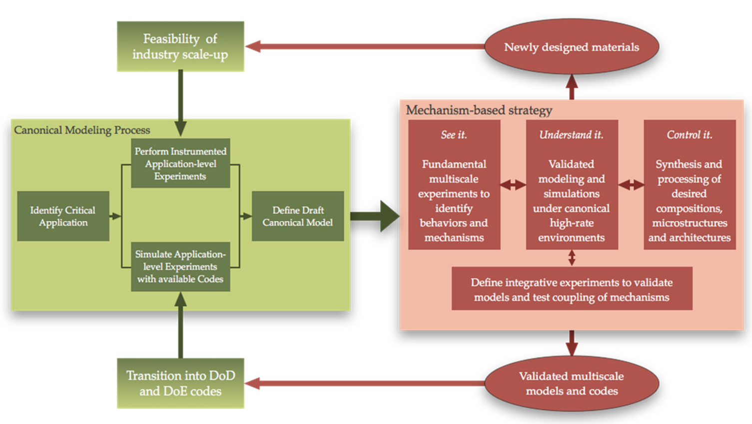
Meso-Mechanical Modeling of Canonical Perforation Experiments

Christopher S. Meyer (UD/CCM, ARL), Bazle Z. (Gama) Haque (UD/CCM), John W. Gillespie, Jr. (UD/CCM), Daniel J. O'Brien (ARL), Enoch Bonyi (MSU), Kadir Aslan (MSU)

Enterprise for Multi-scale Research of Materials

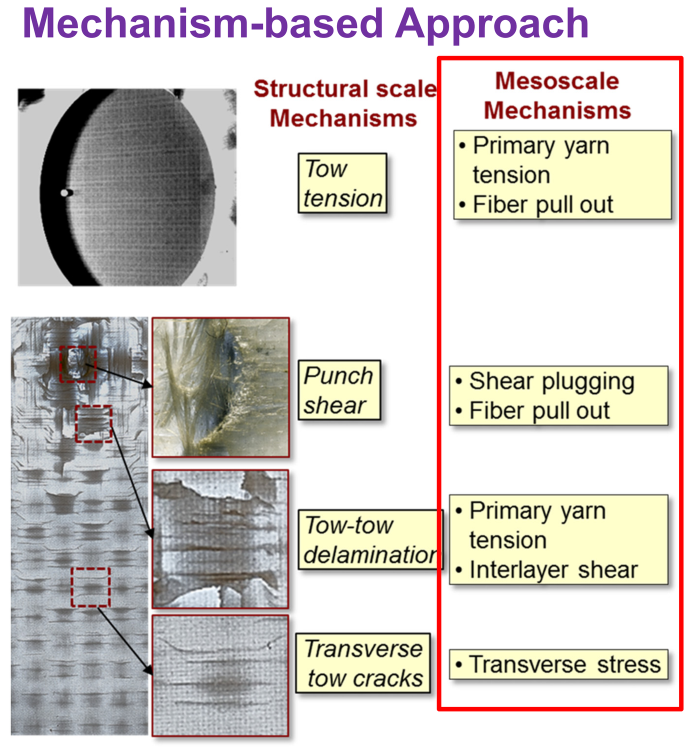
How We Fit

Materials-by-Design Process



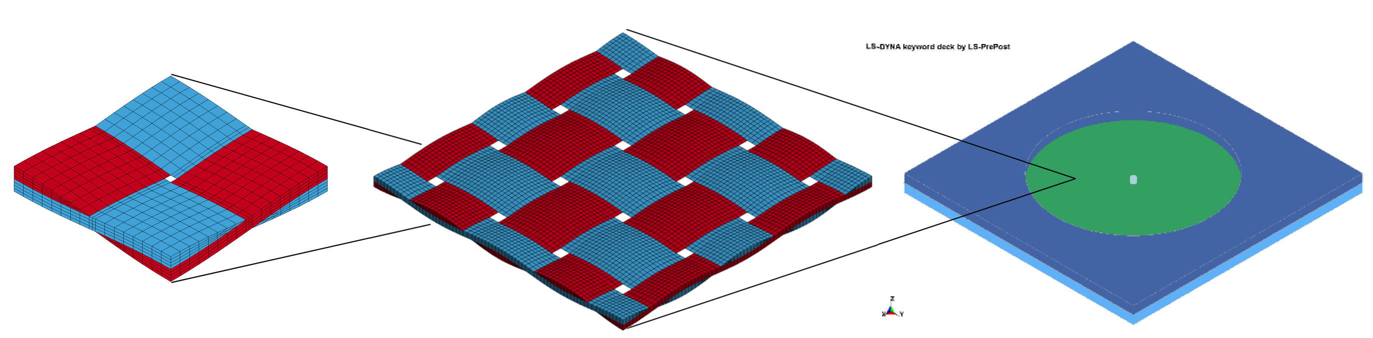
- Experiments to see mesoscale damage mechanisms: matrix cracking, tow-tow debonding, tension-shear tow failure
- Modeling & simulation to understand mesoscale damage mechanisms

Mechanism-based Approach



- Meso-mechanical model to capture mechanisms occurring at mesoscale:
  - Transverse cone wave speed
  - Transverse tow cracking
  - Tow-matrix and tow-tow debonding
- Model damage and failure modes from understanding of mechanisms

Key Goals



Collaboration:
- Experiments (tension and impact): ARL, UD/CCM
- Damage mapping, characterization, visualization: MSU, ARL, UD/CCM
- Microscale modeling and model inputs: JHU, UD/CCM
- Uncertainty quantification: JHU, UD/CCM

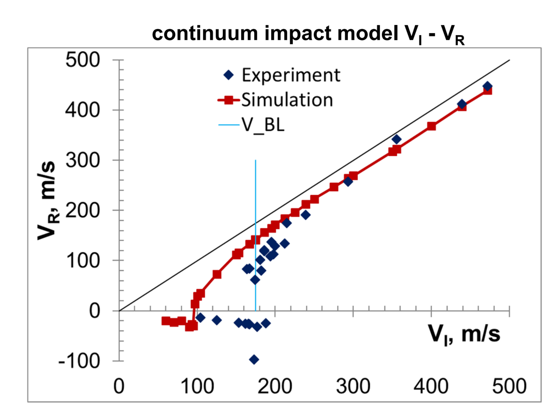
Meso-mechanical modeling:
- Develop mesoscale test method for tow-tow delamination traction-separation for model input properties
- Quasi-static and dynamic impact testing for model validation
- Impact experiments for through-thickness deformation wave propagation and effect on mesoscale damage modes and energy dissipation
- Build mesoscale model to better predict energy dissipation and damage over continuum model, validate with experimental data:
  - Tension and Punch-shear (transverse cracking, tow-tow delamination)
  - Impact (deformation wave propagation, back-face deflection, impact vs. residual velocity)
- In materials-by-design framework, use model to evaluate novel composite material systems and lead to enhanced soldier protection and lethality

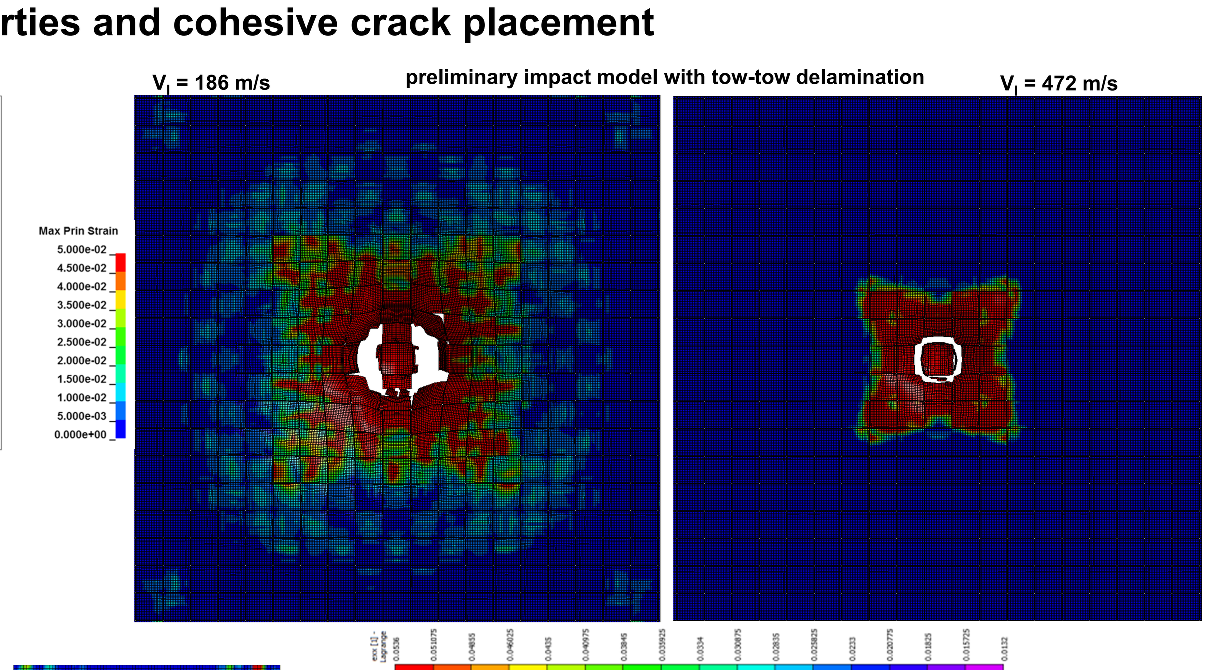
Technical Approach

- 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 that lead to damage modes ("See It")
  - Single layer eliminates delamination mode, interlaminar stress field, nesting
  - Focus on perforation phase (eliminate penetration and transition)
  - Isolate and characterize tension and shear damage modes and energy dissipation
  - Characterize elastic wave propagation and effect on mesoscale damage modes and energy dissipation
- Systematically build up complexity of models ("Understand It")
  - Homogenized continuum with plain weave properties
  - Meso-mechanical plain weave model geometry with cohesive zones bonding constituents

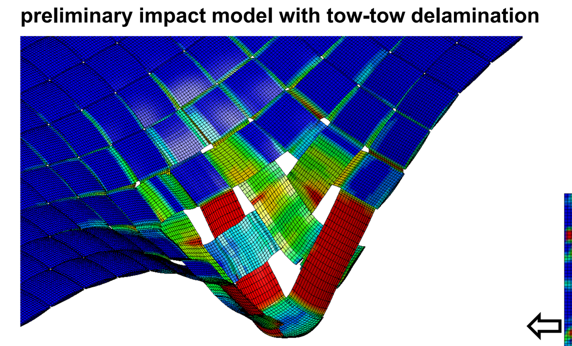
Major Results

- Continuum model reproduces experimental results above $V_{BL} \approx 175$ m/s, not at or below
- Preliminary meso-model results with tow-tow delamination indicate model is approximating energy dissipating delamination and sliding between tows, but need experimental results to provide correct tow-tow delamination cohesive parameters
- Preliminary model results also indicate strain localization at high velocity and strain concentrations in transverse tows where we expect to see transverse cracking, need experimental crack properties and cohesive crack placement

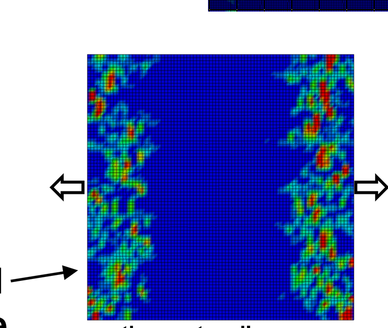




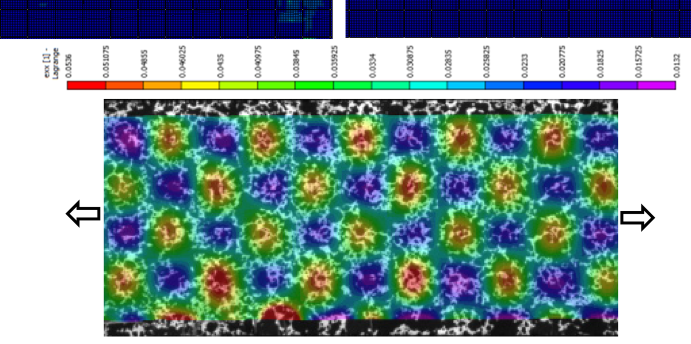
preliminary impact model with tow-tow delamination



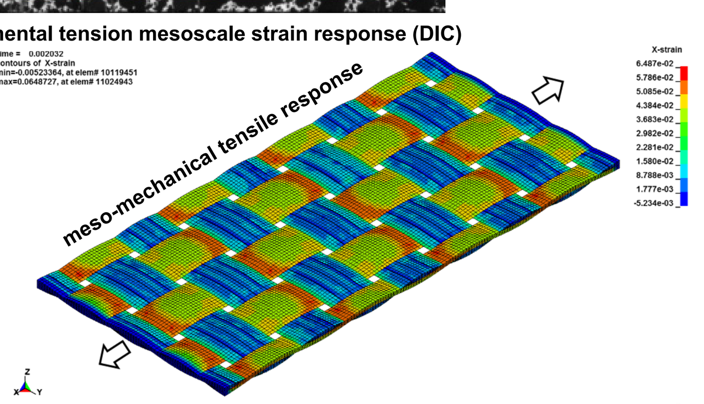
Continuum tension model cannot capture mesoscale strain response



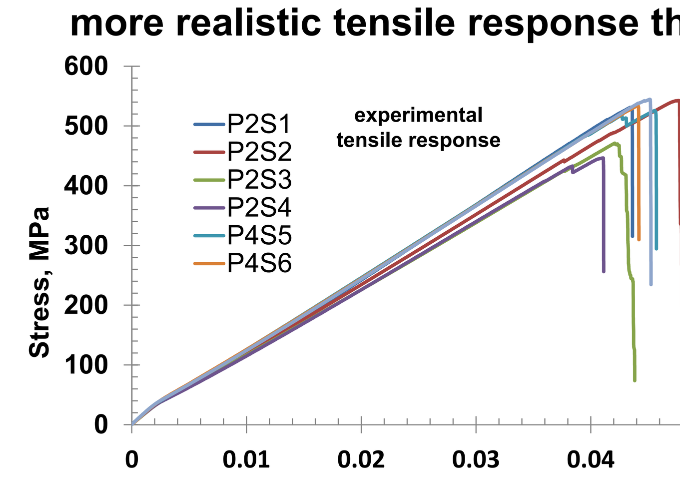
continuum tensile response



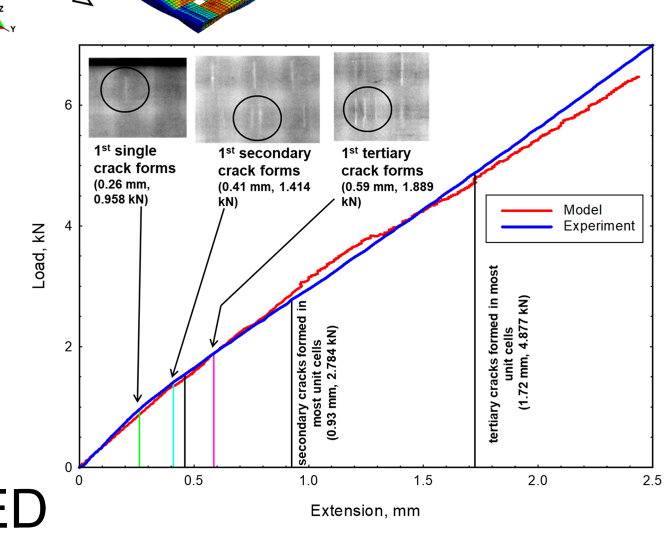
experimental tension mesoscale strain response (DIC)



Tensile testing of single-layer plain weave composite:
- experiments toward determining tensile strength distribution for model validation and UQ input
- preliminary meso-mechanical model results show more realistic tensile response than continuum

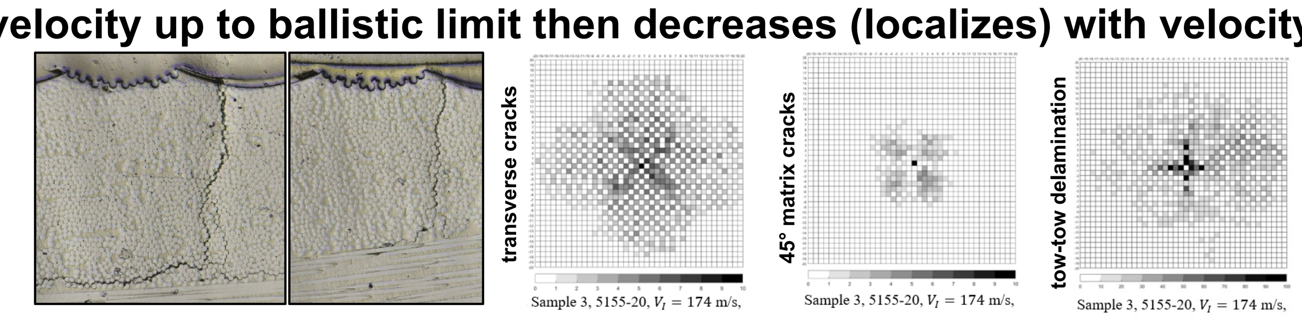


Spcmn	Width (in)	E_1 (GPa)
P2S1	1	12.477
P2S2	3	13.194
P2S3	3	13.650
P2S4	1	13.282
P4S5	2	13.543
P4S6	2	14.720
P4S7	2	13.887



Key Accomplishments

- Demonstrated that at mesoscale, there is a perforation energy difference depending on impact location relative to a unit cell
- Damage characterization at microscale showed damage evolves from transverse matrix cracks to tow-to-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



Ongoing and Future Work

- Refine meso-model in terms of delamination response and transverse matrix cracking by evaluating/optimizing cohesive zone formulation, bilinear traction-displacement behavior, and predefined fracture planes
- Conduct tension testing 2-in wide single-layer PW tensile specimens, determine quasi-static tensile strength distribution, use DIC to identify strain levels at which transverse matrix cracks initiate and proliferate
- Demonstrate state-of-the-art continuum model (MAT_162) cannot adequately capture low-velocity VI-VR curve and transverse deformation wave propagation / back-face deflection
- Develop test methodology and specimens for determining quasi-static tow-tow delamination load-displacement behavior using punch-shear fixture, also conduct higher-rate drop testing to determine dynamic tow-tow delamination behavior for rate-dependent model inputs
- Develop test methodology and test specimens for determining quasi-static transverse crack load-displacement behavior using Keyence microscope and micro-tension test fixture
- In collaboration with ARL, conduct low velocity impact experiments of single-layer PW specimens large enough to measure transverse deformation cone wave velocity and back-face deflection
- Model the quasi-static and dynamic responses to validate meso-model

Impact

- 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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