Lighter Armored Vehicles • Reduced Soldier Loads • Increased Reliability

Materials in Extreme Dynamic Environments

A Collaborative Research Alliance

Professor K.T. Ramesh
The Johns Hopkins University (LRO)
Recipient Program Manager

Dr. John H. Beatty
US Army Research Laboratory
Cooperative Agreement Manager

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What are “Extreme Dynamic Environments”?

Strain Rates up to $10^6$, Pressures up to 50 GPa
Outline

• Background for MEDE CRA & Goals
• Approach and Uniqueness
• Research Team and Program Structure
• Science of Materials in Extreme Dynamic Environments
• Technical Challenges and Activities by Material Class
• The Collaboration
Program Basis: Why MEDE

From BAST/NMAB report:
DoD should establish a defense initiative for protection materials by design... it should include a combination of computational, experimental, and materials testing, characterization, and processing research conducted by government, industry, and academia.

FUTURE PAYOFF
Vehicle and Soldier Protection - 1/3 savings in weight
MEDE Uniqueness:

Canonical model used to translate the application to basic science needs

Discovery phase is critical – we don’t yet know property/performance trade-offs

Materials by design for protection materials
Approach
Fundamental research with a “materials by design” approach to relate the material response across critical length & time scales to specific properties

Multiscale/Multidisciplinary Materials Design Approach

Modeling & Simulation

Bridging the Scales

Transformational Protection and Electronic Materials

Synthesis & Processing

Advanced Experimental Techniques

Validation and Verification

Multiscale Material Characteristics & Metrics

Protection and Electronic Materials for U.S. Army Systems
Materials in Extreme Dynamic Environments (MEDE) Collaborative Alliance Members

LRO: Johns Hopkins University
Program Director: K.T. Ramesh
Hopkins brings expertise in experiments under extreme conditions, characterization and modeling from atomistic to continuum scales, scale-bridging, and science-based parameterization

Rutgers University
Principal: Richard A. Haber
Rutgers brings expertise in the processing and fundamental properties of ceramic materials, characterization and modeling at multiple scales, process modeling

California Institute of Technology
Principal: Kaushik Bhattacharya
Caltech brings expertise in modeling across the scales, scalable computational methods, nanoscale and microscale experiments, and high strain rate characterization

University of Delaware
Principal: John W. Gillespie, Jr.
UDel brings expertise in polymers, the design, characterization and modeling of composites across multiple scales, processing of polymers and composites, interphase science

US Army Research Laboratory
Collaborative Alliance Manager: John H. Beatty
ARL Brings expertise in armor design and armor materials, constitutive modeling, multiscale modeling, high strain rate characterization, computational tool development, transition
MEDE CRA Institutions

Army-Academic-Industrial-National & Global Collaboration Engine
MEDE
“Four Material Classes for Protection”

Significant Efforts within ARL and the JHU MEDE Consortium

**Magnesium**
- Deformation Processing increases mechanical properties by reducing grain size.

**Boron Carbide**
- Unique High Loading-Rate Apparatus for Single-Fiber (~10 um diameter) Experiment

**Ultra-High Molecular Weight PolyEthylene**
- Load transducer
- Bar supports
- Incident bar
- Fiber mounting flats

**S-Glass/Epoxy**
- Monomer Chemistry and Structure
  - Group rotation
  - Flexibility
  - Molecular interactions
  - Functionality and spacing
- System
- Fiber Reinforced Composite
  - Fiber / fiber type
  - Weave structure
  - Resin-fiber interface
- Formulation
  - Additives
  - Fillers (nano to micro)
  - Interfaces
- Chain Structure
  - Crosslink density - M
  - Defects / dangling ends
  - Chain topology / distribution
- Composition and Morphology
  - Monomer mixtures
  - Blends
  - Phase behavior

Mg, B4C, UHMWPE, S-Glass/Epoxy are important to future protection systems for Soldiers and Vehicles
Technical Structure

4 Materials Collaborative Materials Research Groups (CMRGs)

Each CMRG has 3 Collaborative Technical Research Groups (CTRGs)

Experimental CTRG

Modeling CTRG

Processing CTRG
Tasks Organized by Material

CMRG Magnesium
T. Weiss
H. Maupin

CMRG Composites
J. Gillespie
J. Sands

CMRG UHMWPE
G. Palmese
M. VanLandingham

CMRG Boron Carbide
R. Haber
J.P. Singh

Mg Processing
CTRG

Mg Experimental
CTRG

Mg Modeling
CTRG

Composites Modeling
CTRG

Composites Experimental
CTRG

Composites Processing
CTRG

UHMWPE Processing
CTRG

UHMWPE Experimental
CTRG

UHMWPE Modeling
CTRG

Boron Carbide Modeling
CTRG

Boron Carbide Experimental
CTRG

Boron Carbide Processing
CTRG
Collaboration by Cross-cutting Themes

- Mg Processing CTRG
- Composites Processing CTRG
- UHMWPE Processing CTRG
- Boron Carbide Processing CTRG
- MSME Processing

- Mg Experimental CTRG
- Composites Experimental CTRG
- UHMWPE Experimental CTRG
- Boron Carbide Experimental CTRG
- MSME Experimental

- Mg Modeling CTRG
- Composites Modeling CTRG
- UHMWPE Modeling CTRG
- Boron Carbide Modeling CTRG
- MSME Modeling
## MEDE CRA Schedule

<table>
<thead>
<tr>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
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<th>2017</th>
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</table>

### Discovery Experiments
- Develop prediction of several continuum properties from sub-scale modeling

### Integrative Experiments
- Real time Micro-structural interrogation during high rate experiments

### Characterization of High Strain Rate Behavior

### Advanced Characterization Techniques

### Development of Validated Models at Appropriate Scales
- Validation of High Strain Rate Physics Across Material Scales

### New Approaches to Scale Bridging
- 30% Improvement Concurrent Key Properties

### Development of New Theoretical and Computational Modeling Approaches
- 1 Gen Designed Materials for Protection

### Provide Baseline Model Materials
- Develop iterative controlled materials

### Linking to Industry
- Develop first-generation designed protection materials

### Spin-outs to Armor Design Codes and Industry
An Overview of the Science of MEDE

- Conceptual approach (design constraints)
- The science of extreme dynamic events
- The mechanism-based Materials by Design strategy for Materials in Extreme Dynamic Environments
- State of the art for each material system
- Collaborative approaches for each material system
Conceptual Approach to the Design of Protective Materials for Extreme Dynamic Environments
Science of Extreme Dynamic Events: Mechanisms

- Extreme dynamic events (e.g. terminal ballistics) involve deposition of large amounts of energy in very short times.

- The speeds at which energy can propagate away from point of deposition are finite (wave speeds, crack speeds).

- As a result, the local energy density rises very rapidly, and the material seeks new internal pathways to dissipate this energy.

- We call these energy pathways “mechanisms.”

- Which pathways (mechanisms) are available and are then expressed depends on the material and on the severity of the threat.
Mechanisms in Extreme Dynamic Events

• Dynamic deformation and failure *mechanisms* (not just material properties) dominate extreme dynamic events

• What are the mechanisms? Have to be able to see them *during* the extreme event.

• Each combination of material and threat leads to a specific spectrum of dynamic mechanisms.

• To *control* response to extreme event, we must control the mechanisms.

• To *design* the material for performance in the extreme event, we must *design* the expression of that mechanism spectrum.
A Mechanism-Based Materials by Design Strategy for MEDE

- See it.
  EXPERIMENTAL CTRG
- Understand it.
  MODELING CTRG
- Control it.
  PROCESSING CTRG

Design it.
The Science of Extreme Dynamic Events: Scales

• As the local energy density increases, the energy dissipation in the system must explore smaller and smaller length scales.

• For example, such an analysis suggests that many blast problems can be addressed through mm-scale structural control.

• However, for ballistic problems we must design and control energy pathways at the micron-scale.

• Micron-scale dynamic mechanisms are very strongly dependent on nanoscale and atomistic behaviors at very short times.

• The extreme dynamic environment typically exercises the full range of length scales and timescales, making this the quintessential multiscale problem.
Multiscale Modeling Strategy for MEDE

- **Canonical Model**
- **Discovery Phase**: Discovery Experiments identify mechanisms
- **Multiscale Science Phase**: Modeling and Simulation at Appropriate Length and Timescales and Scale Bridging
- **Integration Phase**: Integrated model or code
- **Validation Phase**: Integrative Experiments with deep multiscale diagnostics and rich datasets

Clearly identify “discovery experiments” and “integrative experiments” in EDE
Expanding the Domains of Validity of Current Experiments and Modeling

Time Scale

Length Scale

Nanoindentation
STM AFM
Transmission EM
In Situ Deformation Experiments
Scanning EM
Microcompression Microtension
Continuum Mechanics
Kolsky Bar Experiments
Plate Impact Shock Experiments
Spectroscopy MD
Laser Shock

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Global Multiscale Materials by Design Strategy

Validated multiscale models and codes

ARL Enterprise Collaborative Fundamental Research

Make material samples

Provide materials in quantity

Feasibility to scale-up production

Define "canonical" high rate environment

Industry

RDECOM
What is the State of the Art?
# State of the Art for Metals (Magnesium)

<table>
<thead>
<tr>
<th>Scale or Technical Core Element</th>
<th>Primary Mechanism</th>
<th>Advanced Exper. Tech.</th>
<th>Modeling &amp; Simulation</th>
<th>Bridging the Scales</th>
<th>Material Char. &amp; Prop</th>
<th>Synthesis &amp; Processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic -a-</td>
<td>Electronic structure, thermal motion of nuclei, reactivity</td>
<td>Spectroscopy, Shock Hugoniot, EELS</td>
<td>QM, DFT, MD, EAM</td>
<td>Coarse-grained DFT</td>
<td>Moduli, bond energy, γ-surfaces, core energies, SFE, EoS</td>
<td>Chemistry, alloying</td>
</tr>
<tr>
<td>Crystal -b-</td>
<td>Dislocation cores, slip &amp; interactions (hardening), dislocation density evolution and patterning, twinning, thermal softening, phase transformations</td>
<td>HREM, TEM, Dynamic TEM, Kolsky bar, nanoindentation, microcompression, microtension, in situ X-ray diffraction, pyrometry</td>
<td>MD, discrete dislocation dynamics, discrete twinning dynamics, crystal plasticity, FEM</td>
<td>Hot QC, hyperdynamics</td>
<td>Subgrain and cell structure, inclusions, precipitates and dispersions, twin volume fractions, high rate behaviors</td>
<td>Dispersion and precipitation hardening, nanocomposites</td>
</tr>
<tr>
<td>Mesoscale -c-</td>
<td>Grain boundaries, grain and subgrain rotation, texturing, misorientation distribution, crack nucleation</td>
<td>HREM, TEM, Dynamic TEM, Kolsky bar, X-ray microdiffraction, pyrometry</td>
<td>Crystal plasticity, gradient terms, Lagrangian (FEM, OTM), Eulerian (CTH)</td>
<td>Defect dynamics</td>
<td>Grain size distribution, grain morphology, texture, orientation distribution, high rate behaviors</td>
<td>Grain size control, grain boundary control, microstructural design</td>
</tr>
<tr>
<td>Macroscale -d-</td>
<td>Anisotropic viscoplasticity, texture evolution, shear localization, massive fragmentation, spallation</td>
<td>Shock expts, Kolsky bar, in situ microcompression, spall experiments, torsional Kolsky bar, expanding ring, pyrometry</td>
<td>Viscoplasticity, Lagrangian (FEM, OTM), Uncertainty Quantification, Eulerian (CTH)</td>
<td>Enhanced continua, nonlocal models, defect dynamics</td>
<td>High-strain-rate, high-pressure and high-temperature response, EoS, post-test damage assessment</td>
<td>Casting, rolling, extrusion, forging, ECAP/SPD</td>
</tr>
</tbody>
</table>

**Generally identified, understood or implemented**

**Sometimes identified, some understanding, some implementation**

**Weak identification understanding, or implementation**

**Poorly identified, poorly understood, or early implementations**

**Not identified, not understood or not implemented**
Magnesium: A Model Metal System

- Magnesium has the lowest-density of the structural metals
- One of the most abundant metals in the Earth’s crust
- Density of 1.7 gm/cc - less than a quarter that of steel
- Primary difficulties are low strength and anisotropy
- Most rapidly growing metals industry (but small)
MEDE Multiscale Strategy for Magnesium

Critical Time-resolved and Space-resolved Canonical Dynamic Experiments

Define Dynamic Mechanisms & Corresponding Scales

Synthesis & Processing Controls
Magnesium: Experiments and Characterization

**Discovery Experiments**

- Time-resolved in situ dynamic microdiffraction

- Grain size hardening of prismatic slip and tensile twinning is very pronounced, whereas basal slip shows only small hardening.

**Integrative Experiments**

- Dynamic transmission electron microscopy
Magnesium: Modeling and Scale-Bridging

Influence of Solutes on g-surfaces

Coarse-grained Density Functional Theory

Undeformed and deformed polycrystalline microstructures

The Quasicontinuum Method
Magnesium: Synthesis and Processing

High-quality Mg alloys available in variety of forms.

**True Stress (MPa)**

- 600
- 500
- 400
- 300
- 200
- 100
- 0

**True Strain**

- 0.25
- 0.20
- 0.15
- 0.10
- 0.05
- 0.00

**Diameter (µm)**

- 0.3 – 0.5 µm
- 1-2 µm
- 25 µm
- 2-4 µm

**Alloy AZ31**

- As Received
- Process 1
- Process 2
- Process 3

**Tension- along FD**

**High Pressure Torsion**
Boron Carbide: A Model Ceramic System

• Boron carbide is the armor ceramic with the greatest potential for revolutionary improvements.

• The material has high hardness, and a high Hugoniot Elastic Limit.

• Has a low theoretical density (30% less than that of SiC).

• However, it shows a pronounced loss of strength at high impact velocities.
# State of the Art for Ceramics (Boron Carbide)

<table>
<thead>
<tr>
<th>Scale or Technical Core Element</th>
<th>Primary Mechanism</th>
<th>Advanced Exper. Tech. - 1-</th>
<th>Modeling &amp; Simulation - 2-</th>
<th>Bridging the Scales - 3-</th>
<th>Material Char. &amp; Prop - 4-</th>
<th>Synthesis &amp; Processing - 5-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic -a-</td>
<td>Electronic structure, thermal motion of nuclei, bond rupture</td>
<td>Spectroscopy, Shock Hugoniot</td>
<td>QM, DFT, EoS</td>
<td>Coarse-grained DFT, potentials</td>
<td>Moduli, bandgap</td>
<td>Chemistry</td>
</tr>
<tr>
<td>Crystal -b-</td>
<td>Cleavage, Amorphization, Twinning, Dislocation motion, stacking fault nucleation, twin-induced cracking</td>
<td>HREM, TEM, Dynamic TEM, Kolsky bar, microcompression, nanoindentation, DAC</td>
<td>MD, discrete dislocation dynamics, discrete twinning dynamics, crystal plasticity</td>
<td>Coarse-grained DFT, hot QC, hyperdynamics</td>
<td>Anisotropic moduli, cleavage and twinning planes, intrinsic toughness</td>
<td>Powder production and control</td>
</tr>
<tr>
<td>Mesoscale -c-</td>
<td>Triple-junction crack nucleation, Grain boundary failure, defect activated cracks, intergranular vs. transgranular fracture, crack interactions, anisotropic elastic effects on residual stresses and cracking</td>
<td>HREM, TEM, Dynamic TEM, Kolsky bar, X-ray microdiffraction, instrumented indentation, phase contrast, in situ microcompression for GB strength, acoustic spectroscopy</td>
<td>Crystal plasticity, gradient terms, microstructure-resolved FEM and OTM</td>
<td>Defect dynamics, probabilistic models</td>
<td>Grain size distribution, grain morphology, texture, damage characterization</td>
<td>Grain size control, grain boundary control, microstructural design, advanced processing techniques</td>
</tr>
<tr>
<td>Macroscale -d-</td>
<td>Fast crack growth, effective plasticity, anisotropic damage growth, short vs long cracks, texture, fragmentation</td>
<td>Shock expts, Kolsky bar, spall experiments, in situ visualization of damage</td>
<td>Viscoplasticity, FEM, OTM, Uncertainty Quantification</td>
<td>Enhanced continua, nonlocal models, defect dynamics</td>
<td>High-strain-rate and high-pressure response, non-proportional loading, damage characterization</td>
<td>Sintering, hot-pressing, advanced processing techniques</td>
</tr>
</tbody>
</table>

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Boron Carbide: Experiments and Characterization

Discovery Experiments

Integrative Experiments
Boron Carbide: Modeling and Scale-Bridging

OTM Simulations of Massive Dynamic Failure

Failure of Unconfined and Confined Boron Carbide

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Multiscale Modeling of Ceramics
Boron Carbide: Synthesis and Processing

Modeling Scale
- Atomic
- Crystal
- Mesoscale
- Continuum

Experiments
- Raman & IR Spectroscopy
- Nanoindentation, DAC, microcompression
- Shock, Kolsky, X-ray diffraction
- Confined dynamic compression

Processing
- Chemistry (doping)
- Designer crystals (polytypes)
- Grain boundaries, grain sizes, texture, defect distribution
- Device/Structure

Graph showing Vickers hardness vs. B/C ratio:
- Boron carbide 20 vol.% Y-doped aluminoborosilicate glass

Image showing phase diagram of boron carbide structures:
- B,C polytypes
- B_{12}C (CBC)
- B_{14}C (CCC)
- B_{11}C (CBC)
- B_{10}C (CCB)
- B_{12} + Graphite
- B_{11}C (CCB)
- B_{12}C (BCB)
- B_{11}C (CCB)
- B_{12} + a-C (M = 10)
- B_{12} + a-C (M = 1)

Image showing microstructure with a measurement of ~30 nm.
# State of the Art for Polymers (PE, Epoxy)

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<tbody>
<tr>
<td><strong>Atomistic/ Molecular</strong> -a-</td>
<td><em>Thermal motion, Chain conformation changes, Crystallinity, Bond rupture</em></td>
<td><strong>Flash DSC(Tg, Tm)</strong> In situ XRD, FTIR, In situ Electron Diffraction</td>
<td>All atom MD simulations</td>
<td>Coarse-grained potentials, models</td>
<td>Molecular conformation, Orientation, Molecular relaxation times, Molecular stiffness</td>
<td>Irradiative crosslinking of linear chains, Crystallization catalysts, Development of new catalysts for linear polymers</td>
</tr>
<tr>
<td><strong>Nano/Meso (Filament phase domains)</strong> -b-</td>
<td><em>Local defects motion (chain ends, kinks, entanglements), Chain orientation and stretching, Crystal/amorphous interphase</em></td>
<td><strong>High strain rate filament testing, In situ XRD, FTIR, Polarized Light Microscopy, High strain rate interface testing</strong></td>
<td><strong>MD simulations –united atom / coarse-grained; Constitutive models for domains, interphase</strong></td>
<td>Coarse and fine-graining – hierarchical and simultaneous, time-temperature scaling, defect dynamics</td>
<td>High rate – properties, Crystal morphology, % crystallinity, Surface morphology and chemistry, Crystal orientation, Intermolecular shear strength</td>
<td>Surface modification, Draw ratio, Fiber diameter, Annealing steps, Molecular weight, End group termination</td>
</tr>
<tr>
<td><strong>Continuum (Filaments)</strong> -c-</td>
<td><em>Viscoelasticity Plasticity Strain hardening Fracture patterns Domain evolution</em></td>
<td><strong>High rate testing (SPHB, Shock), in situ WAXD</strong></td>
<td><strong>FEM, EOS, Homogenization</strong></td>
<td>Coupled atomistic and continuum calculations of deformation and fracture</td>
<td>Viscoelastic, Viscoplastic Shock EOS</td>
<td>Cure kinetics, Process parameters (temperature, time, pressure)</td>
</tr>
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UHMWPE: Experiments and Characterization

Discovery Experiments

Unique High Loading-Rate Apparatus for Single-Fiber (~10 um diameter) Experiment

Integrative Experiments
UHMWPE: Modeling and Scale-Bridging

Crystalline and Amorphous Domains
<table>
<thead>
<tr>
<th>Scale or Technical Core Element</th>
<th>Primary Mechanism</th>
<th>Advanced Exp. Techniques</th>
<th>Modeling &amp; Simulation</th>
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<th>Material Characteristics</th>
<th>Synthesis &amp; Processing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Molecular (Network polymer)</strong></td>
<td>Network deformation</td>
<td>High strain rate testing, In situ XRD, FTIR, Polarized Light Microscopy, High strain rate interface testing</td>
<td>MD simulations of networks to describe failure behavior of model networks</td>
<td>Development of constitutive relationships based on MD simulations</td>
<td>Distribution of crosslinks and mobility as a function of T relative to Tg, local network deformation - nanocavitation</td>
<td>Design of networks containing passive protovoids and thermally activated protovoids</td>
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<tr>
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<td>Crosslink density</td>
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<td>Network connectivity</td>
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<td>Nanocavitation</td>
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<td>Relation to Tg</td>
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<td><strong>Nanoscale (Interphase)</strong></td>
<td>Debonding, fiber pull-out, sliding friction, interphase failure</td>
<td>High rate interphase test methods (DILA, modified droplet, fragmentation etc.)</td>
<td>Peridynamic EMU, LS-Dyna, FEA, Cohesive zone</td>
<td>Nano- to micro-scale force potentials, Peridynamics, homogenization methods</td>
<td>Rate dependent interphase strength and energy dissipation</td>
<td>Interphase chemistry, fiber surface texture, resin wetting of textured fiber</td>
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<tr>
<td><strong>Microscale (Fiber/tow)</strong></td>
<td>Fiber fracture (tension, compression), Fiber shear, Fiber crush, Statistical strength distributions</td>
<td>High rate filament/bulk testing, High speed photography, Fiber indentation</td>
<td>Peridynamics EMU, LS-Dyna, FEA</td>
<td>Peridynamics, homogenization methods (HCDM)</td>
<td>High rate nonlinear properties of filaments and composite tows, statistical strength distributions</td>
<td>Fiber sizing and surface treatments, filament count, yarn twist</td>
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<tr>
<td><strong>Mesoscale (Weave Architecture)</strong></td>
<td>Delamination, matrix cracking, micro buckling, friction, strain rate sensitivity, crack propagation, wave propagation and interaction</td>
<td>High rate testing (SPHB and Shock), Dynamic Yarn pullout, delamination (butterfly, wedge crack), High speed photography/DIC</td>
<td>FEA methods (LS-Dyna), Homogenization methods (HDCM), Peridynamic EMU, Analytical, Resin flow dynamics</td>
<td>Homogenization methods (HCDM), Coarse element, Non-linear micromechanics, RVE</td>
<td>Rate dependent non-linear stress-strain behavior, statistical property distributions, shock EOS</td>
<td>Fabric weave architecture control, fabric multi-scale permeability and resin flow</td>
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<tr>
<td><strong>Continuum</strong></td>
<td>Matrix softening, delamination and friction, fiber tension and compression shear, fiber crush, compressibility</td>
<td>High rate testing (SPHB, Shock, Ballistic), Composite property measurement</td>
<td>Micro-mechanics, failure envelopes, continuum damage models; Analysis using FEM, SPH, EFG, Cohesive Zone, Analytical</td>
<td>Homogenization theory (HCDM), RVE, multi-scale, Wave propagations across length scales, hierarchical approaches</td>
<td>Rate dependent non-linear stress-strain behavior, shock EOS, statistical property distributions</td>
<td>2D and 3D fiber architecture, multi-layered constructions, resin flow and permeability</td>
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S2-Glass Epoxy Composites: Experiments and Characterization
S2-Glass Epoxy Composites: Modeling and Bridging the Scales

- Continuum version of molecular dynamics
- Atomistic-to-continuum coupling
- Multi-scale modeling
- Nano-scale modeling of material failure

Peridynamic integral equation of motion
\[ \rho \ddot{u}(x,t) = \int_{R} f(u^r - u^s, x^r - x^s) dV^r + b(x,t) \]

Interaction of forces
- Bond stretch
- Bond force
- Yielding
- Tension
- Compression
- Bond failure

Numerical implementation
\[ \rho \ddot{u}_i = \sum_{k \in H} f(u_i^r - u_i^s, x_i - x_k) dA_i + b(x_i,t) \]

Effect of 2D/3D fabric architecture
- Optimize performance and reduce weight through architectural modifications

Integrated CAD-FE environment
- Textile composite
- Finite element
- Polymer coating on filament surface
- Fabric windowing effect (detrimental to improved performance)
- Filament-filament interactions

Filament redistribution under transverse load
- Filament redistribution under transverse load
- Fabric penetration via windowing and principal yarn pullout – no yarn failure

Effect on Filament Spreading:
- Friction, twist, dry filaments, convoluted filaments, interfacial treatments, nano particle inclusions, resin impregnation

Fabric windowing (beneficial to impact performance)
S2 Glass Epoxy Composites: Processing and Synthesis
• Challenge: how to translate materials needs for armor applications to basic scientific research in an open scholarly setting?

  • Canonical model is the key to this connection

• Challenge: how to get this large, geographically dispersed group to work together effectively?

  • Develop a structure that connects research groups along multiple dimensions of individual interests (by material class, by common research tools)

  • Develop an infrastructure that supports collaboration (data sharing, collaborative space, facilitate visits)
• 40+ faculty/senior researchers
• 40+ graduate students/posdocs
• 40+ ARL scientists
• Many corporate partners, undergraduates, administrative staff
• ~150 active participants
• Collaboration is key
• 4 Collaborative Materials Research Groups (CMRG – red hexagons)

• 3 cross-cutting themes that are uniform across CMRGs

• 3 themes x 4 CMRG = 12 CTRG’s

• CTRG: focal points for interaction between Consortium and ARL researchers with similar interests

• Regular meetings are structured around both CMRG and cross-cutting CTRG themes

• Software/tools coordination committee
MEDE Collaborative Plans

• Regular meetings (details next slide)

• Regular visits between ARL and Consortium, in both directions

• Development of computational infrastructure for sharing data

• Establish collaborative space, both at Consortium and at ARL

• Educational efforts

• MEDE Corporate Partnership Program - currently ~90 members

• Contribute to the science of collaboration:

  *HEMI as a testbed for JHU Systems Institute to study information flow in collaborative networks and help to identify best practices*
• Regular meetings, with the following rough quarterly schedule:

  • **Winter**: CTRGs meet in context of CMRG, time/location set by individual CMRG
  
  • **Spring**: MEDE Conference, open to broad scientific community (CTRG meetings held here, as well as Codes/Tools Coordination Committee)
  
  • **Summer**: CTRGs meet in context of cross-cutting themes, time/location set by individual cross-cutting themes
  
  • **Fall**: MEDE Workshop, meeting of entire MEDE community (CTRG meetings held here, as well as Codes/Tools Coordination Committee)
• Regular visits between ARL and Consortium, in both directions

**Consortium**
- Faculty: sabbatical, summer, part-time
- Ph.D. students/postdocs: long-term visit, summer in residence, part-time
- M.S./BS. Students: summer internships, part-time

**University personnel visit ARL**

**ARL**
- All staff: short-term visits, part-time regular visits
- Upper-level staff: faculty appointments possible
- Junior staff: as full-time or part-time students

**ARL staff visit universities**
• Establish collaborative space, both at Consortium and at ARL

Future home of MEDE at JHU, Malone Hall to be completed Spring 2014

ARL is pursuing new collaborative computational facilities
We have established a great team

Collaboration-Collaboration-Collaboration

NOT a collection of individual projects

The goal is not just better Mg, B4C, UHMWPE & Composites, but the ability to design future materials for future defeat mechanisms for future armors for future threats

Cross-cutting themes will form the foundation for future success for the ARL Enterprise