Meso-Mechanical Modeling of Canonical Perforation Experiments

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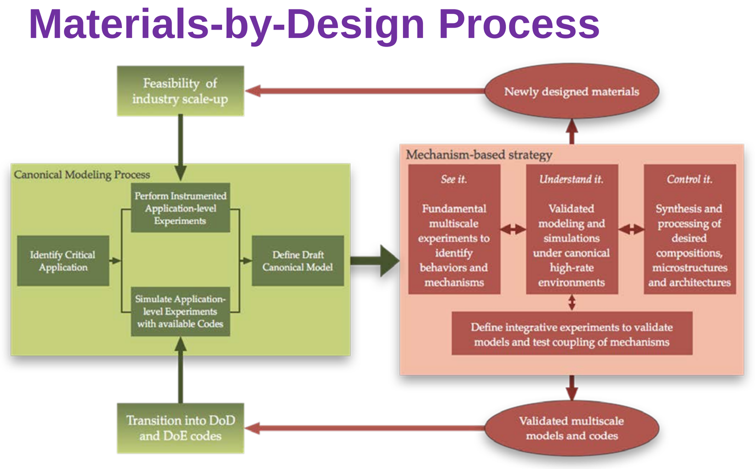
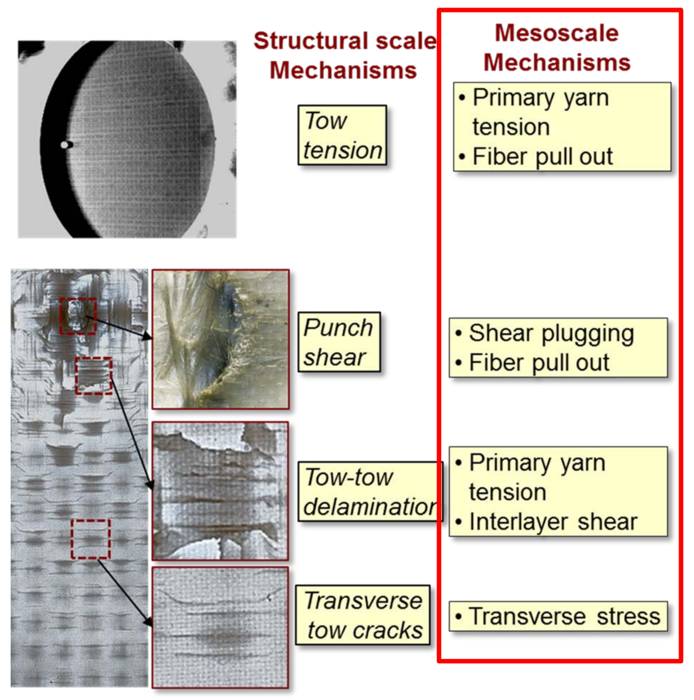
How We Fit

Materials-by-Design Process

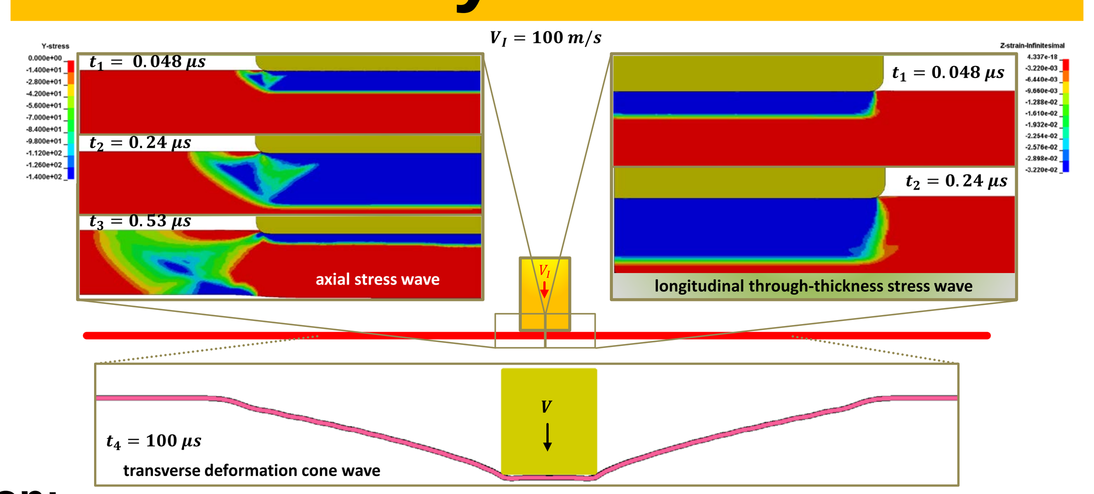


Mechanism-based Approach



- Experiments to see mesoscale damage evolution in space and time
- Modeling & simulation to understand mesoscale damage mechanisms
- Meso-mechanical model of mesoscale mechanisms under impact:
  - Plain weave architecture, tow undulation, tow-tow overlap and bond, primary tow tension, secondary tow tension-shear
  - Tow-matrix and tow-tow debonding, matrix cracking continuum damage and plasticity
  - Longitudinal and radial stress waves, transverse deformation wave
- Model damage and failure modes from understanding of mechanisms

Key Goals



Collaboration:

- UD-JHU: Mesomechanical Modeling and Uncertainty Quantification
- UD-MSU: Damage Assessment of Single-layer Ballistic Impact
- ARL-UD-Drexel: Fabrication of Single-layer Woven Composites for Canonical Ballistic Impact
- ARL-UD-JHU: Filament Winding of Unidirectional Composites

Understand impact damage evolution in space/time for plain weave composite:

- Quasi-static and dynamic material characterization for composite constitutive model
- Impact experiments for cone wave velocity and damage evolution in time
- Simulations of through-thickness stress wave for contribution to tow-tow delamination and debonding
- Canonical single-layer impact experiments for model validation and meso-mechanical modeling of canonical perforation experiments
- In materials-by-design framework, use model to evaluate novel composite material systems and lead to enhanced soldier protection and lethality

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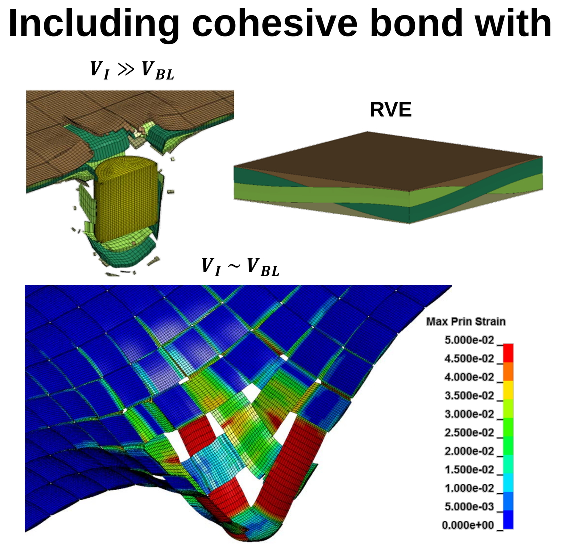
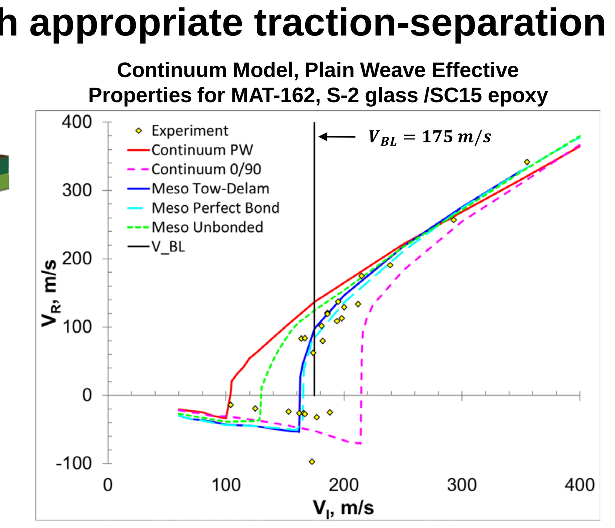
Technical Approach

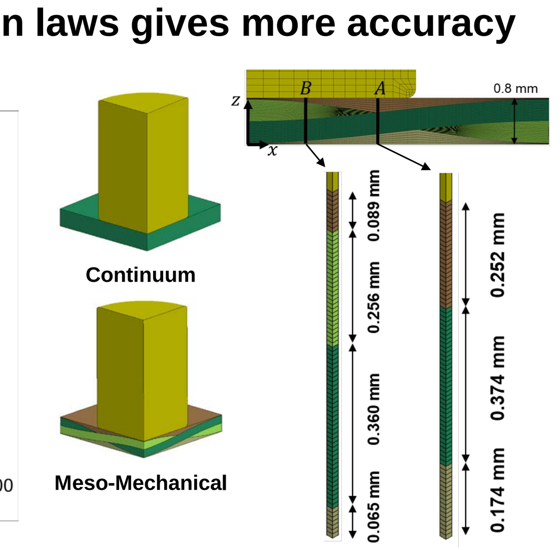
- Macroscopic damage modes dissipate energy through
  - Elastic strain energy (wave motion, vibration), plasticity
  - Meso- and micro-mechanical damage mechanisms:
    - Matrix cracking, debonding, tensile fiber fracture, etc.
- Isolate mechanisms and characterize properties and damage evolution ("See It")
  - Single layer eliminates delamination mode, interlaminar stress field, nesting
  - Focus on perforation phase (eliminate penetration and transition)
  - Characterize quasi-static and dynamic material constitutive model parameters
  - Characterize cohesive law properties for tow-tow delamination damage mode
  - Characterize wave propagation and effect on mesoscale damage modes
- Systematically build up complexity of models ("Understand It")
  - Continuum vs. Meso-mechanical plain weave composites under impact loading
  - Stress wave propagation in 1D and 3D continuum and mesoscale models
  - Meso-mechanical plain weave model geometry with cohesive zones bonding constituents with material properties and geometry validated by experiments

Major Results

- Continuum model reproduces experimental results for $V_I \gg V_{BL} \approx 175\ m/s$, not $V_I \sim V_{BL}$
- Meso-mechanical model more accurately reproduces V_R results and predicts V_{BL}
- Meso model with unbonded tows shows improved $V_I - V_R$ results over continuum
- Meso model with perfectly bonded tows predicts V_{BL} more accurately
- Including cohesive bond with appropriate traction-separation laws gives more accuracy







- Continuum model lacks important mechanisms at meso length scale derived from woven architecture including tow-tow delamination as seen in $V_I - V_R$ results, but also stress wave interaction with the architecture, which may initiate tow-tow delamination cracking leading to tension in primary tows, the dominant energy dissipation mechanism
- Through-thickness stress wave modeling and validation vs 1D theory is examining the effects of stress wave on initiating tow-tow delamination

1D, A, $\dot{u}$, $V_I = 100\ m/s$ — Node-Merged / Cohesive Zones

Matl Layer	Thk, mm	τ, μs	1D Thry, $\dot{u}$, m/s	1D FEM, $\dot{u}$, m/s (Node-Merged)	Error, % (Node-Merged)	1D FEM, $\dot{u}$, m/s (Cohesive Zones)	Error, % (Cohesive Zones)
Epoxy	0.252	0.181	96.0	95.8	0.2	96.0	0.006
Compo	0.374	0.325	51.7	53.5	3.2	53.5	3.2
Epoxy	0.174	0.450	75.6	77.28	2.2	77.3	2.1

1D, A, σ, $V_I = 100\ m/s$ — Node-Merged / Cohesive Zones

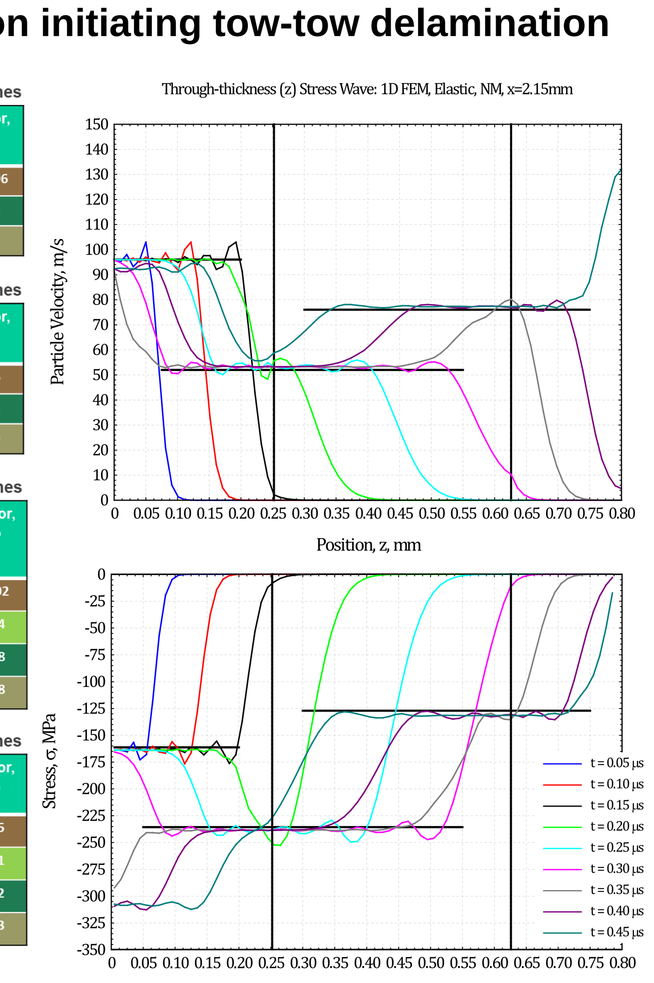
Matl Layer	Thk, mm	τ, μs	1D Thry, σ, m/s	1D FEM, σ, m/s (Node-Merged)	Error, % (Node-Merged)	1D FEM, σ, m/s (Cohesive Zones)	Error, % (Cohesive Zones)
Epoxy	0.252	0.181	161.5	164.0	1.6	164.0	1.6
Compo	0.374	0.325	235.9	238.8	1.2	238.8	1.2
Epoxy	0.174	0.450	127.2	131.6	3.5	131.6	3.5

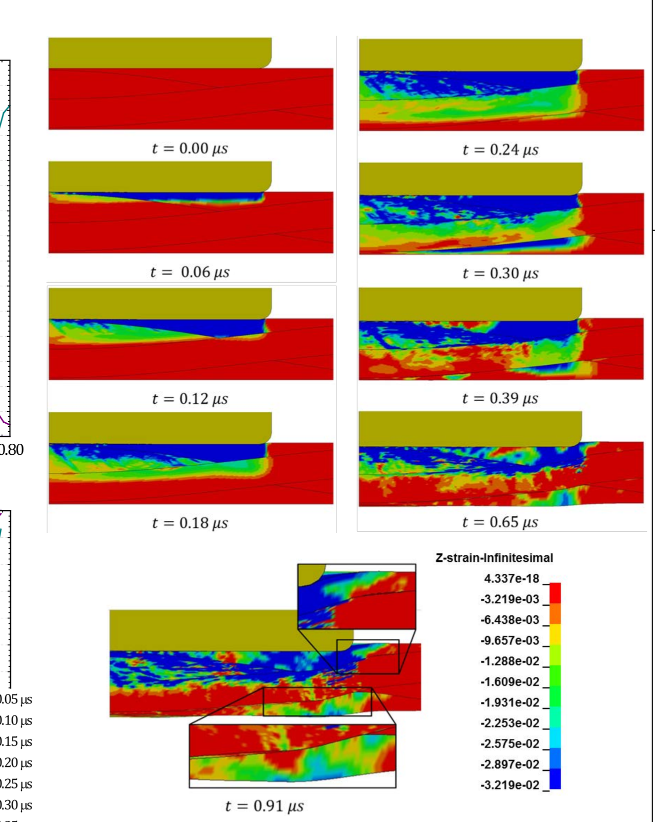
1D, B, $\dot{u}$, $V_I = 100\ m/s$ — Node-Merged / Cohesive Zones

Matl Layer	Thk, mm	τ, μs	1D Thry, $\dot{u}$, m/s	1D FEM, $\dot{u}$, m/s (Node-Merged)	Error, % (Node-Merged)	1D FEM, $\dot{u}$, m/s (Cohesive Zones)	Error, % (Cohesive Zones)
Epoxy	0.089	0.060	96.0	96.0	0.01	96.0	0.02
Compo	0.256	0.159	51.8	53.2	2.7	53.0	2.4
Compo	0.360	0.298	51.8	53.3	2.9	53.2	2.8
Epoxy	0.065	0.342	75.6	77.3	2.2	77.0	1.8

1D, B, σ, $V_I = 100\ m/s$ — Node-Merged / Cohesive Zones

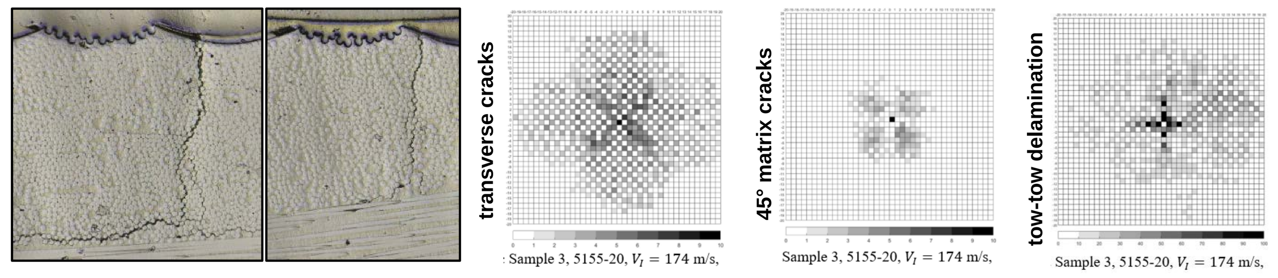
Matl Layer	Thk, mm	τ, μs	1D Thry, σ, m/s	1D FEM, σ, m/s (Node-Merged)	Error, % (Node-Merged)	1D FEM, σ, m/s (Cohesive Zones)	Error, % (Cohesive Zones)
Epoxy	0.089	0.060	161.5	163.9	1.5	163.9	1.5
Compo	0.256	0.159	235.9	238.5	1.1	238.4	1.1
Compo	0.360	0.298	235.9	238.9	1.3	238.6	1.2
Epoxy	0.065	0.342	127.2	127.5	0.2	127.6	0.3





Key Accomplishments/Path Forward

- Demonstrated that at mesoscale, there is a perforation energy difference depending on impact location relative to an RVE
- Damage characterization at microscale showed damage evolves from transverse matrix cracks to tow-tow delamination cracks
- Demonstrated characteristic patterns of mesoscale damage that relate to the mechanisms of damage formation:
  - Transverse cracks – x pattern – tension in primary tows transferred to transverse tows
  - 45° cracks – ◊ pattern – shear between orthogonal tows cracks interstitial matrix pockets
  - Tow-tow delamination – + pattern – delamination of overlap between primary tows in tension and transverse secondary tows
- Found quantity of mesoscale damage increases with increasing impact velocity up to ballistic limit then decreases (localizes) with velocity



- Path Forward includes characterization of quasi-static and dynamic (SHPB) material constitutive model parameters
- Develop test methodology and specimens for determining traction-separation law for tow-tow delamination
- Conduct highly instrumented canonical impact experiments, measure back face deflection, cone wave velocity, and damage evolution for validation
- Use validated model for evaluating impact performance of novel resin/fiber composite systems

Transitions to ARL, within CMRG and to other CMRGs

- Continuum model and meso-mechanical model transitioned within CMRG to JHU group (Brady/Bhaduri) for uncertainty quantification studies
- Fabrication of unidirectional composites by filament winding at ARL, panels and experimental results transitioned within CMRG to JHU group (Ghosh)
- Lower length scale molecular dynamics simulations (Chowdhury, et al.) and micromechanical simulations (Haque, et al.) transition within CMRG to inform the meso-mechanical model, providing traction-separation and material constitutive model inputs
- Validated meso-mechanical model will be transitioned to ARL for evaluation of plain weave composite impact performance

Contribution to MEDE Legacy

- Validated meso-mechanical plain weave composite model will be applied to woven composites of interest to the Army
- In materials-by-design framework, model will be used to evaluate novel composite material systems in ballistic impact leading to enhanced protection for the soldier

Journal publications:

- Meyer et al., Mesoscale Ballistic Damage…, Intl J Impact Engineering 113, 2017
- Bonyi, Meyer, et al., Quantification of Ballistic Impact Damage, Intl J Damage Mechanics, 2018.

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