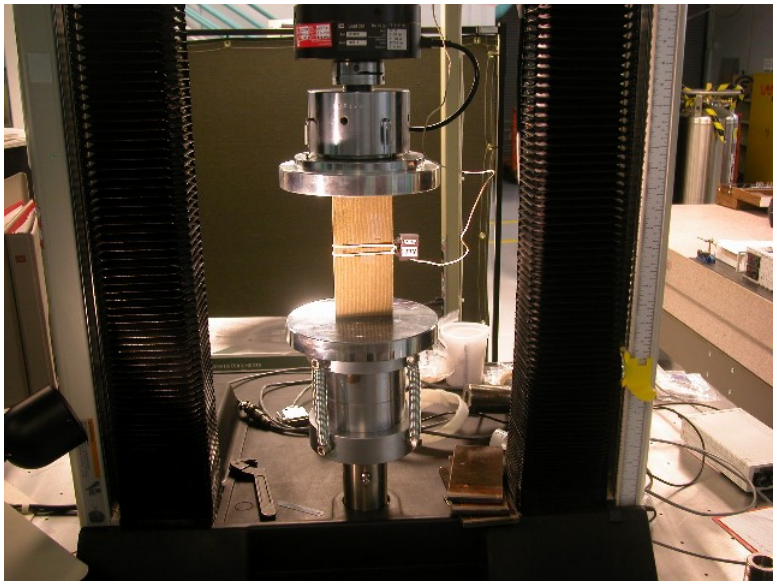


Gas Gun Setup



- 60.96cm x 60.96cm x 0.635cm plate
- Nitrogen gas gun with steel projectile
  - Hemispherical impact face
  - 191.8g projectile
  - 5 shots in cross pattern
  - 31-44m/sc

Buckling analysis used to determine coupon size



General buckling equation

$$P_{cr} = \frac{\pi^2 E_x h^3 b}{12 L^2}$$

Critical buckling equation including transverse shear

$$P_{cr} = \frac{\pi^2 b}{L^2 D_{11}^{*}(1 + S'\pi^2)}$$

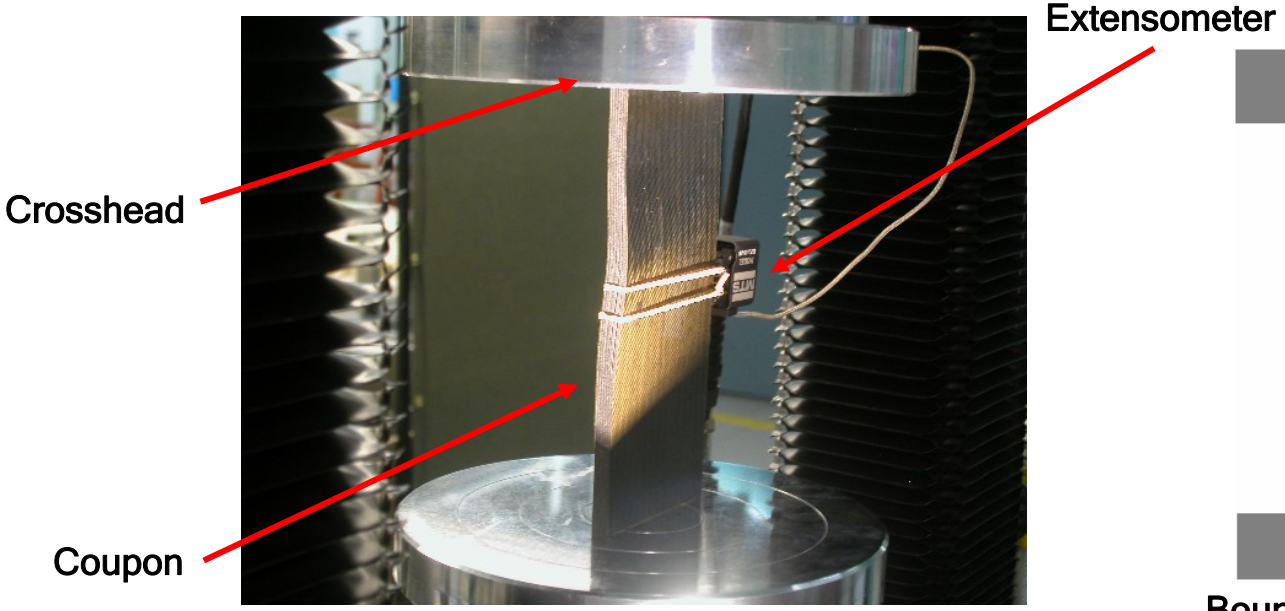
inverse bending stiffness coefficient

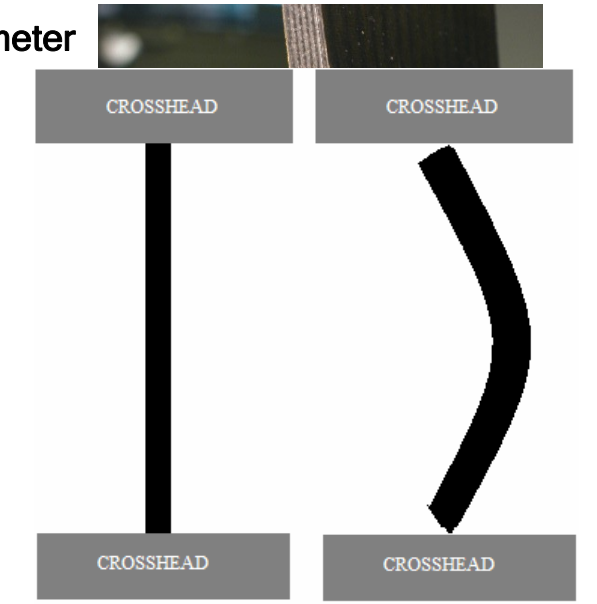
$$S' = \frac{E_x}{12 G_{xz}} \left(\frac{h}{L}\right)^2$$

shear coefficient

Damage Propagation

- Flat-plate crossheads
  - Fixed-Fixed boundary conditions until buckling
  - Then becomes pinned-pinned
- 0.004mm/s constant crosshead displacement with PID control
- Loading range 64.3-89.4kN
  - Dependent on stress/strain curve and buckling

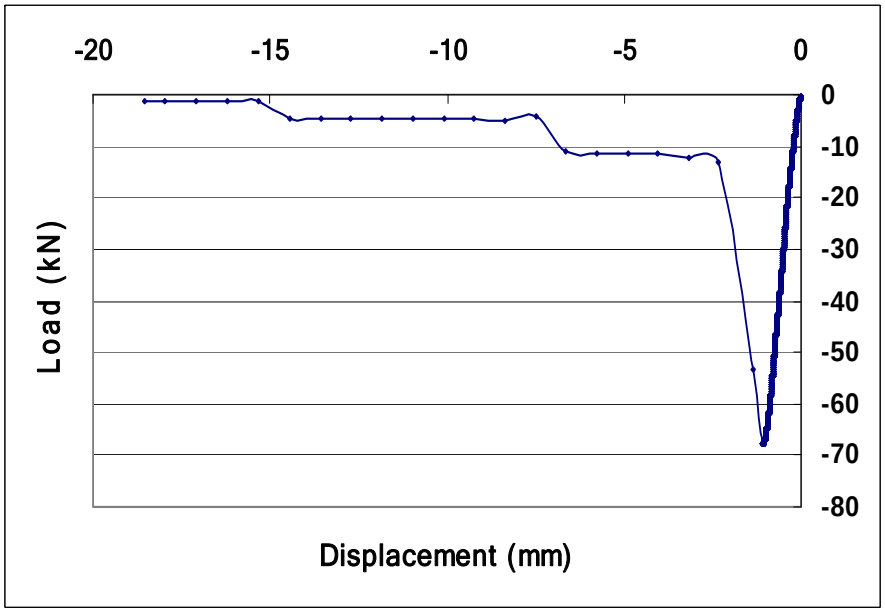




Boundary Condition Transformation

Compression Test Results

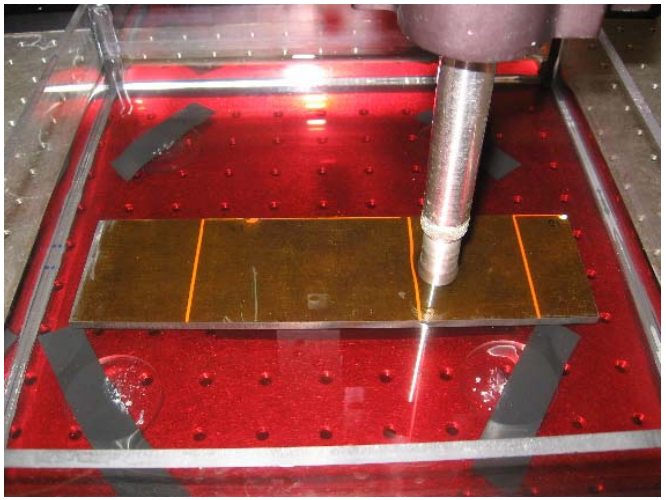
- Load based control led to unrestrained compression at failure
- Displacement rate control alleviated this problem



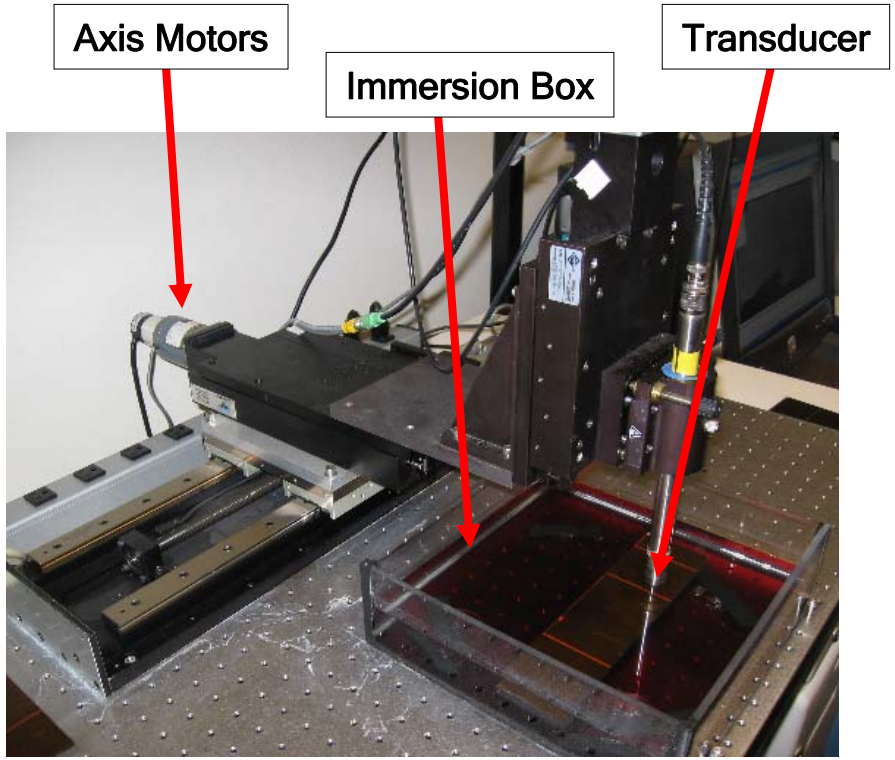
Load vs. Displacement – Plate 1

Damage condition evaluated with baseline ultrasonic tests

- Conducted using ultrasonic tests
  - 10Mhz pulsed square wave
  - 0.2mm resolution
- Identified total area of delamination
- Estimated ply/depth of delamination



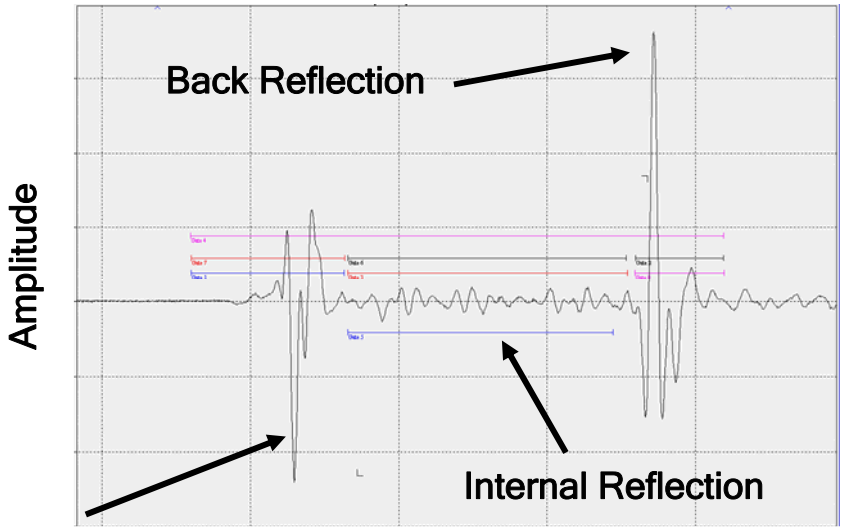
Ultrasonic Immersion C-Scan



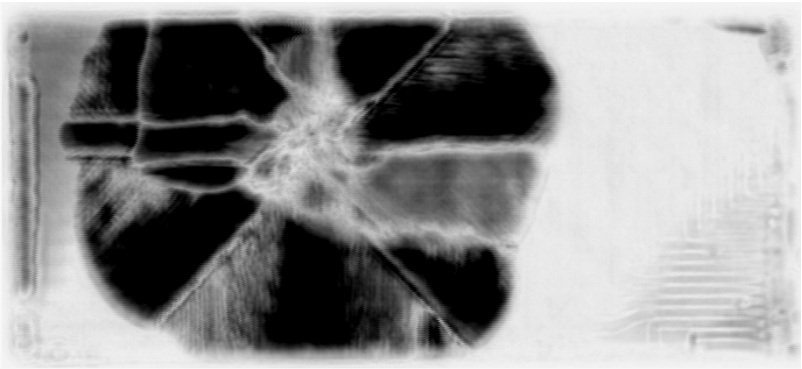
Ultrasonic Characterization

- Analysis of maximum amplitude
  - Area of delamination
  - Visualization of delamination
- Gating separates areas of interest

Ultrasonic Waveform



Post Impact Scan of Coupon 4



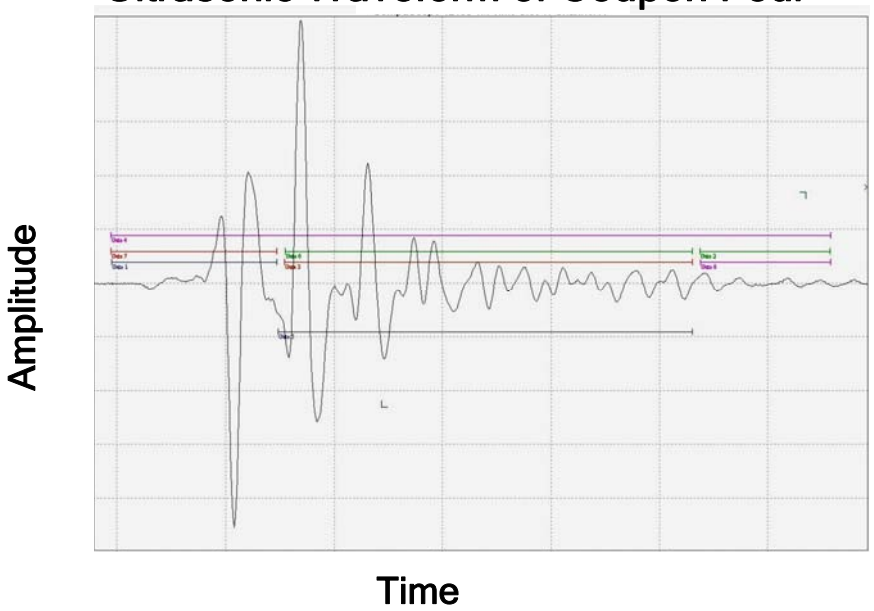
Monochromatic shading indicates changes in reflected amplitude - dark indicates delamination closer to surface

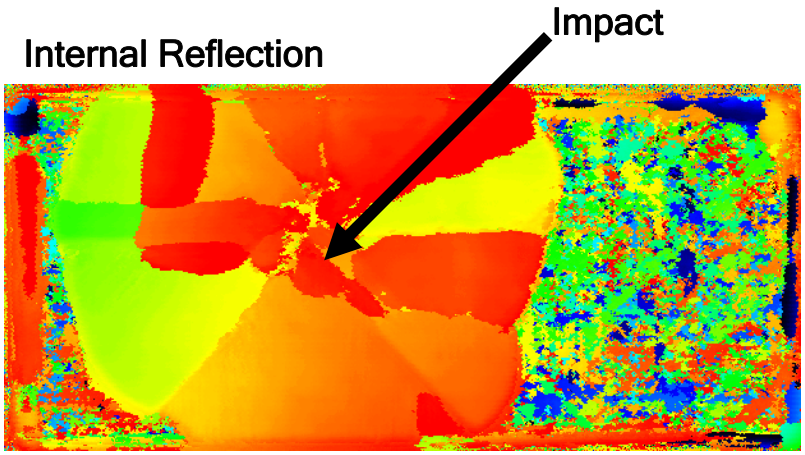
Post Compression Scan of Coupon 5

Ultrasonic Characterization

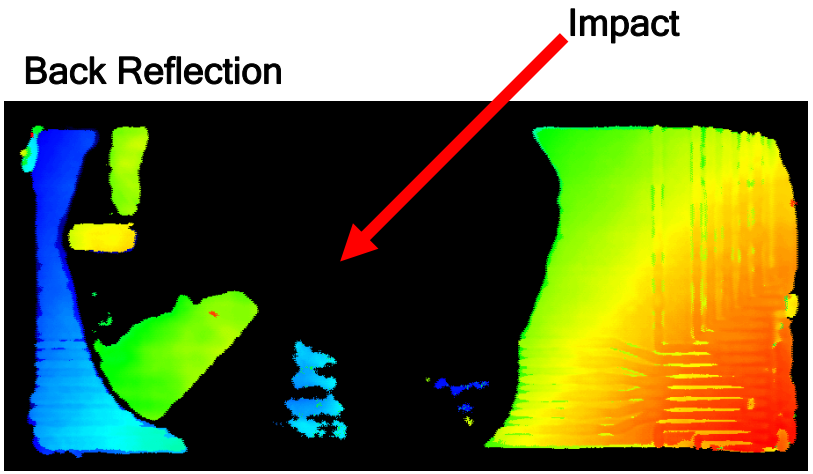
- Analysis of time-of-flight
  - Area of delamination
  - Better approximation of ply layer/depth
- Gating separates areas of interest

Ultrasonic Waveform of Coupon Four

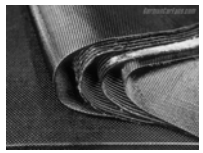




Red color denotes faster response times



Black region denotes signal attenuation



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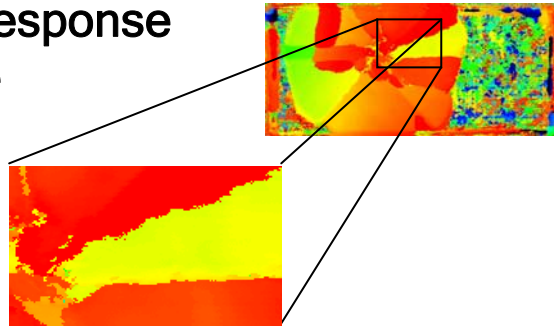
Delamination Characterization

- Percent delamination
  - Ratio of pixels with no-response to those with response
  - Compensated for test area surrounding sample
- Ply-by-ply delamination zones
  - Utilized as initial conditions in FEM

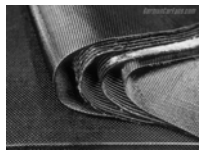


Matlab script output

Pixels delaminated post-compression	13,310
Pixels with no data pre-compression	8,120
Coupon size	13,550 pixels
Delamination area pre-damage	324.8 mm²
Delamination area post-damage	532.2 mm²
Percent delamination pre-damage	2.397%
Percent delamination post-damage	3.928%
Ratio of delamination growth	1.639

$$P = \frac{T_{Dam} - T_{Top}}{T_{Bot} - T_{Top}} 48$$

P=Damaged Ply Location
T=Time of Flight

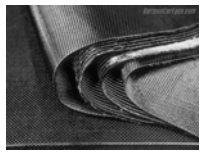


Delamination Characterization Results

Delamination Parameters for Several Coupons

Coupon	Avg. % Delam. Pre-compression	Avg. % Delam. Post compression	Percent Delamination Growth	Maximum Loading (kips)
2	5.0	6.1	1.1	17.6
3	7.9	29.2	21.3	20.1
4	52.0	53.3	1.3	14.1
5	4.2	89.3	85.1	19.8
6	4.4	8.0	3.4	14.5

- Predictive model compared to actual damage
  - Area of delamination
  - Growth of delamination regions
- Coupons 1 and 7 were critically damaged



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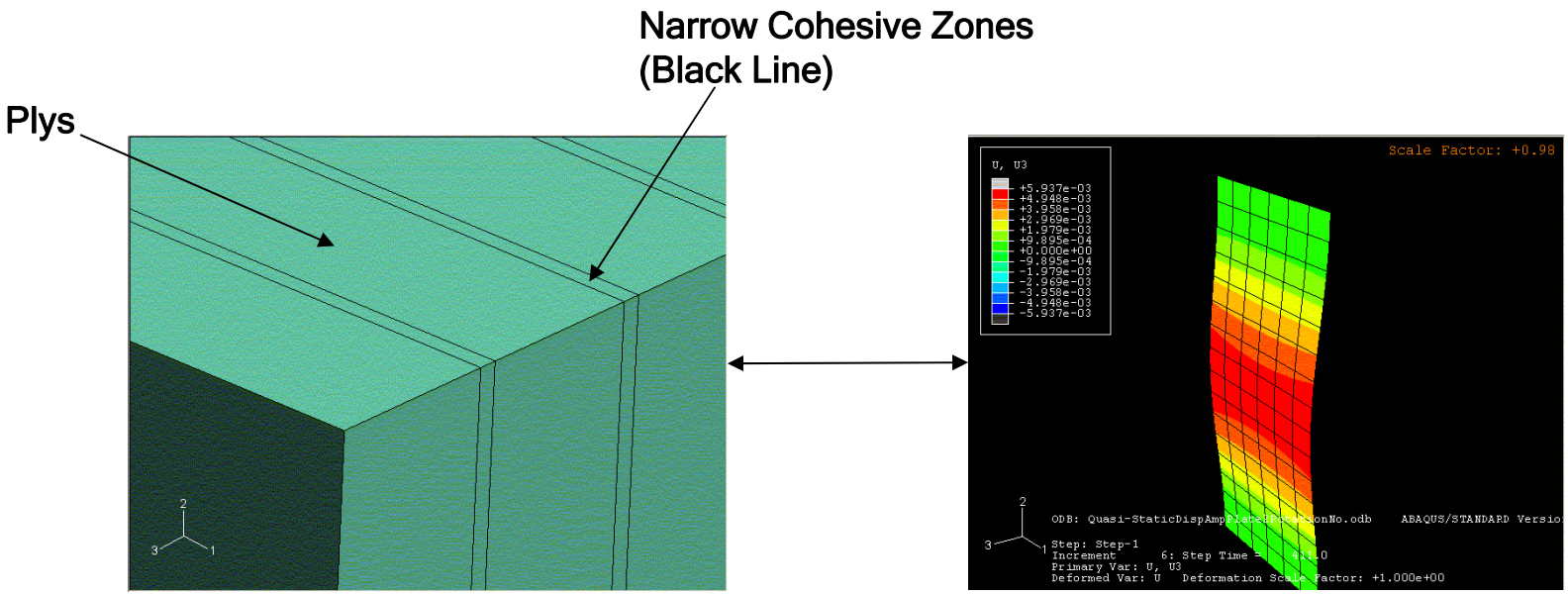
Coupon Finite Element Model

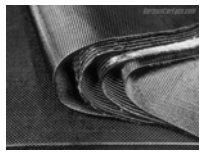
- Composite coupons modeled with applied in-plane compression loads
- 48 plys (with cohesive zones) created using partitioning techniques



Mesh Cross-section showing "cohesive zones"

FEM Buckling Simulation

- Cohesive zone modeling can be employed to predict damage interactions

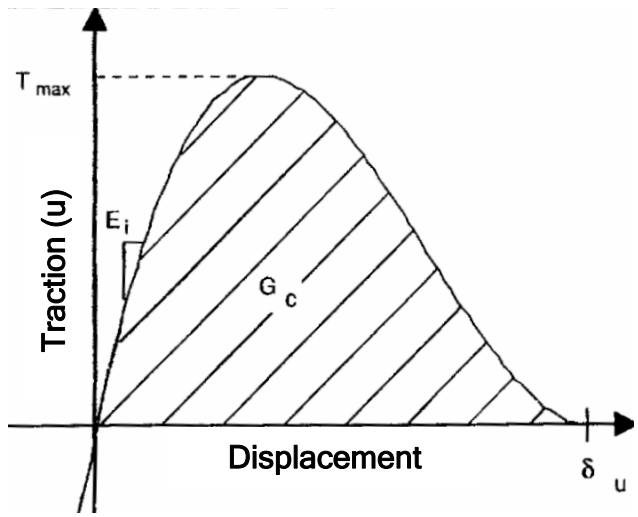


Cohesive Zone Theory

- Activate interactions in systems when a critical value of a field quantity is reached.
- Boundaries in material structure serve as activation zones for the CZM interaction.
  - Finite sized region of elements created on interfaces/boundaries.
- Delamination characterized by Traction-Separation functions as well as energy release rates.

(Tvergaard et al, 1990)

Traction Function



Elasticity

Displacement Field

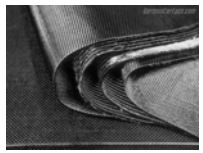
$$T = E_i F(\lambda) \frac{u}{\delta}$$

Displacement at Separation

Damage Function

$$F(\lambda) = \begin{cases} (1-\lambda)^2 & \lambda \le 1 \quad \text{Traction} \\ 0 & \lambda > 1 \quad \text{Separation} \end{cases}$$

Damage Parameter



Preliminary Modeling

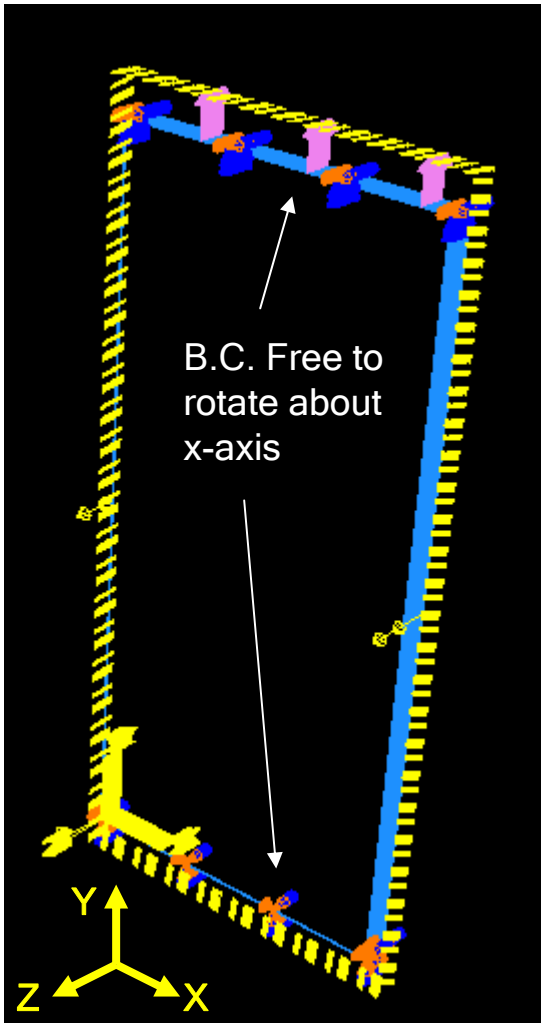
- Boundary conditions (B.C.s) allow plate to rotate about x-axis

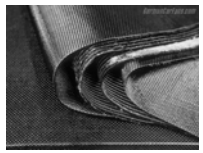
- Multiple compression scenarios:
  - displacement-time
  - load-time functions

- Small perturbation loads were prescribed at the midspan of the model.

- Analysis conditions were quasi-static.

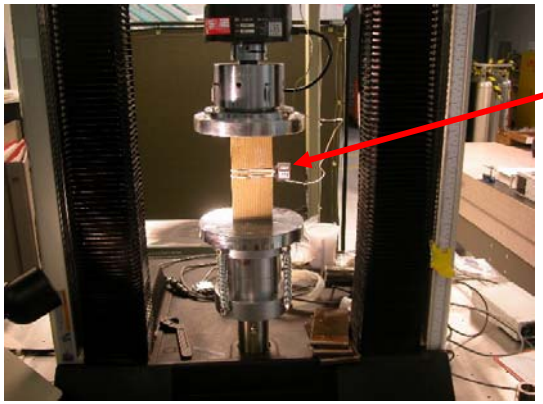
- Convergence was tested between both load conditions (displacement or distributed force)

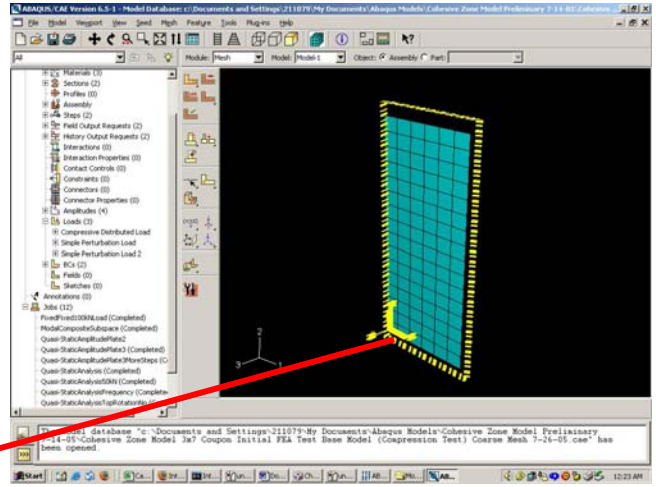




Comparative Analysis of Modeling and Experimental Results

- Previously acquired modal data confirms system characteristics.
- Displacement-time curves from experimentation are used in the model.
- Final outputs in preliminary model correlated with experimental results.



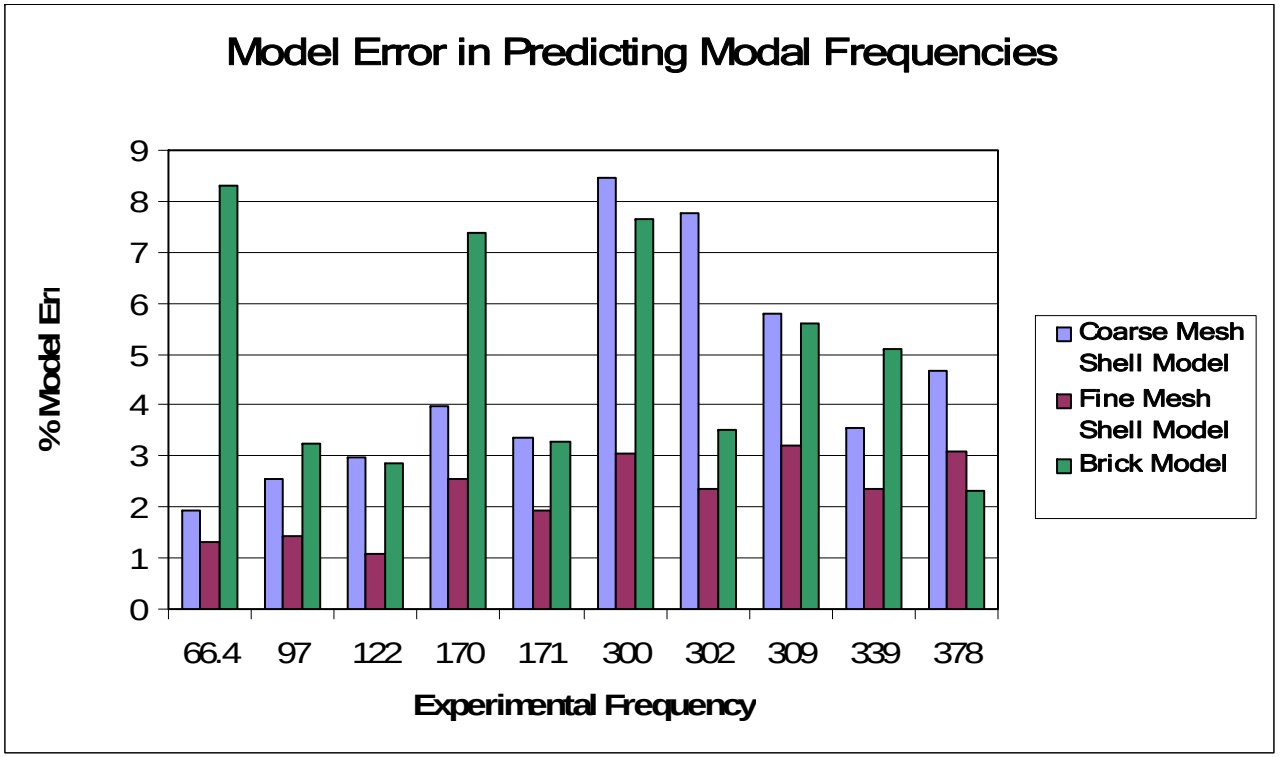


ABAQUS CAE Modeling View

- Use load-based vs. displacement based modeling
  - Selection based on experimental vs. numerical strains.
  - Excessive distortion in elements with load-based model

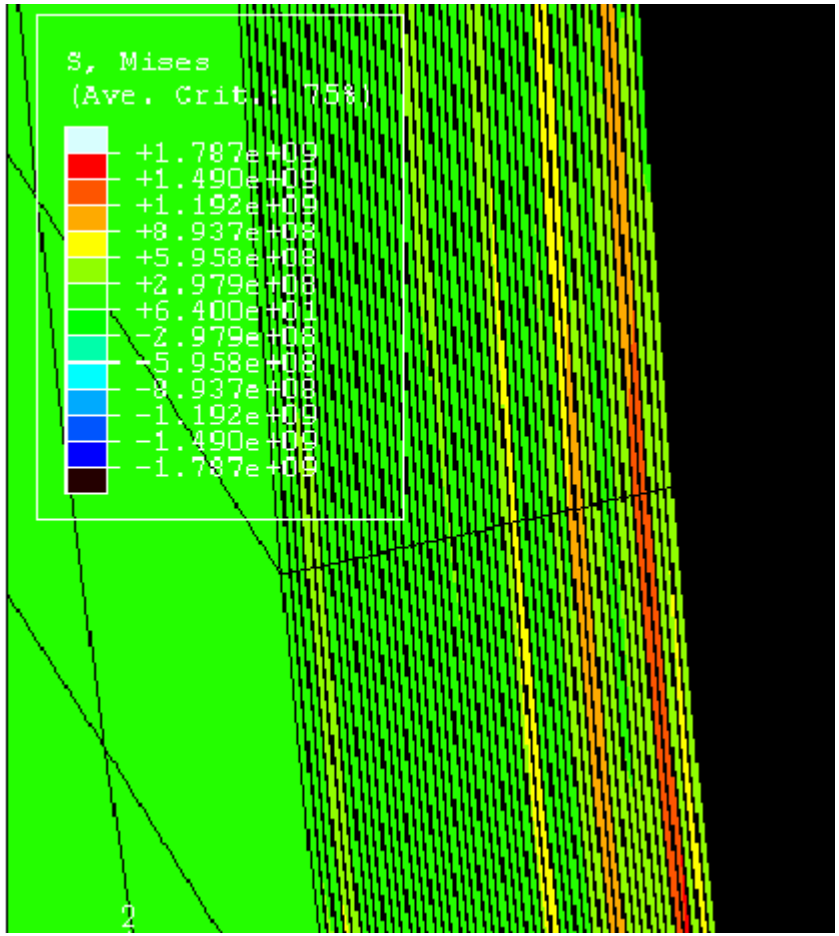
Comparison of first ten modal frequencies

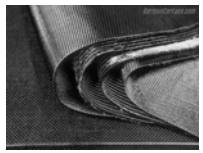
- Modal frequencies of first 10 modes compared to numerical model
  - Coarse Shell Model – max 8.46% error
  - Fine Shell Model – max 3.19% error
  - Brick Model – max 8.3% error



Preliminary stress analysis results

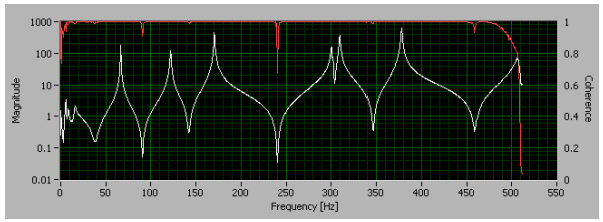
- Analysis done with pristine model of composite coupons
- Interface boundaries created between plys, but CZM code not implemented
- Results show stresses localized on particular plys.
- Will compare these results from time-of-flight calculations from ultrasonic scans.
- Incorporate damage scenarios into model.



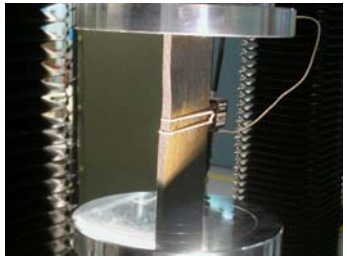


Summary

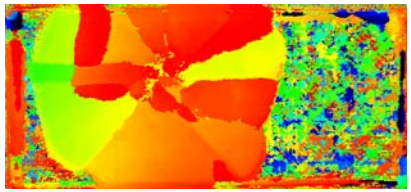
Modal analysis of entire plate



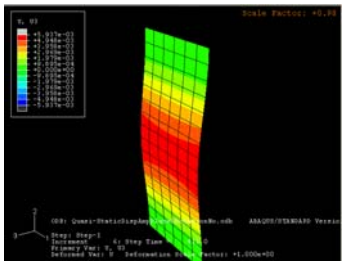
Compression testing to extend damage



Ultrasonic scan quantifies damage

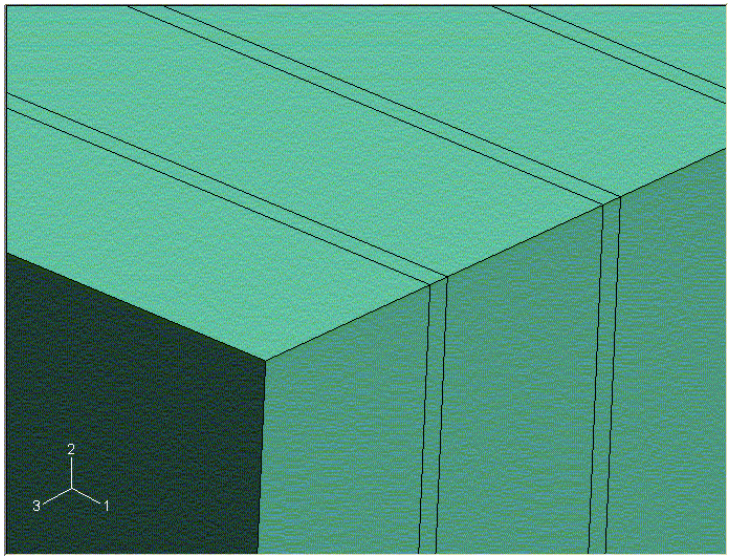


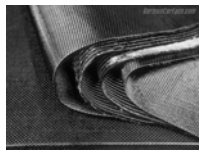
Numerical simulations of tests



Future Research

- CZM code implementation
- Improving Model Performance
  - Modeled contact boundary conditions
  - Improved material characterization
  - Model updating
- More adaptive model validation methods





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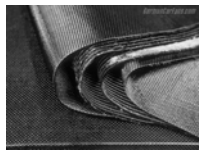
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