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CAMX

THE COMPOSITES AND ADVANCED MATERIALS EXPO

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October 13 – 16, 2014 / Orlando, FL , USA

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VALIDATION OF CARBON-FIBER LAMINATE SIMULATIONS WITH LOW VELOCITY IMPACT EXPERIMENTS

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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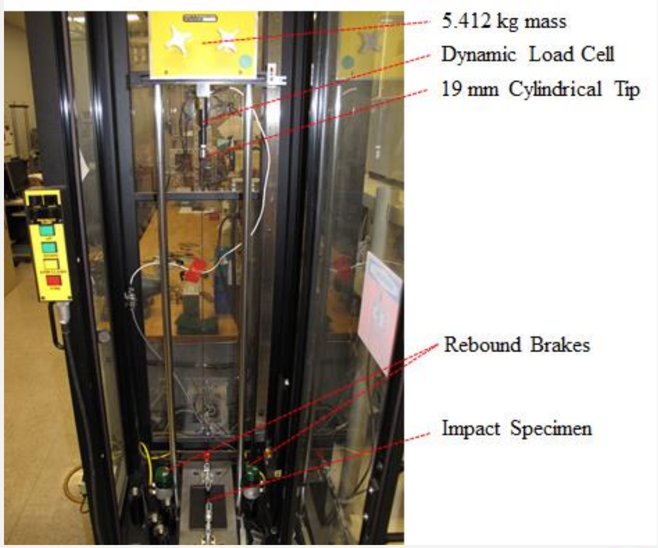
Outline of Presentation

- Material and Experimental Set-up
- Finite Element Model Description
- Verification
- Sensitivity Analysis
- Material Models and Characterization
- Experimental Results
- Model Results and Validation
- Calibration and Conclusions

Material and Experimental Setup

- Carbon fiber reinforced polymer (CFRP) 8-harness satin weave prepreg with an epoxy based resin.
- Stack Sequence: $[(0/90)_6]_s$
- The impact tip was a 19 mm diameter cylinder with a flat face made of stainless steel.



- Specimen Dimensions:

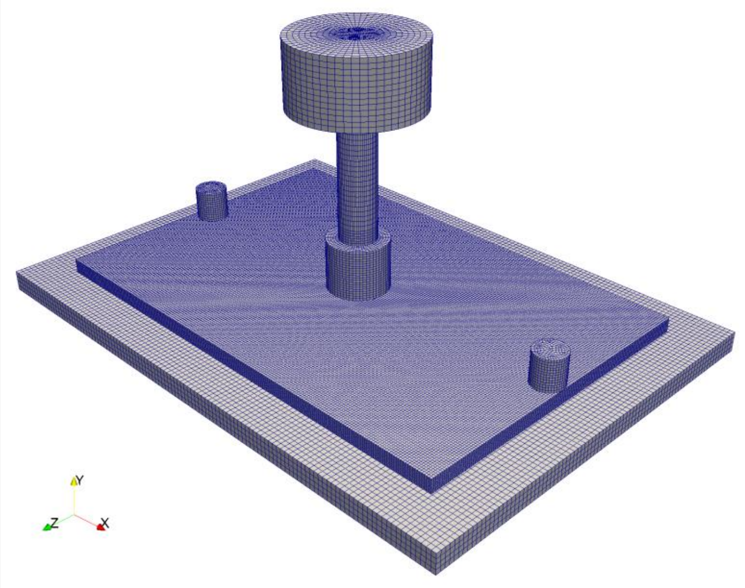
Width (mm)	Length (mm)	Thickness (mm)
102	*155*	*4.49*

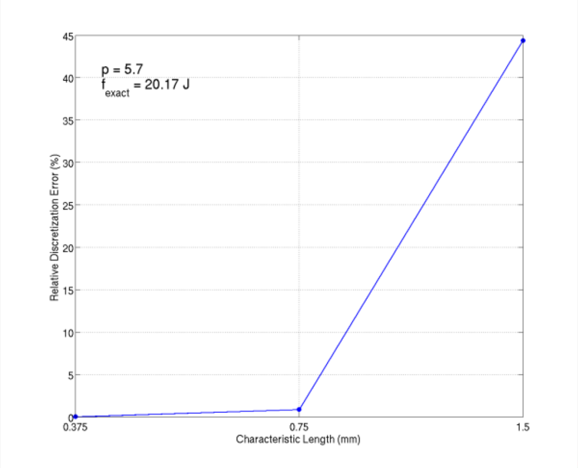
- Experimental Inputs:

Impact Energy	Crosshead Mass	Impact Velocity
50 J	*5.42 kg*	*4.3 m/s*

Finite Element Model

- Oblique impact of 0.45° is included. Half symmetry is modeled.
- The final mesh consists of 1.1 million reduced integration hexahedral elements.
- Excellent mesh convergence for energy absorbed, but mesh sensitive for damage initiation load





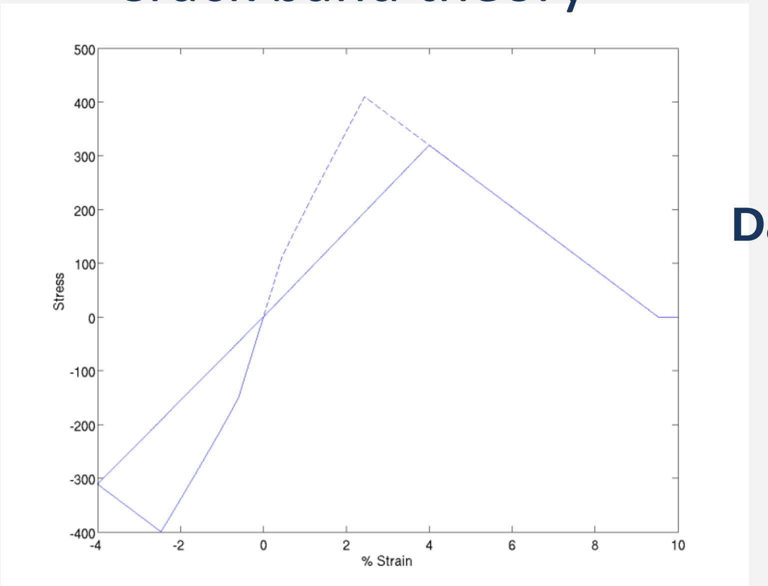
Sensitivity Analysis

- 52 inputs are sampled with Box Behnken Design of Experiments method
- This resulted in 5305 simulations on a reduced mesh.
- Based on the mean squared values of ANOVA, the most important parameters that effect the energy absorbed are:

Mode II interlaminar fracture toughness:	CZ_ENERGY_II
Mode II interlaminar peak traction	CZ_PEAK_TRAC_II
Interlaminar friction (active through fracture)	FRICTION_COEF
Weft Stiffness	E22
In-plane Shear Stiffness	G12
In-plane Poisson's Ratio	NU12
Warp Stiffness	E11

Elastic Orthotropic Failure

- An elastic orthotropic damage evolution and failure material model is developed for this study.
- Phenomenological
- Partially interactive
- Damage evolution
- Crack band theory



Compliance tensor:

$$\mathbf{S} = \begin{bmatrix} \frac{1}{E_{11}(1-d_{11})} & \frac{-\upsilon_{21}}{E_{22}} & \frac{-\upsilon_{31}}{E_{33}} & 0 & 0 & 0 \\ \frac{-\upsilon_{12}}{E_{11}} & \frac{1}{E_{22}(1-d_{22})} & \frac{-\upsilon_{32}}{E_{33}} & 0 & 0 & 0 \\ \frac{-\upsilon_{13}}{E_{11}} & \frac{-\upsilon_{23}}{E_{22}} & \frac{1}{E_{33}(1-d_{33})} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{2G_{12}(1-d_{12})} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{2G_{13}(1-d_{13})} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2G_{23}(1-d_{23})} \end{bmatrix}$$

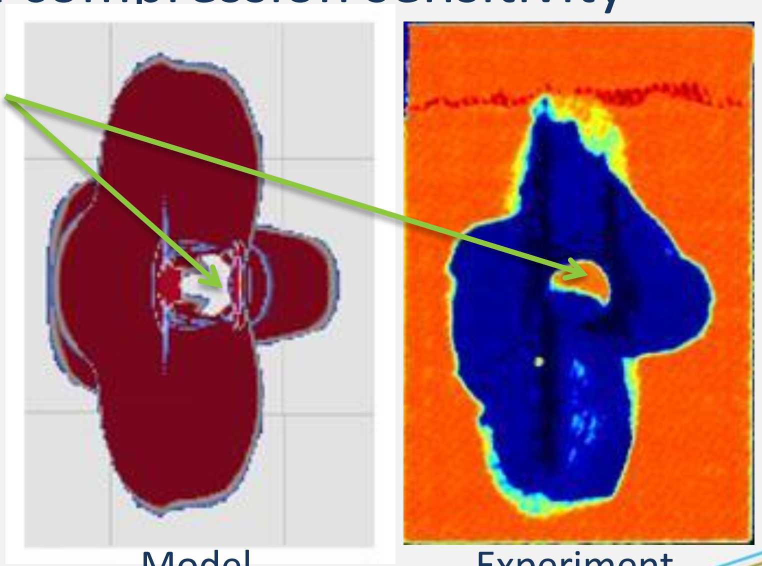
Damage activation functions

$$\varphi_{11+}^{m} = \sqrt{\left(\frac{E_{11}\langle\varepsilon_{11}\rangle}{X_{11+}^{m}}\right)^2 + \left(\frac{G_{12}\gamma_{12}}{S_{12}^{m}}\right)^2 + \left(\frac{G_{13}\gamma_{13}}{S_{13}^{m}}\right)^2}$$

Interlaminar Failure (Delamination)

- Each lamina is separated by cohesive zone (CZ) elements
- Mixed mode traction separation law [1]
- Contact is defined without regards to the CZ elements
- Friction is therefore used to add compression sensitivity

No delamination under high compression



Model Experiment

Effective Traction:

$$\tau^* = \tau + \mu\langle -\sigma_n \rangle$$

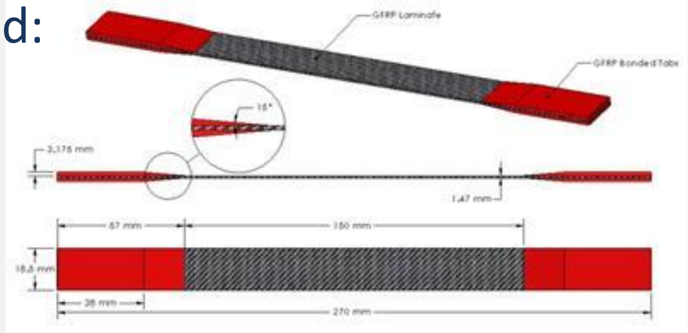
Effective Fracture Energy:

$$G_{II}^* = G_{II} + \mu\delta_{TC}\langle -\sigma_n \rangle$$

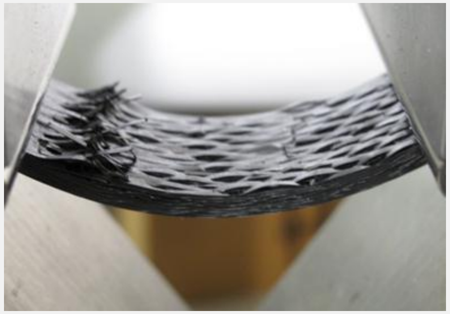
[1] S. Li, M. Thouless, A. Waas, J. Schroeder, and P. Zavattieri, "Mixed-mode Cohesive-zone Models for Fracture of an Adhesively-bonded Polymer-matrix Composite," *Eng. Fract. Mech.,* vol. 73, pp. 64-78, (2006)

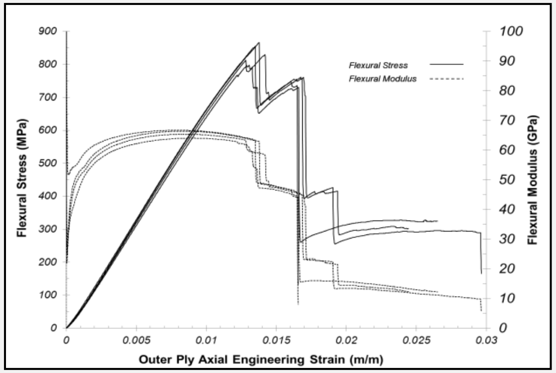
Model Inputs

Measured:

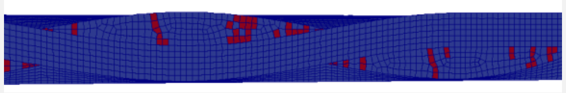


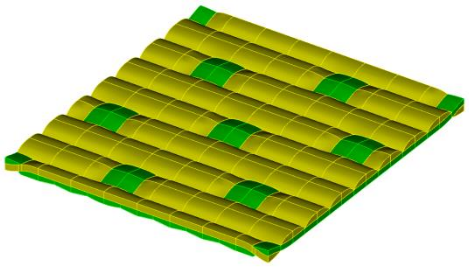
Calibrated:

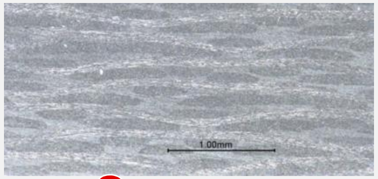




Micromechanics:







Literature/Engineering Judgment:

Interlaminar Properties:

Identification	Values
G_I (J/m^2)	282 (45)
G_{II} (J/m^2)	782 (87)
μ	0.45 ± 0.25
σ_0 (MPa)	10 ± 1.0
τ_0 (MPa)	32.4± 7.4

Lamina Properties:

Identification	Values	Identification	Values
E_{11} (GPa)	63.9 (2.4)	F_{1T} (MPa)	769 (37)
E_{22} (GPa)	62.7 (3.8)	F_{1C} (MPa)	-816 (69)
E_{33} (GPa)	8.19 ± 0.40	F_{2T} (MPa)	823 (26)
v_{12}	0.048 (0.018)	F_{2C} (MPa)	-816 (69)
v_{23}	0.399 ± 0.018	F_{3T} (MPa)	56.2 ± 13
v_{13}	0.400 ± 0.017	F_{3C} (MPa)	-56.2 ± 13
G_{12} (GPa)	3.44 (0.058)	S_{12M} (MPa)	48.4 (0.84)
G_{23} (GPa)	3.27 ± 0.27	S_{12F} (MPa)	77.3 (1.1)
G_{13} (GPa)	3.25 ± 0.26	S_{23M} (MPa)	32.4 ± 7.4
G_{I11}	80 ± 20	S_{23F} (MPa)	65.5 ± 12
G_{I22}	80 ± 20	S_{13M} (MPa)	32.4 ± 7.4
G_{I33}	2.6 ± 2.5	S_{13F} (MPa)	65.5 ± 12
G_{II12}	12 ± 1.2	K_{12m} (MPa)	152 (10.1)
G_{II23}	10 ± 1.0	K_{23m} (MPa)	152 ± 15.2
G_{II13}	10 ± 1.0	K_{13m} (MPa)	152 ± 15.2

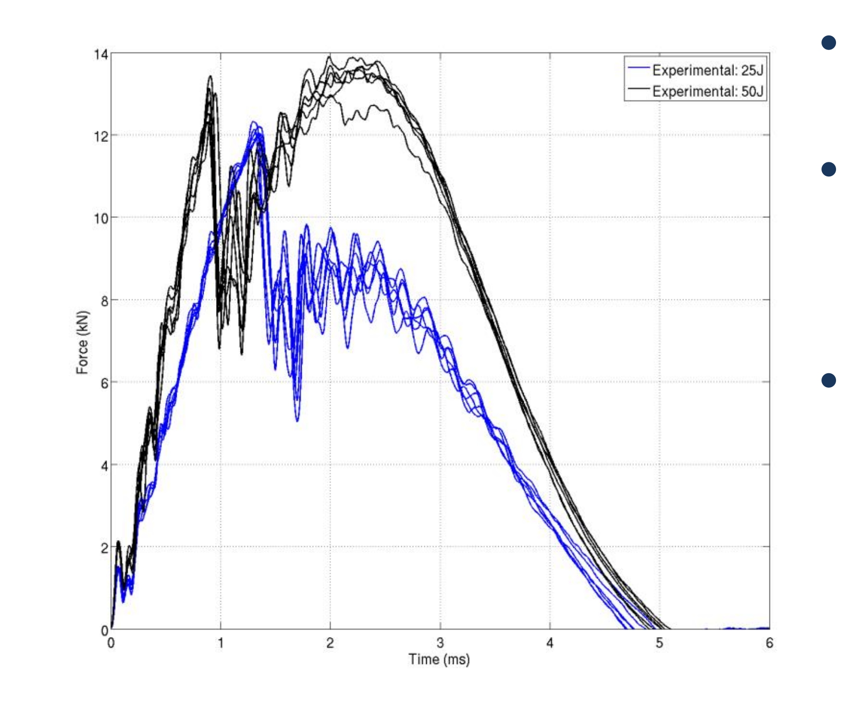
Experimental Results

50J with 5.42 kg:

	Impact Velocity	Impact Energy	Maximum Load	Energy Absorbed	Impact Duration	Rebound Velocity
Averages	*4.3 m/s*	*49.1 J*	*13575.1 N*	*22.9 J*	*5.0 ms*	*3.1 m/s*
Std Dev	*(0.002 m/s)*	*(0.047 J)*	*(317.8 N)*	*(0.953 J)*	*(0.069 ms)*	*(0.058 m/s)*

25J with 5.42 kg:

	Impact Velocity	Impact Energy	Maximum Load	Energy Absorbed	Impact Duration	Rebound Velocity
Averages	*3.06 m/s*	*25.4 J*	*12120 N*	*11.1 J*	*4.76 ms*	*2.30 m/s*
Std Dev	*(0.0008 m/s)*	*(0.012 J)*	*(132 N)*	*(0.64 J)*	*(0.11 ms)*	*(0.057 m/s)*



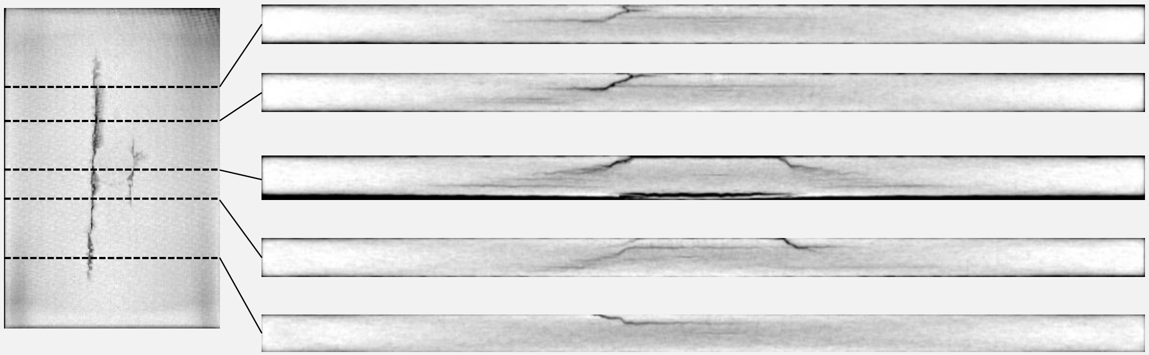
- Velocities are measured by a light sensor, just above the specimen
- Energy absorbed is calculated as:

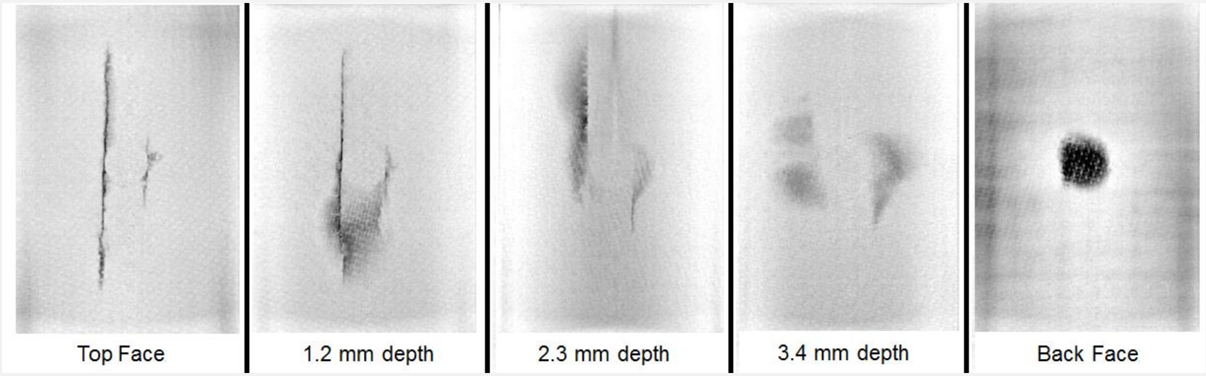
$$\Delta KE = \frac{m}{2}(V_1^2 - V_0^2)$$

- The force time history can be integrated to obtain velocity and displacement, but errors occur.

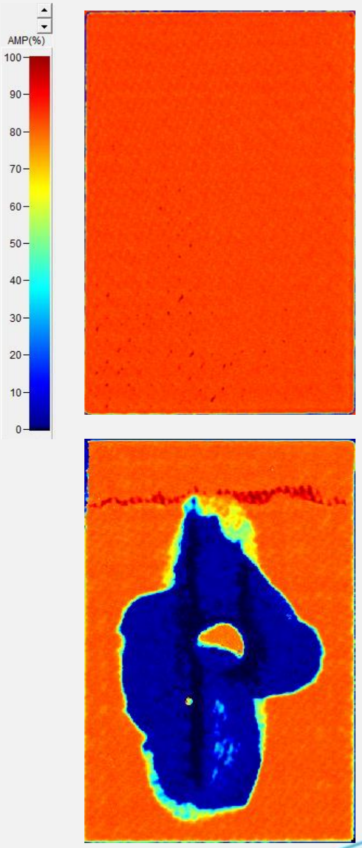
Non-Destructive Evaluation

Post-impact 3D computed tomography:





Pre and post-impact scans using ultrasonics:



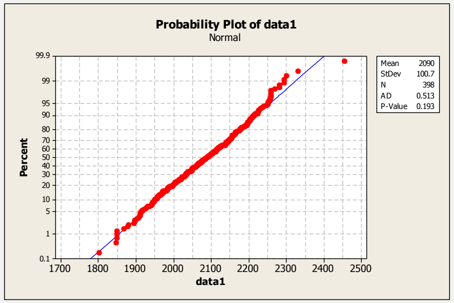
Objective Validation

- Student's t-test or Mann-Whitney non-parametric rank test p-values. A p-value > 0.05 provides confidence in the null hypothesis of equal populations
  - 50J Energy absorbed: 0.095
  - 50J Rebound velocity: 0.096
  - 25J Energy absorbed (non-normal): 0.007
  - 25J Rebound velocity (non-normal): 0.008
- 95% interval on differences of means

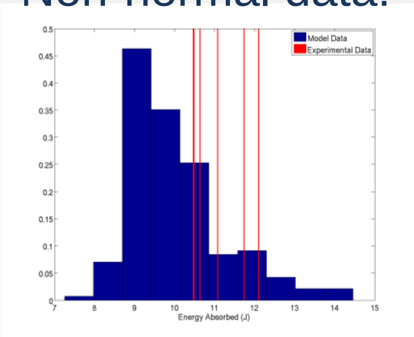
$$\delta X \approx \left(\bar{X}_{model} - \bar{X}_{exper}\right) \pm t_{\alpha/2,df}\hat{\sigma}_{\bar{X}_{model}-\bar{X}_{exper}}$$

  - 50J Energy absorbed: [-5.17, 2.43] J
  - 50J Rebound velocity: [-0.142, 0.299] m/s
- 95% interval on difference of medians
  - 25J Energy absorbed: [-1.88, -0.38] J
  - 25J Rebound velocity: [0.028, 0.15] m/s

Check for normality:



Non-normal data:



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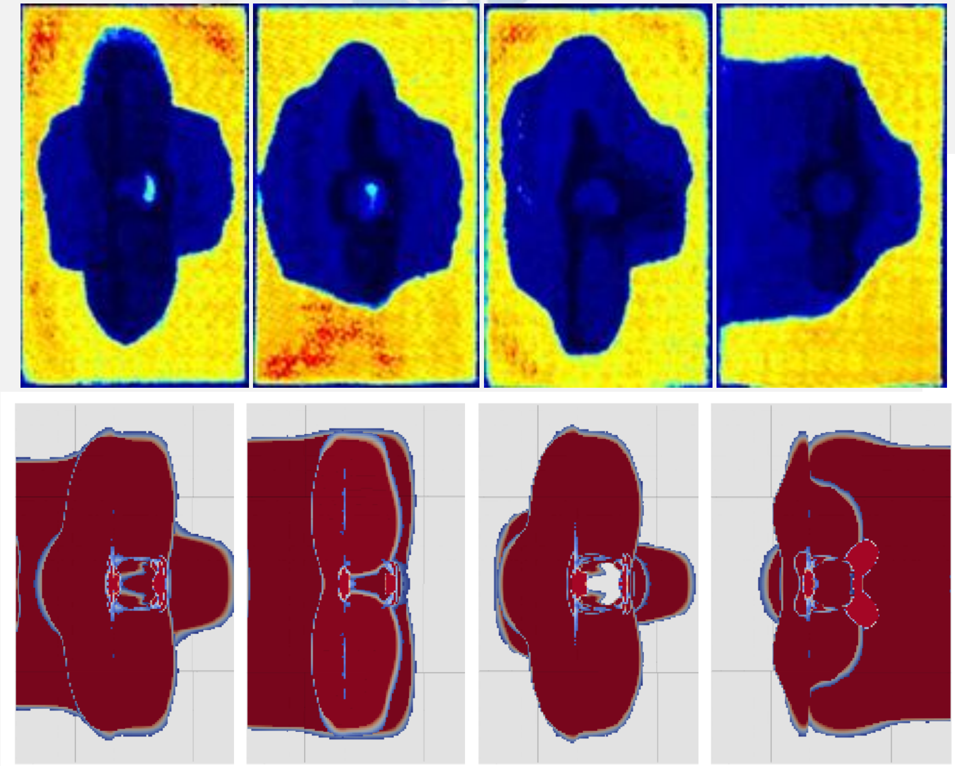
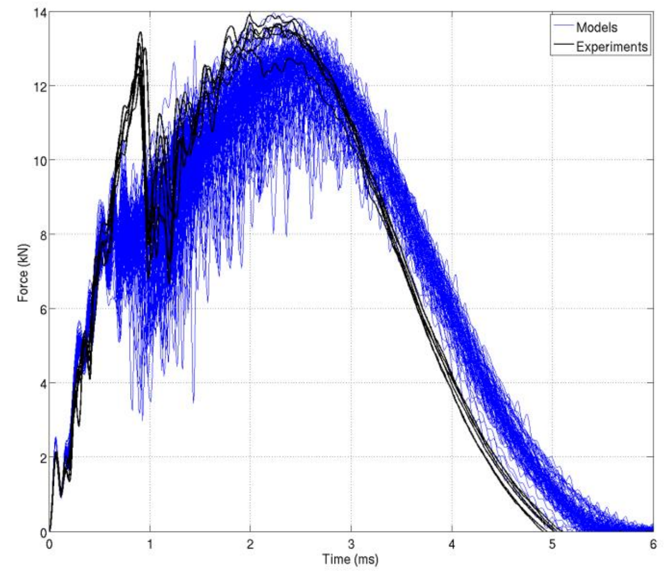
Subjective Validation (50J)

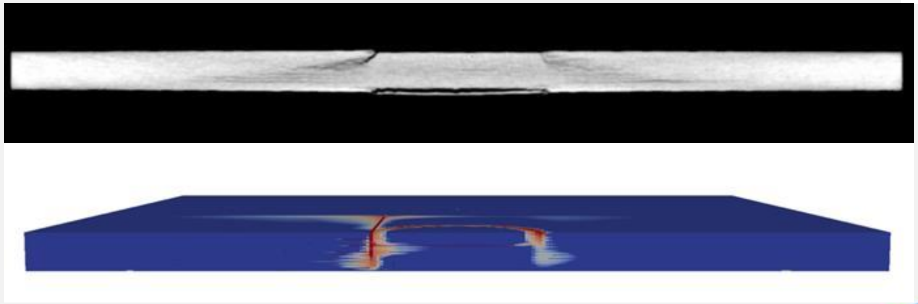
Post-impact ultrasonic scans:



Load vs. time for experiments and 100 simulations:



Post-impact 3D computed tomography:

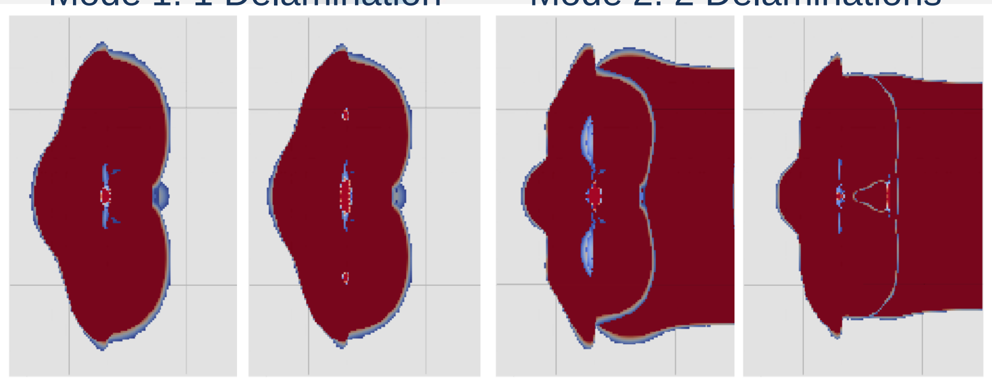


Calibration(50J)

Post-impact ultrasonic scans:

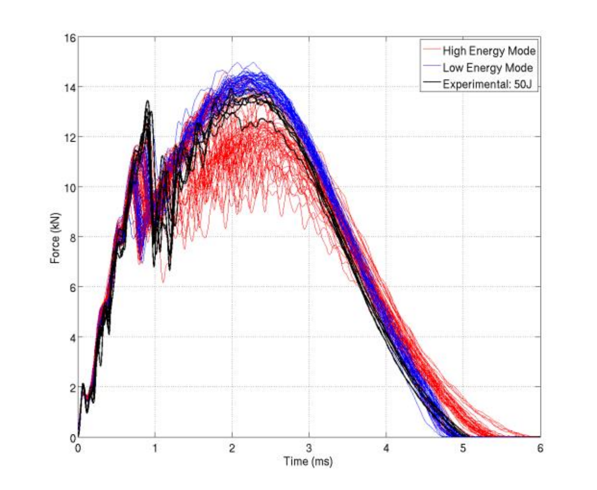
Mode 1: 1 Delamination

Mode 2: 2 Delaminations

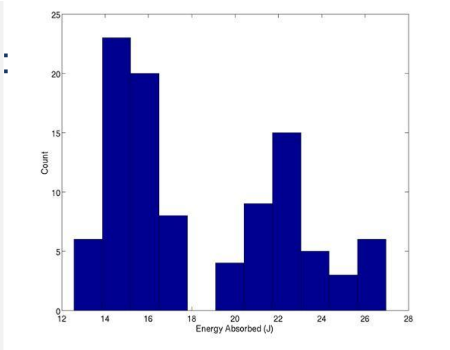


Increasing absorbed energy

Load vs. time for experiments and 100 simulations:



Bimodal:



T-test is used to determine significant differences between groups. The out-of-plane compressive strength is higher in Mode 2, and the interlaminar mode II toughness is lower in mode II.

Deficiencies in the delamination initiation and coupling of compression and shear are identified. It is postulated and shown in literature that the shear-compression coupling is not a simple quadratic summation and delaminations follow an increasing resistance curve.

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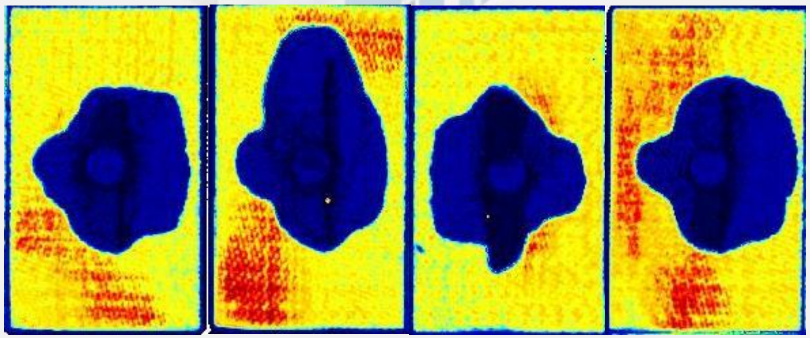
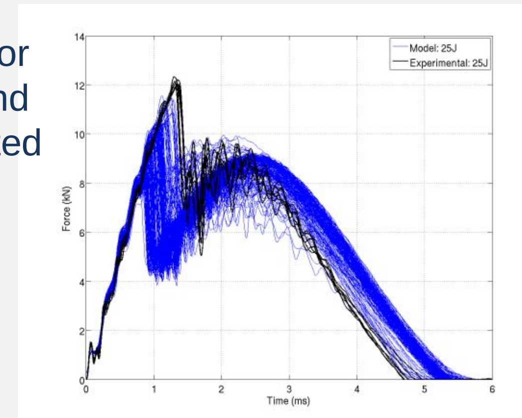
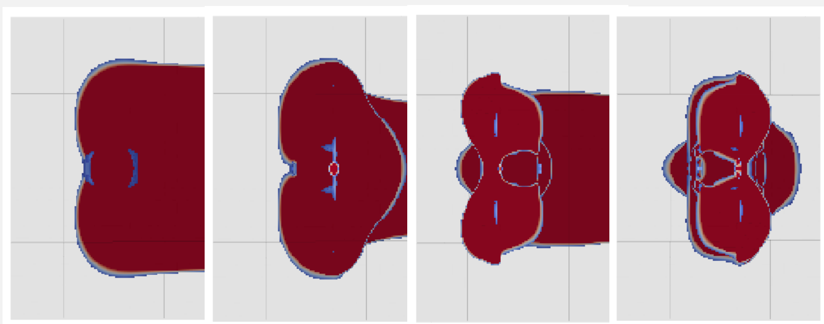
Post-impact ultrasonic scans:



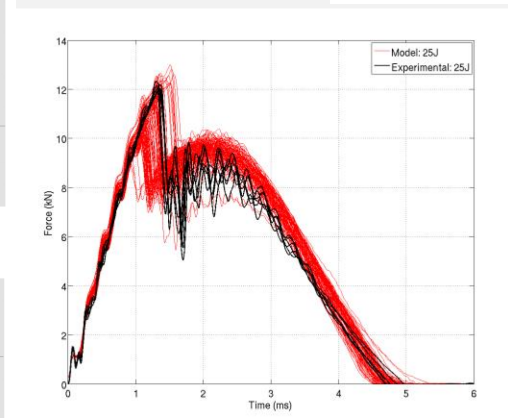
Load vs. time for experiments and 200 un-calibrated simulations:



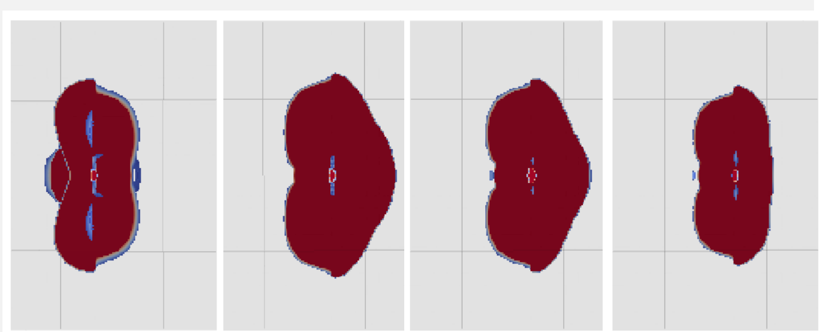
Un-calibrated:



Load vs. time for experiments and 100 calibrated simulations:



Calibrated:



Summary

- The initial model produces accurate energies and damage patterns, but cannot predict the force time histories
- 25J model cannot be validated quantitatively
- Calibration produces better qualitative results for both 25J and 50J simulations
- Quantitative results with calibration identify model deficiencies

Questions?