Meso-Mechanical Modeling of Canonical Ballistic Impact Experiments

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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, transverse matrix cracks to tow-tow delamination cracks
  - 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 $v_f > v_{ref} \approx 175 \text{ m/s}$, not $v_f \sim v_{ref}$
- Meso-mechanical model more accurately reproduces $v_f$ results and predicts $v_{ref}$
- Meso model with perfectly bonded $v_f$ results over continuum
- Meso model with bonded tow $v_f$ results more accurately
- Including cohesive bond with appropriate traction-separation laws gives more accuracy

How We Fit

- Key Goals
  - Characterize quasi-static and dynamic material constitutive model parameters
  - Characterize wave propagation and effect on mesoscale damage modes
  - Systematically build up complexity of models (“Understand It”)
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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

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

Collaboration:

- UD-JHU: Mesoscale 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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