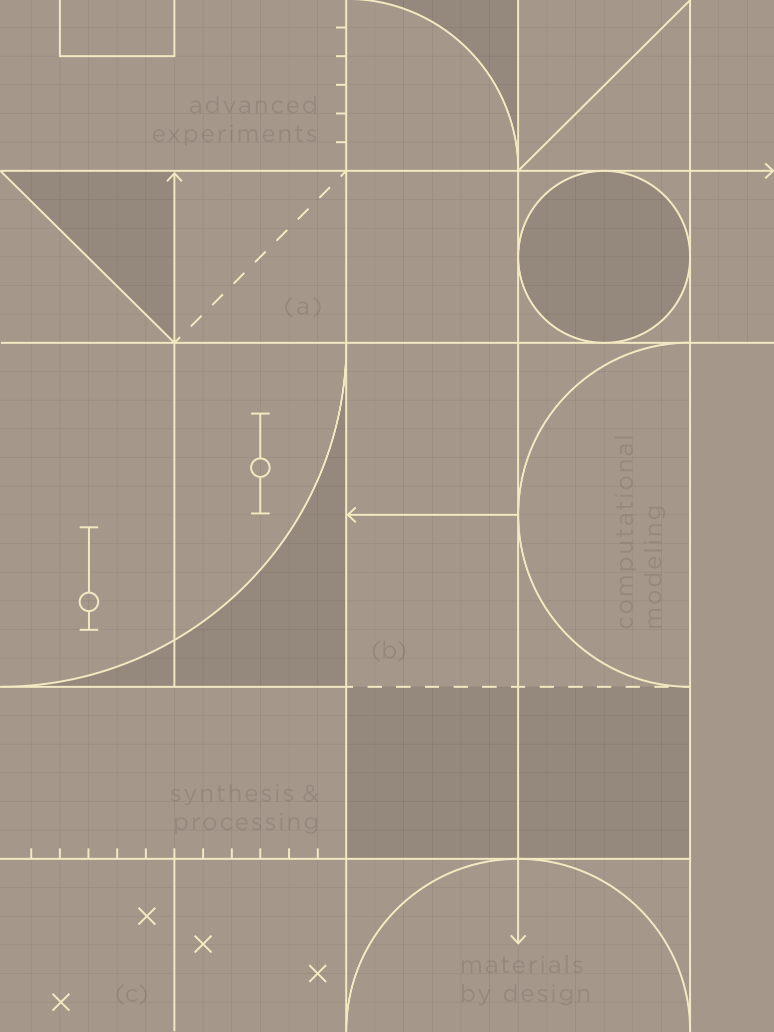

COLLABORATIVE RESEARCH ALLIANCE

CMEDE | CENTER FOR MATERIALS IN EXTREME DYNAMIC ENVIRONMENTS

2020 HIGHLIGHTS

WHAT IS CMEDE?

THE CENTER FOR MATERIALS IN EXTREME DYNAMIC ENVIRONMENTS IS A MULTI-INSTITUTION COLLABORATIVE RESEARCH CENTER LOCATED WITHIN THE HOPKINS EXTREME MATERIALS INSTITUTE AT JOHNS HOPKINS UNIVERSITY.

The Center brings together academia, government, and industry to advance the state of the art for materials in extreme dynamic environments.


IMPACT®
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CONSORTIUM MANAGEMENT COMMITTEE

FROM THE CMEDE DIRECTOR:

2020 will be remembered as an eventful year for the Materials in Extreme Dynamic Environments Collaborative Research Alliance (MEDE CRA). The year started with a successful Research Management Board, a review chaired by Dr. Alexander Kott, chief scientist of the CCDC Army Research Laboratory (ARL). The board included senior executives and senior research scientists from the U.S. Army, Department of Energy, and the National Science Foundation.

In March, laboratory research activities in government and academia came to a sudden halt due to COVID-19. The MEDE CRA quickly adapted to sustain research operations and restart laboratory operations while ensuring the health and safety of all personnel. This swift response allowed us to continue research for our three materials groups across the CRA. As we progress towards restoring full operations, we continue to make scientific advances leading to newly designed materials, as well as advanced computational design codes and tools.

The MEDE CRA continues its dedication to educating and building the future materials-by-design workforce. As of this writing, the MEDE consortium has graduated 65 doctoral students and 46 post-doctoral researchers into DoD/National laboratories, academia, and industry.

In 2020, we again experienced significant Congressional interest that will provide resources and accelerate our research efforts. Our academic activities remain at the forefront of U.S. Army STEM programs. We received the highest number of applications for two Army Educational Outreach Program internship programs this past summer. The Extreme Science Internship program with Morgan State University continues to enhance diversity and inclusion within the MEDE CRA. We executed our summer internships remotely this year, a reflection of the commitment of students, mentors, and faculty.

Sadly, we also experienced a significant loss within the MEDE CRA. Professor Mark Robbins of Johns Hopkins University passed away suddenly in late August. Mark's research spanned two MEDE materials groups and he was a passionate supporter of the student internships. He will be greatly missed.

As always, we are thankful for continued support from the U.S. Army and the Department of Defense, as well as for support from the Enterprise for Multiscale Research of Materials and the partners in the MEDE CRA.

K.T. RAMESH

Director, CMEDE

Alonzo G. Decker Jr. Professor of Science and Engineering

Professor, Department of Mechanical Engineering, Earth and Planetary Sciences, Materials Science and Engineering
Johns Hopkins University

SIKHANDA SATAPATHY

Collaborative Alliance Manager
MEDE CRA
U.S. Army Combat Capabilities Development Command Army Research Laboratory

KAUSHIK BHATTACHARYA

Howell N. Tyson, Sr., Professor of Mechanics and Materials Science

Professor of Materials Science
California Institute of Technology

JOHN W. GILLESPIE, JR.

Donald C. Phillips Professor of Civil and Environmental Engineering

Professor, Mechanical Engineering, Materials Science and Engineering
University of Delaware

RICHARD HABER

Professor, Materials Science and Engineering
Rutgers University

ABOUT US

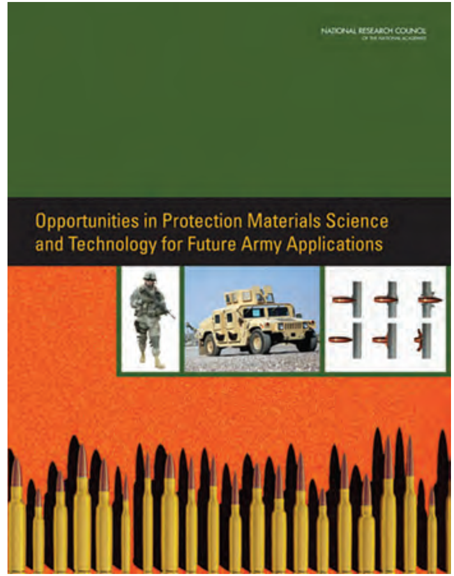
In 2010, two National Research Council boards established a committee to examine opportunities in protection materials science and technology for future Army applications. This committee recommended that the Department of Defense establish an initiative for protection materials by design. This initiative would include a combination of computational, experimental, and materials testing, characterization, and processing research to be conducted by academia, government, and industry.

In response to the committee's recommendation, in April 2012 the U.S. Army Combat Capabilities Development Command Army Research Laboratory (CCDC ARL) established a framework to integrate the Army's multiscale basic research in materials into one coordinated enterprise. Called the Enterprise for Multiscale Research of Materials (EMRM), the focus of the program is to develop a materials-by-design capability for the U.S. Army using validated multiscale and multidisciplinary modeling capabilities to predict material structure, properties, and performance.

> **Called the Enterprise for Multiscale Research of Materials (EMRM), the focus of the program is to develop a materials-by-design capability for the US Army using validated multiscale and multidisciplinary modeling capabilities to predict material structure, properties, and performance.**

The EMRM enables CCDC ARL to coordinate its in-house activities with extramural research efforts. The EMRM is organized into four major areas: protection materials, energetic materials, electronic materials, and cross-cutting computational science.

To launch the protection materials research component of EMRM, CCDC ARL competitively awarded and then signed the Materials in Extreme Dynamic Environments cooperative research agreement with Johns Hopkins University (JHU), the California Institute of Technology (Caltech), the University of Delaware (Delaware) and Rutgers University. The agreement allowed JHU, which is the lead research organization



National Research Council report

within the consortium of university and research partners, to establish the Center for Materials in Extreme Dynamic Environments, or CMEDE. CMEDE is a center within the Hopkins Extreme Materials Institute, and focuses on advancing the fundamental understanding of materials in high-stress and high-strain-rate regimes, with the goal of developing a materials-by-design capability for these extreme environments. This 10-year agreement, valued up to $90 million, represents a significant investment and demonstrates the importance of the design of protection materials to the U.S. Army.

The MEDE program also supports the Presidential Materials Genome Initiative (MGI) for Global Competitiveness. Established in June 2011, MGI aims to double the speed at which materials are discovered, developed, and deployed. The MEDE program represents one of the Department of Defense's largest investments in extramural basic research in support of the MGI.

"This is some incredible work that was done. It's cutting-edge technology as far what it's done for body armor."

- GENERAL JAMES C. MCCONVILLE
40th Chief of Staff of the U.S. Army

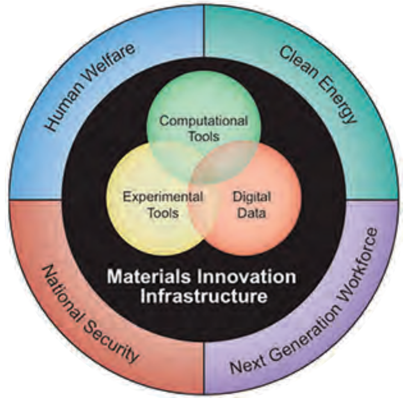


Figure 1: Materials Genome Initiative: MEDE focuses on developing the experimental and computational tools needed to develop protection materials for national security.

ORGANIZATION

The MEDE Collaborative Research Alliance is composed of a consortium of university and research partners and the CCDC Army Research Laboratory. The MEDE consortium members include:

- **Johns Hopkins University (Lead)**
- **California Institute of Technology**
- **University of Delaware**
- **Rutgers University**
- **Defence Science and Technology Laboratory (United Kingdom)**
- **Drexel University**
- **Ernst Mach Institut (Germany)**
- **ETH Zürich (Switzerland)**
- **Lehigh University**
- **Morgan State University**
- **New Mexico Institute for Mining and Technology**
- **North Carolina Agricultural and Technical State University**
- **Purdue University**
- **Southwest Research Institute**
- **Texas A&M University**
- **University of Houston**
- **University of North Carolina at Charlotte**

The MEDE CRA is composed of a consortium of university and research partners and the CCDC Army Research Laboratory. It also works internationally with the Defence Science and Technology Laboratory of the United Kingdom.

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UNIVERSITY OF DELAWARE

PURDUE UNIVERSITY

LEHIGH UNIVERSITY

SwRI

RUTGERS

TEXAS A&M UNIVERSITY

Drexel UNIVERSITY

UNIVERSITY of HOUSTON

MORGAN STATE UNIVERSITY

UNC CHARLOTTE

DEVCOM

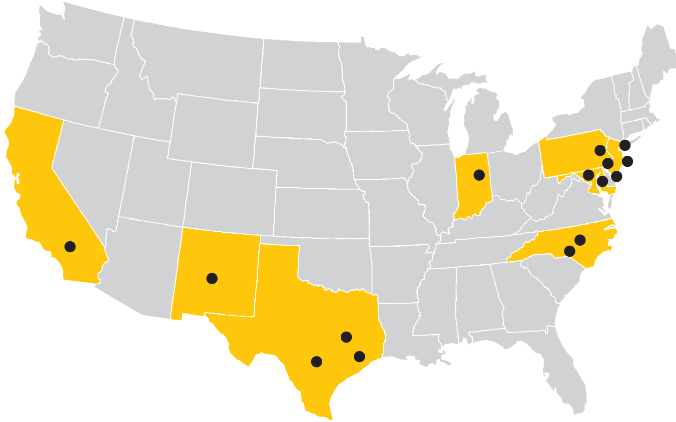


Figure 2: MEDE Collaborative Research Alliance

United Kingdom

[dstl]

Germany

Fraunhofer EMI

Switzerland

ETH zürich

STRUCTURE

- The CMEDE Director is located within CMEDE at Johns Hopkins University, the lead research organization for the MEDE CRA.
- The MEDE Science Advisory Board complements CCDC ARL's Technical Advisory Board. It provides important scientific insight, oversight, and expertise to the CMEDE consortium. The Board reports to the CMEDE Director.
- The Consortium Management Committee (CMC) is composed of a senior representative from the four major consortium partners and the CCDC ARL Collaborative Alliance Manager. The CMC is the final decision authority for the MEDE CRA.
- A Collaborative Materials Research Group (CMRG) coordinates all research activities for each material type. Each CMRG is co-led by a consortium principal investigator and a CCDC ARL researcher.
- Within each CMRG, there are multiple technical areas, separated by scale or mechanism. The CMRGs are highly integrated with a consortium PI and a CCDC ARL researcher co-leading each major effort.

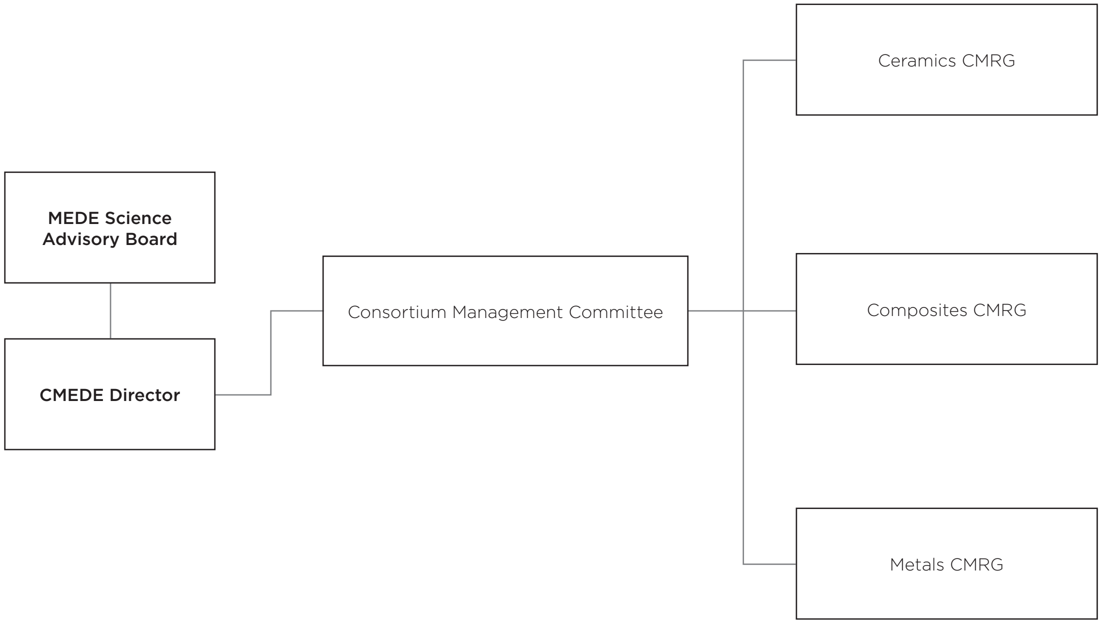


Figure 3: MEDE organizational structure

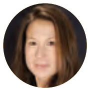
"The progress and accomplishments of the MEDE program over the last nine years to answer not only "how" things happen, but "why" is nothing short of groundbreaking. The materials investigated by the program are representative and critical in their areas (magnesium - metals, boron carbide - ceramics, S2 glass and resins - composites) when subjected to the dynamic environments seen in ballistic applications. This cooperative research program with the Army is rightfully the benchmark for all others, and should be the blueprint for future research."

- DR. DOUG TEMPLETON
Chair, MEDE Science Advisory Board

MEDE SCIENCE ADVISORY BOARD MEMBERS

Dr. Douglas Templeton
DWT Consulting (Chair)

Dr. Charles E. Anderson, Jr.
CEA Consulting



Professor Irene Beyerlein
University of California, Santa Barbara

Professor Horacio Espinosa
Northwestern University

Professor David McDowell
Georgia Institute of Technology

Professor Steve McKnight
Virginia Polytechnic Institute

Professor Marc Meyers
University of California, San Diego

Professor Anthony Rollett
Carnegie Mellon University

Professor Thomas Russell
University of Massachusetts Amherst

Professor Susan Sinnott
Pennsylvania State University

Professor Nancy Sottos
University of Illinois at Urbana-Champaign

RESEARCH STRATEGY

The objective of the MEDE program is to develop the technical and workforce capability to design, create, and optimize novel material systems that exhibit revolutionary performance in extreme dynamic environments. Achieving this objective requires a new paradigm for materials research and workforce development. One cannot use the classical materials science structure-properties-performance approach because path-dependent and time-dependent failure processes are involved in these dynamic environments, and optimal solutions may not exist in the traditional design space. Instead, we must design with knowledge of the dynamic failure processes (mechanisms) that are involved in the actual application.

The objective is not necessarily to produce a specific material system that is optimized for a specific range of applications, but rather to produce a way of thinking that will allow the design of lightweight protective material systems that can be used for extreme dynamic environments.

To achieve the MEDE program objectives, research activities are focused on a materials-by-design process involving a canonical model and a mechanism-based strategy as shown in Figure 4. We have established a canonical model for each model material under investigation. A canonical model is defined as: "A simplified description of the system or process, accepted as being accurate and authoritative, and developed to assist calculations and predictions."

Typically such a canonical model defines key variables and their ranges, defines critical mechanisms, and then prioritizes the variables and mechanisms. Beginning with a canonical model allows a large group of researchers to ensure that efforts are relevant in terms of both science and application.

Once the canonical description is established, researchers can then proceed with the mechanism-based strategy. Researchers seek to see the mechanisms during the extreme dynamic event, to understand them through multiscale models, and to control them through synthesis and processing. Understanding the mechanisms through multiscale models provides the capability to define integrative experiments and to test the coupling of mechanisms. This information leads to validated models and codes, which feed back into the canonical model, by transitioning into Department of Defense (DoD) and Department of Energy (DoE) codes. Similarly, controlling the mechanism through synthesis and processing leads to newly designed materials for the canonical environment. Industry helps to determine the scale-up feasibility of these newly designed materials, which are then fed back to the experiments in the canonical modeling effort.

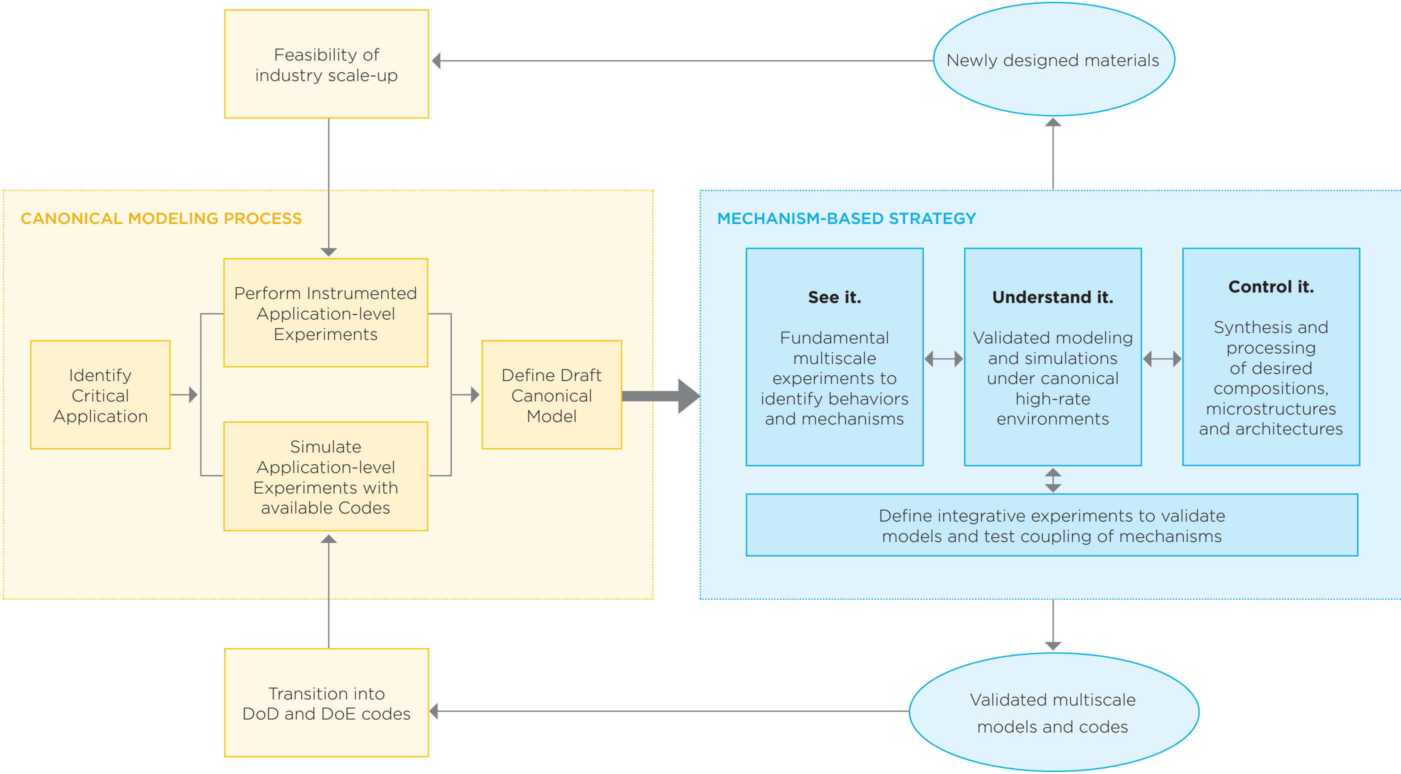


Figure 4: Overall design strategy for protection materials. Left hand boxes are driven by CCDC ARL, while right hand boxes are driven by the MEDE Consortium.

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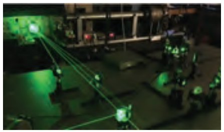
MATERIALS-BY-DESIGN STRATEGY

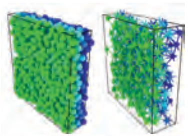
Advanced Experiments

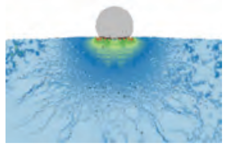
Simulating ballistic events through high strain rate experiments



Computational Modeling

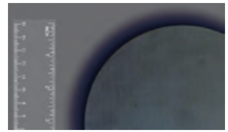
Modeling from the atomistic to the continuum scales

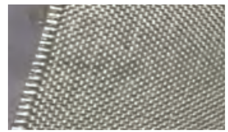




Synthesis & Processing

Creating new materials to validate experimental and modeling data





MATERIALS-BY-DESIGN RESULTS

- **New lightweight materials**
- **Computational codes for armor material design**
- **Knowledge products**
- **Scientific discovery**
- **Use-inspired research**

"**Tactical overmatch** is the product of adaptable, aggressive leaders and soldiers organized in cohesive, well-trained formations; and **aircraft, fighting vehicles, small units, and individuals with superior mobility, protection, and lethality.**"

Army Material Modernization Priorities

Developing material solutions to support new protection concepts:

- **Soldier Lethality**
- **Next Generation Combat Vehicle**
- **Future Vertical Lift**

Army Priority Research Area

- **Materials by Design: Protection overmatch against future threats**

CCDC ARL Core Competencies & Essential Research Programs

- **Terminal ballistics and materials research**
- **Physics of soldier protection to defeat evolving threats**
- **Convergence of lethality, protection and autonomy to dominate ground combat**

MEDE Provides Foundational Research

- **Advanced Experiments**
- **Computational Modeling**
- **Synthesis & Processing**

RESEARCH ACTIVITIES

The MEDE program examines one model material in each of the following four material classes: ceramics, composites, and metals. The discoveries and insights developed can be used for other materials in the same class.

Ceramics: Boron Carbide

Boron carbide is the model material for the Ceramics CMRG because it has the unrealized potential of dramatic improvements in ballistic performance for vehicular protection at very low weight. The Ceramics CMRG seeks to understand and control the dynamic failure processes in this protective ceramic material and to improve its dynamic performance by controlling mechanisms at the atomic and microstructural levels through multiscale modeling, advanced powder synthesis, control of polytypes, and microstructural improvements.

Application: Boron carbide is one of the component materials used to protect soldiers and military vehicles from blast and ballistic threats.

Composites: S-2 Glass/Epoxy

Composite materials subjected to dynamic loads are essential examples of high performance systems in the conventional sense. In order to focus on the complexities raised by the interfaces and architectures, S-2 Glass/Epoxy is the model system for the Composites CMRG. The Composites CMRG develops the fundamental understanding of the role of interfaces, component interactions, and composite architecture over the full range of length scales and time scales that are manifested in the system during the dynamic event.

Application: S-2 Glass/Epoxy provides a strong, structural backing system to support protective plates for military vehicles.

Metals: Magnesium

The magnesium alloy system is the model material for the Metals CMRG because it is the lightest-weight structural metal that offers the potential of approaching steel-like ballistic performance while using conventional low-cost and time-tested processing techniques. We are enhancing the dynamic performance of this hexagonally-close-packed metal using experimentally validated modeling and alloy design to control dynamic strengthening and failure mechanisms, including deformation twinning.

Application: In comparison to steel, magnesium offers the potential for a lightweight metal system that could enhance the deployability and protection of military vehicles.

CMEDE RESEARCH ACTIVITIES ADDRESS THE FOLLOWING FIVE CORE ELEMENTS:

- **Advanced Experimental Techniques:** developing experimental methodologies to interrogate and characterize the in-situ materials response to extreme dynamic environments at critical length and time scales.

- **Modeling and Simulation:** developing computational approaches to predict the materials response to extreme dynamic environments at critical length and time scales.

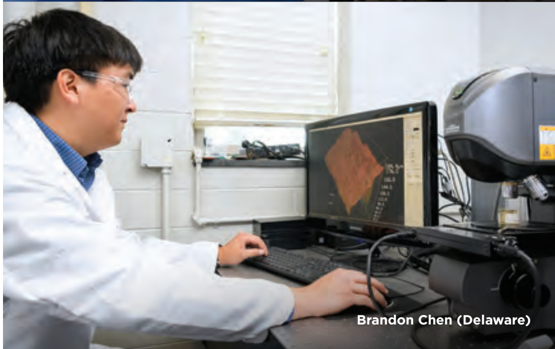
- **Bridging the Scales:** developing physical and mathematical constructs necessary to bridge critical length and time scales.

- **Material Characteristics and Properties at Multiple Scales:** utilize existing and novel experimental methodologies to identify the comprehensive set of material characteristics, microstructural features, and dynamic properties that govern high rate deformation and failure phenomena, and to validate computational approaches in order to bridge the characteristic length and time scales.

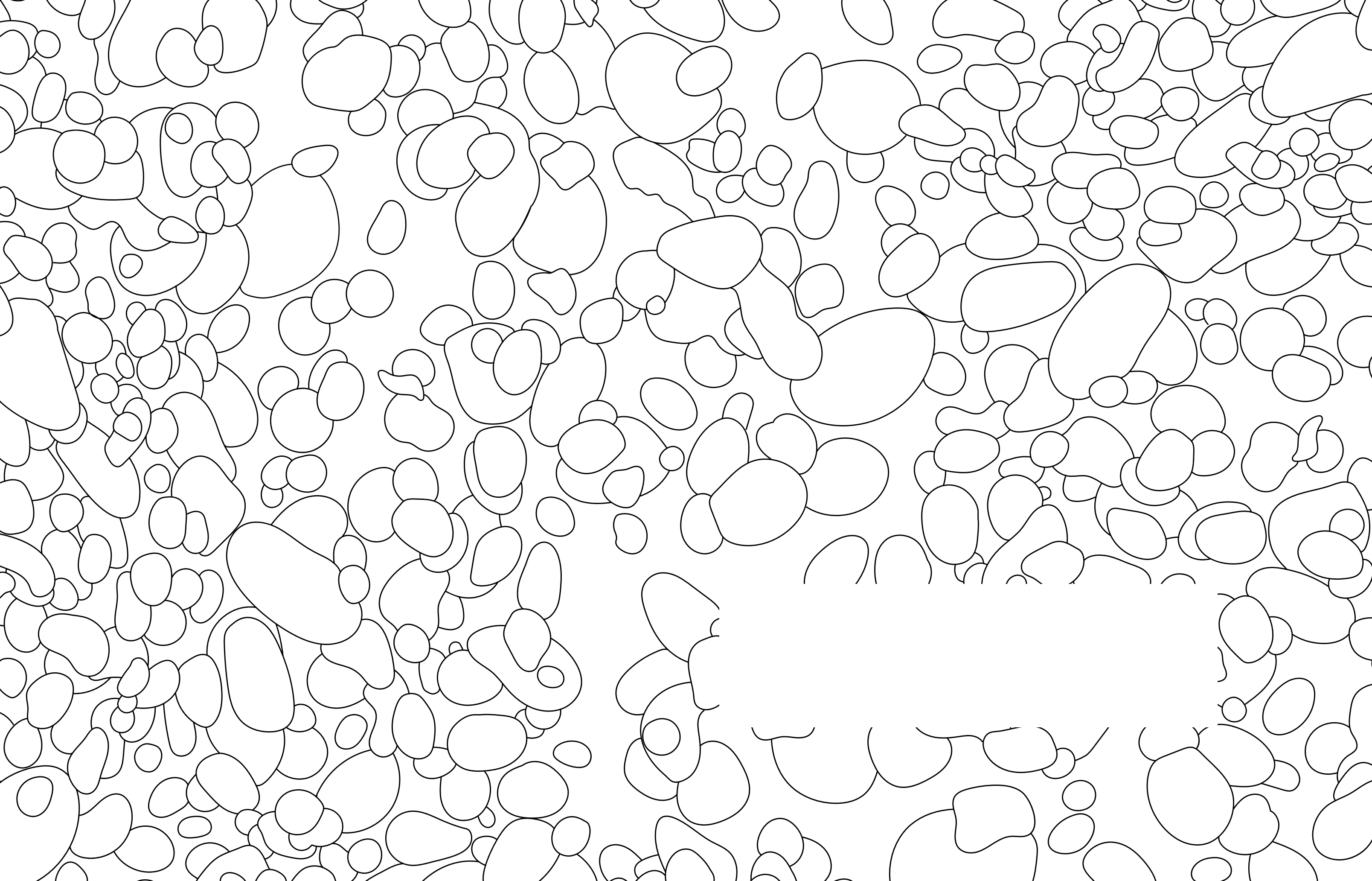
- **Synthesis and Processing:** incorporate research discoveries to enable the synthesis of novel materials and the processing of final products with critical material characteristics and resulting properties.

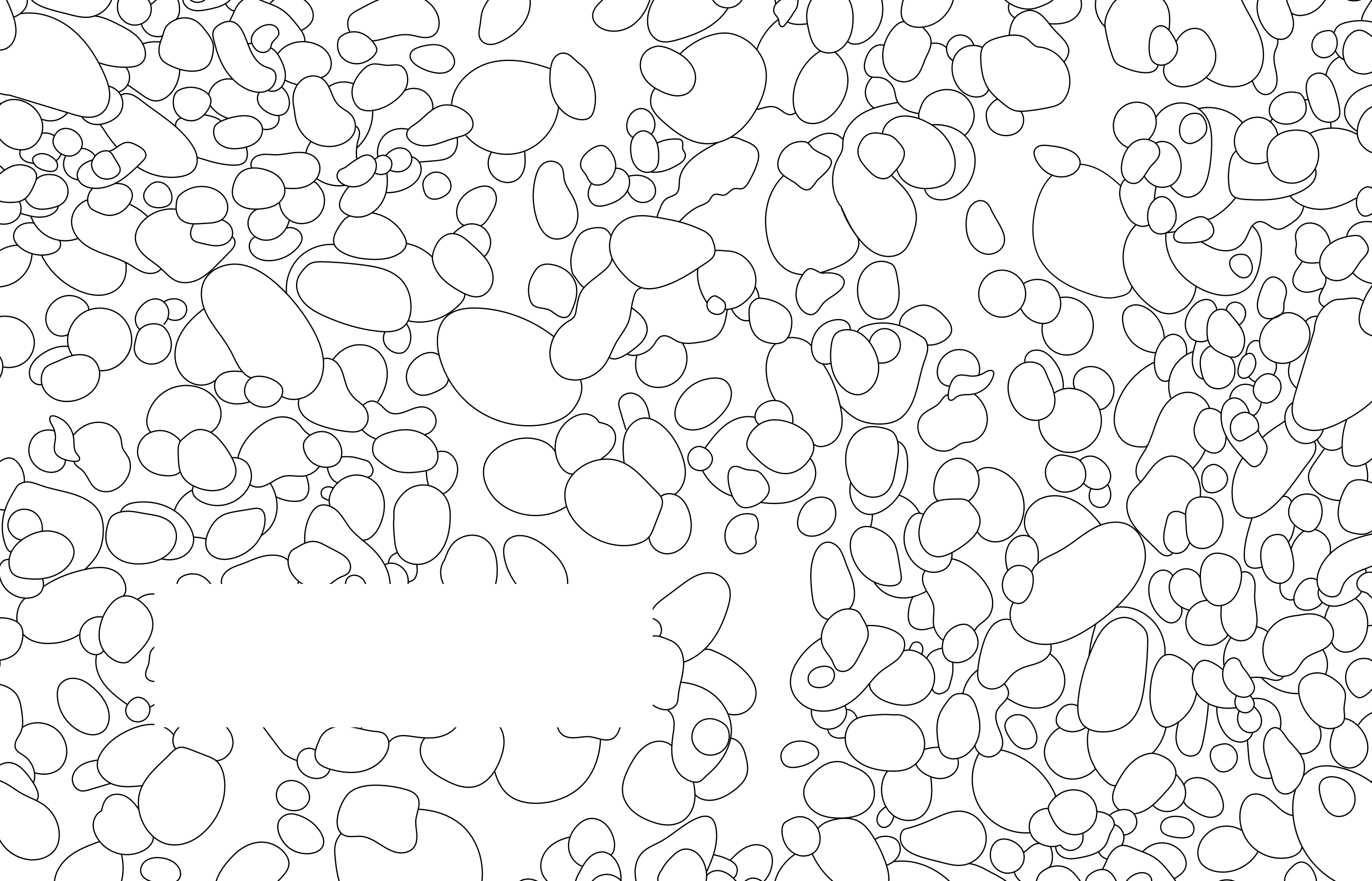

Atiyya Davis (MSU)


Suhas Eswarappa Prameela (JHU)


Brandon Chen (Delaware)

Artistic rendering of the atomic-level view of boron carbide as seen through a transmission electron microscope.





CERAMICS

Consortium Lead - Prof. Richard Haber (Rutgers)

CCDC ARL Lead - Dr. Jerry LaSalvia

Ceramics CMRG

Note: photo taken in 2019

CONSORTIUM INVESTIGATORS

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Dr. Chris Marvel, Lehigh

Prof. K.T. Ramesh, JHU

Prof. Mark Robbins, JHU

Prof. Michael Spencer, Morgan State

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Dr. Jason McDonald

Dr. John Pittari

Dr. Brian Schuster

Dr. Taylor Shoulders

Dr. Jeffrey Swab

Dr. Jennifer Synowczynski-Dunn

Dr. Andrew Tonge

Dr. Lionel Vargas-Gonzalez

Dr. Scott Walck

Dr. Cyril Williams

CONSORTIUM RESEARCH TASKS

- Atomic-Resolution Characterization of Boron Icosahedra Ceramics (Harmer and Marvel, Lehigh)
- Boron Carbide Single Crystal Synthesis and Characterization (Spencer, Morgan State)
- Calibrating and Validating Granular Flow Model Parameters to Aid in Integrative Model Predictions and Materials by Design Efforts (Hurley, JHU)
- Canonical Experiments for the Ceramics CMRG using HyFIRE (Ramesh, JHU)
- Experiments on High-Rate Granular Flow in Boron Carbide (Ramesh, JHU)
- Granular Flow Transitions and Parameter Sensitivities in the Integrative Model to Guide Materials by Design (Graham-Brady, JHU)
- High-Strain-Rate Experiments on CMRG Boron Carbide Materials and BC crystals (Ramesh, JHU)
- Integrative Modeling Subtask (distributed over all 3 mechanisms) (Ramesh, JHU)
- Investigation of Amorphization and Quasi-Plasticity Mechanisms in Boron Carbide (Haber, Rutgers)
- Materials Synthesis and Processing Integrative Task (Haber, Rutgers)
- Particle Based Modeling of Fragmentation Transition and Granular Flow (Robbins and Ramesh, JHU)
- TEM Characterization of Quasiplasticity in Boron Carbide (Hemker, JHU)

Mitigating Stress-induced Amorphization in Boron Carbide via Silicon Doping

Mr. Qirong "Bruce" Yang *Rutgers University*	**Dr. Sisi Xiang** *Texas A&M University*	**Dr. Luoning Ma** *Johns Hopkins University*
Dr. Chawon Hwang *Rutgers University*	**Dr. Jun Du** *Rutgers University*	**Dr. Jerry C. LaSalvia** *CCDC Army Research Laboratory*
Prof. Kelvin Y. Xie *Texas A&M University*	**Prof. Kevin J. Hemker** *Johns Hopkins University*	**Prof. Richard A. Haber** *Rutgers University*

Consolidated boron carbide ceramics experience accelerated fragmentation when subjected to high applied pressures such as achieved in a ballistic event. The large shear stress triggers the collapse of boron carbide structure, manifesting in a network of nano-sized amorphous bands. These amorphous bands act as "the path of least resistance" for crack propagation leading to a catastrophic failure of the ceramic.

Theoretical model suggests Si doping can be an effective strategy to suppress stress-induced amorphization in boron carbide. Si doping modifies the boron carbide structure by altering the C-B-C linear chain to a C-Si-C kinked chain, as shown in Fig. 5. Si-doped boron carbide ceramics were processed through reaction sintering using boron carbide, amorphous boron, and silicon hexaboride powder mixtures. Preliminary indentation and Raman spectroscopy studies demonstrated that Si doping can suppress amorphization by 31% (Fig. 5a and 5b). Complementary transmission electron microscopy (TEM) carried out in the quasi-plastic zones under the nano-indentation reveals salient differences in the deformation behavior between the undoped and Si-doped boron carbide. The undoped boron carbide deforms by nucleating amorphous shear bands, which facilitates crack formation (Fig. 5c). In contrast, Si-doped boron carbide deforms through micro-cracking rather than amorphization (Fig. 5d). Our findings suggest Si doping alters the deformation behavior of boron carbide by promoting micro-cracking, which dissipates strain energy leading to less amorphization.

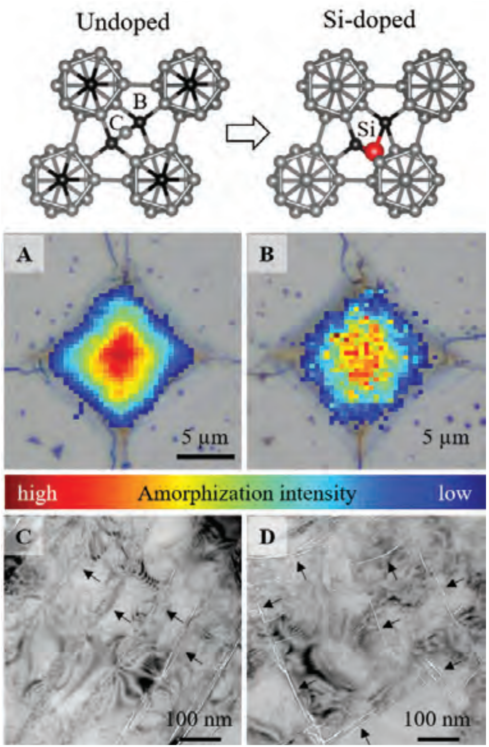


Figure 5: Si doping alters the crystal structure of boron carbide by forming a C-Si-C kinked chain. Amorphization intensity map, acquired using Raman spectroscopy, overlaying the Vickers indentation of (a) undoped and (b) Si-doped boron carbide. Bright-field TEM imaging captures the deformation behavior of (d) undoped and (d) Si-doped boron carbide.

Characterization of the Mechanical Properties of Single Crystal Boron Carbide

Mr. Michael Straker *Morgan State University*	**Dr. Arezoo Zare** *Johns Hopkins University*	**Prof. Mo-Rigen He** *Johns Hopkins University*
Prof. MVS Chandrashekhar *University of South Carolina*	**Dr. Christopher Marvel** *Lehigh University*	**Prof. Kevin Hemker** *Johns Hopkins University*
Prof. K.T. Ramesh *Johns Hopkins University*	**Prof. Michael Spencer** *Morgan State University*	**Dr. Jerry LaSalvia** *CCDC Army Research Laboratory*

Despite the need for engineering composites based on boron carbide, and the numerous studies characterizing mechanical failure in these composites there are few studies on the mechanical properties of single crystal boron carbide. Boron carbide is highly anisotropic, with measured elastic moduli varying by as much as 10x between different crystallographic orientations. It is critical to obtain high purity single crystals to completely characterize the elastic moduli, hardness, and dynamic failure mechanisms along various crystal directions. This information can be used in constitutive computer models of boron carbide mechanical failure. For these models to have predictive power for rational material design the mechanical properties as a function of crystal orientation should be determined with a high degree of confidence.

Well-oriented boron carbide single crystals can be grown using a Laser-Diode Floating Zone (LD-FZ) method (Fig. 6a). In LD-FZ growth, lasers melt the polycrystalline feed material small single crystals spontaneously nucleate and grow into long boules as the crystal cools. Due to the anisotropy of the crystal properties, one growth domain dominates and large area single crystal regions are achieved. The phase diagram of boron carbide shows that at the eutectic point, solid phases with carbon content in the range of ~17-20% exist. The large phase region allows for the potential creation of a wide range of boron carbide compositions. Single crystals of boron carbide (Fig. 6b) ~6 cm long with a diameter of 8mm could be reproducibly obtained. There were no apparent graphitic inclusions in the center of the crystal. The crystal orientation was measured with a white beam X-ray Laue camera (Fig. 6c) and electron backscattered diffraction (EBSD). Using these two techniques the crystal growth direction was found to be [003] ± 15 degrees and uniform single crystal regions were found to extend distances of greater than 100 microns. Using a calibrated X-ray energy dispersive spectrometry (XEDS) technique the boron to carbon ratio was determined to be 4.9 (17%). Using Glow discharge mass spectroscopy (GDM) it was found that Si (7.7ppm), Al (.93ppm) and Mg (.60ppm) were the predominate impurities.

Transmission electron microscopy (TEM) was used to characterize the as grown defects. It was determined that the principal defects were twins and stacking faults. In order to determine the mechanical properties of the material quasi-static nanoindentation experiments were performed using a Berkovich indenter under an applied strain rate of 0.05 s-1 to a maximum indentation depth of ~1 μm. As shown in Fig. 7a, to examine the dependence of elastic modulus and hardness on in-plane orientation, nanoindentation experiments were performed by rotating the single crystal about the indenter axis from 0° to 60° and then to 120°, with each of these directions approximate to the <1120> axis.

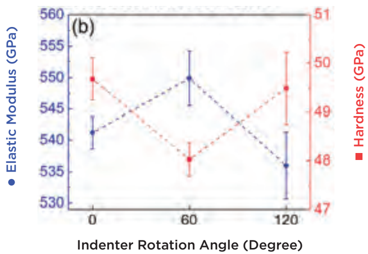
For each rotation angle, Fig. 7b shows the average values (plus/minus one standard deviation) of elastic modulus and hardness obtained from 10 separate indentations. For a rotation angle of 0°, an elastic modulus of 541.2 GPa and a hardness of 49.7 GPa were obtained. The elastic modulus and hardness values at a rotation angle of 120 were comparable to those measured at 0°. However, a rotation angle of 60 resulted in an increase in the elastic modulus, while decreasing the hardness. Such variations in elastic modulus and hardness by rotation angle suggest in-plane anisotropy in both elastic and quasi-plastic response of the crystal. Post-indentation SEM image of an indent, shown in Fig. 7c, reveals formation of surface cracks at a rotation angle of 60°. Similar observations were made for rotation angles of 0° and 120°and the orientation of surface cracks at each rotation angle was found to be highly repeatable, suggesting preferred crystallographic orientations may exist for indentation crack propagation.

The quasi-plastic behavior under the indent in Fig. 7c was further examined in a cross-sectional specimen lifted out and polished to electron transparency by using focused ion beam (FIB). In the bright field TEM image as shown in Fig. 7d, un-deformed region of the specimen was tilted to the [1210] zone axis, whereas the region around the indent was highlighted with brighter contrast, indicating severe lattice rotation and distortion.

Detailed characterization of the deformed region revealed various microstructural defects. For instance, the high-resolution TEM images in Figs. 7e and 7f shows formation of amorphous bands and fragmentation, respectively. These features observed at different locations may be driven by the inhomogeneous and anisotropic stress fields under the indent or reflect the different stages of deformation and failure. The surface crack (as seen in Fig. 7c) was also found to initiate from an amorphous band formed in the deformed region (details not shown here). Importantly, the mediators of quasi-plasticity were always found along specific low-index crystallographic planes, as marked in Figs. 7e and 7f, indicating the role of crystal anisotropy that governs the mechanical behaviors at the atomic scale.

Figure 6: Growth of single crystal Boron Carbide showing (a) an image of the molten zone of the crystal during growth at 2400°C (b) the resulting 8mm crystal boule (c) the measured Laue pattern of the nominal growth direction of the crystal.

b Nanoindentation Results



d FIB Lift-out from 60° Rotation

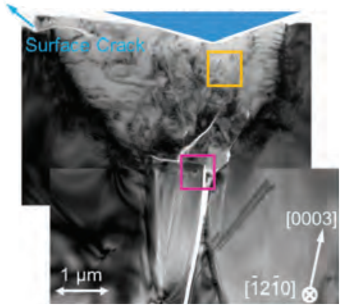
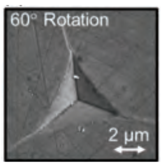


Figure 7: Summary of nanoindentation results showing (a) a schematic representation of the array of indents, (b) average values of reduced elastic modulus and hardness; (c) post-indentation SEM image and (d) cross-sectional TEM micrograph of an indent performed at a rotation angle of 60° revealing formation of surface cracks, (e) amorphous bands, and (f) material fragmentation.

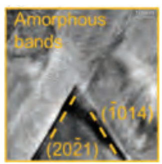
Array of Berkovich Indents
h_{max}~1 μm

a

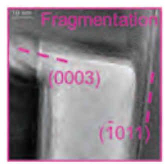
c



e



f



DR. BRIAN E. SCHUSTER

Associate Professor, Dept. of Metallurgical, Materials and Biomedical Engineering, University of Texas at El Paso (UTEP)
Former Team Leader, Experimental and Computational Team, CCDC Army Research Laboratory

MEDE Area of Research:
Experimental Collaborative Technical Research Group

> "During my tenure at ARL, I was fortunate to work closely with academic and government colleagues who are the world's leaders in data science, advanced processing, computational modeling, and experimental solid mechanics. These collaborations inspired me to develop new experimental methodologies to examine the incipient failure and fracture mechanisms that control the response of ceramic materials during terminal ballistic impact and penetration. The lasting legacy of the MEDE consortium is the unique way in which this multidisciplinary team to responded to the challenge by rapidly developing and critically screening new candidate materials for extreme loading applications. This approach will serve as the template for the development of new materials for protection applications and is one that I will continue to follow in my research group at UTEP."

MR. MICHAEL STRAKER

Graduate Student, Dept. of Physics, Morgan State University

MEDE Area of Research:
The Growth and Investigation of Boron Carbide Single Crystals

"The MEDE program has been extremely impactful in the progression of my career and growth as a scientist. The experience I gained working within the program has helped me to broaden my skill set and ignited my interest in the field of material science. Through the program, I've been able to grow a network of hard working, knowledgeable professionals with whom I hope to continually exchange knowledge in the future."

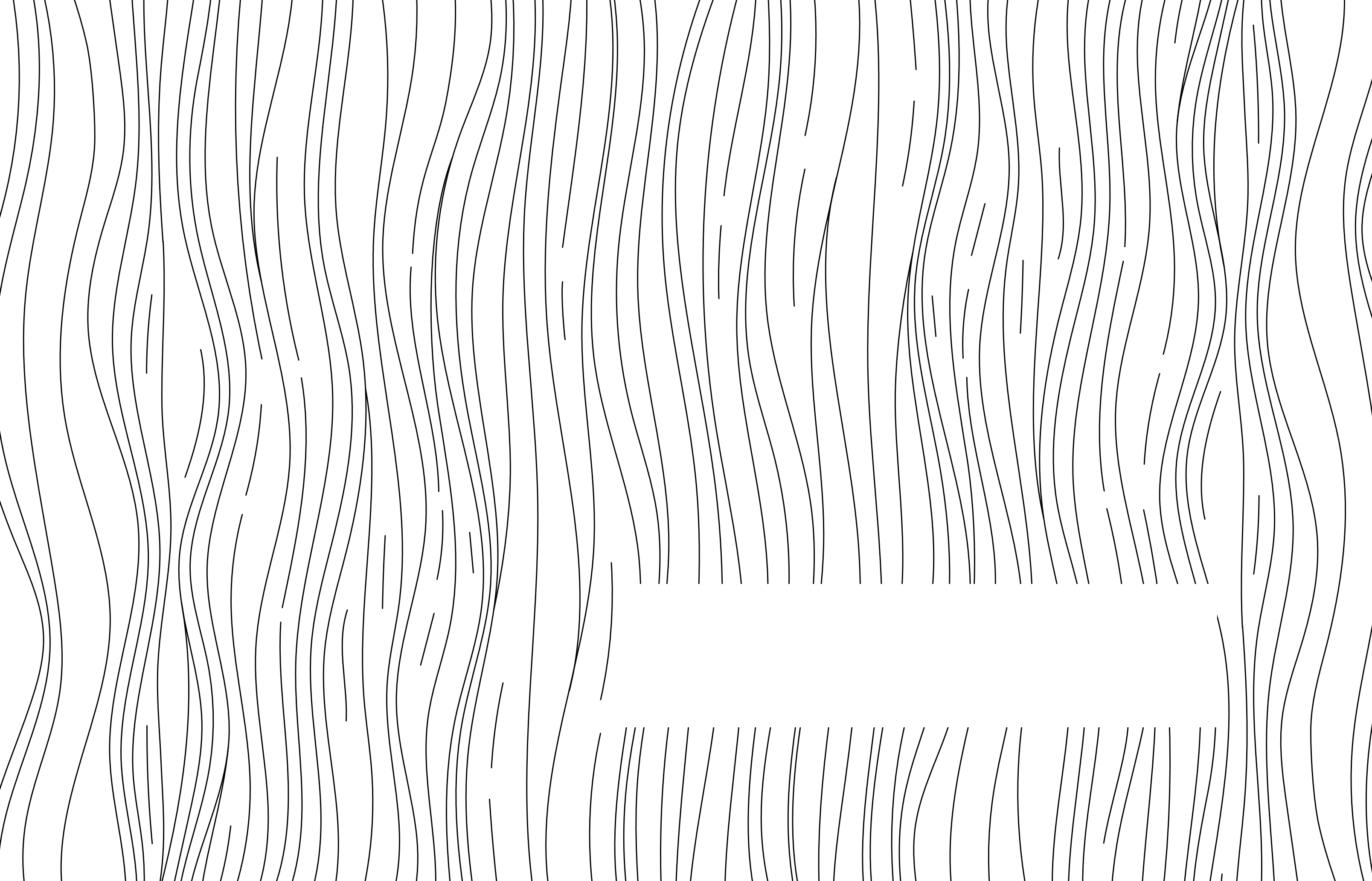
PROF. MICHAEL SPENCER

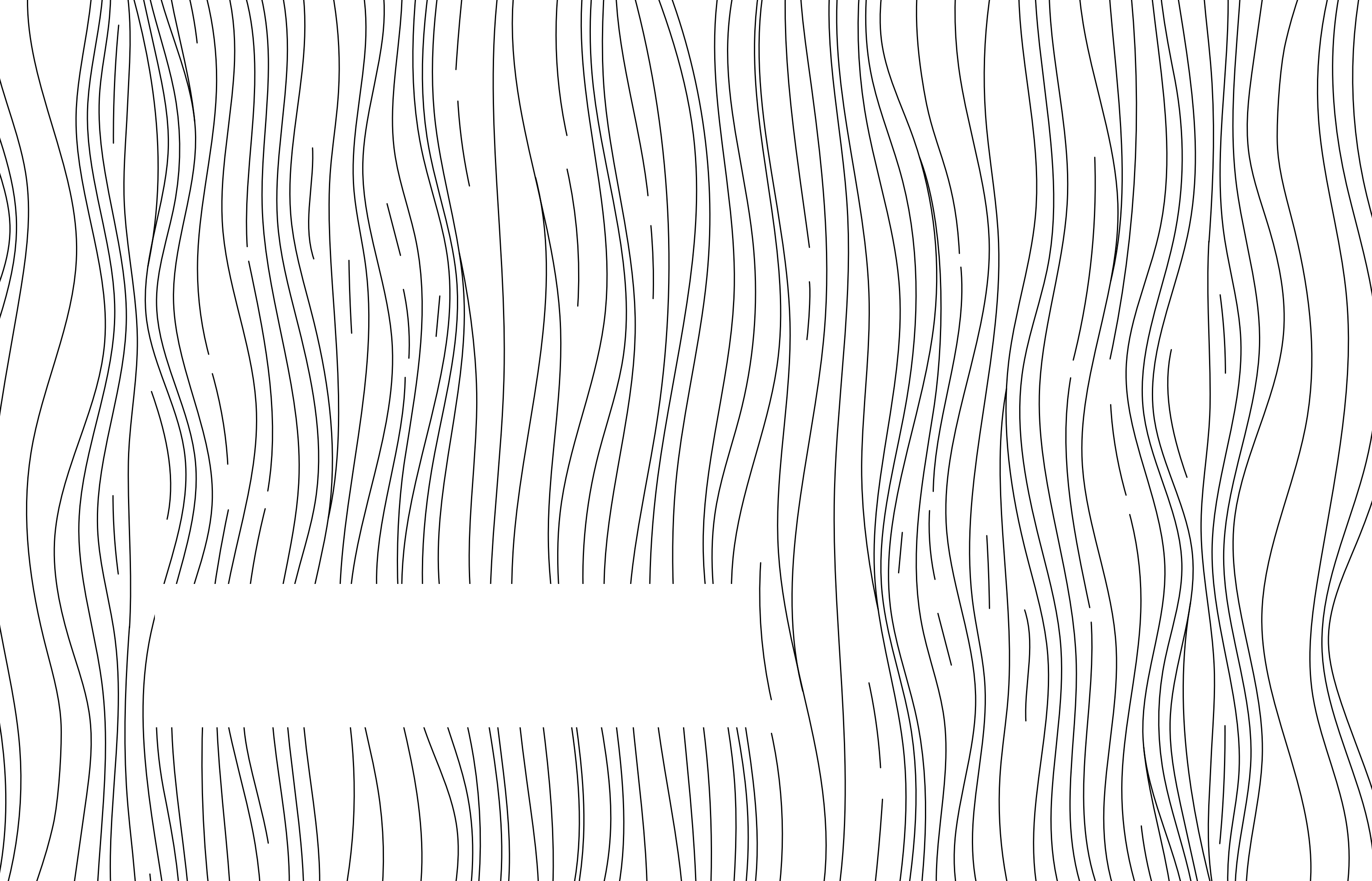
Dept. of Electrical Engineering, Morgan State University

MEDE Area of Research:
Growth and Characterization of Single Crystal Boron Carbide

"The MEDE program has allowed me to develop new capabilities and become familiar with an important material (Boron Carbide). I value all the interactions that have been made possible by the MEDE program."

Artistic rendering of a cross-section of the S-2 Glass/Epoxy composite material.





COMPOSITES

Consortium Lead - Prof. John W. Gillespie, Jr. (Delaware)

CCDC ARL Lead - Dr. Daniel J. O'Brien

Composites CMRG

Note: photo taken in 2019

CONSORTIUM INVESTIGATORS

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Dr. Timothy Sirk

Dr. Chian Fong Yen

CONSORTIUM RESEARCH TASKS

- Characterization of Macroscale Damage in Composite Materials (Aslan, MSU)
- Development of a Rate-Dependent Progressive Damage Model for 2D and 3D Composites in LS-DYNA (Haque and Gillespie, Delaware)
- Meso-Mechanical Modeling of Canonical Perforation Experiments (Haque and Gillespie, Delaware)
- Micro-Mechanical Modeling of Progressive Punch-Shear, Punch-Crush & Tensile Behavior of Unidirectional Composites (Haque and Gillespie, Delaware)
- Micromechanical FE Modeling of Tensile Failure of Unidirectional Composites (Gillespie, Delaware)
- Molecular Simulations of Sizing Deposition and Interphase Structure in S-Glass/Epoxy Composites (Abrams, Drexel)
- Multi-scale Modeling of Damage and Failure in Composites (Ghosh, JHU)
- Multi-Scale Modeling of Fiber-Matrix Interphase (Gillespie and Chowdhury, Delaware)
- Real-time Damage Visualization in Composites Under Transverse Impact (Chen, Purdue)
- Sensitivities and Uncertainty Quantification in the Composites Integrative Model Using Surrogate-based Approaches (Graham-Brady, JHU)
- Synthesis of Epoxy Networks and Interphases with Controlled Topology (Palmese, Drexel)

Real-time Damage Characterization for Glass Fiber Reinforced Composites

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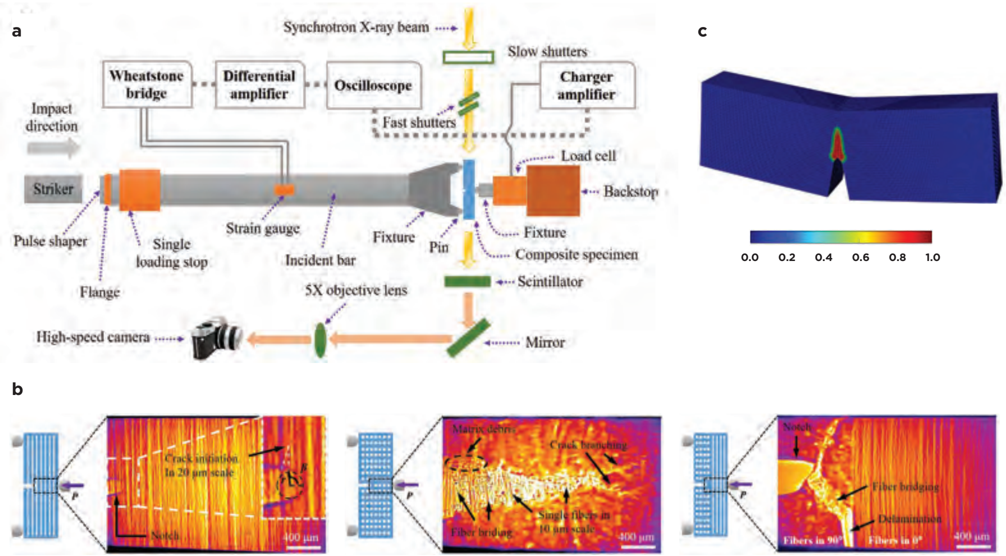
We integrate the high-speed synchrotron X-ray phase contrast imaging capabilities available at APS Beamline 32 ID-B into the dynamic single-edge notched bending experiment on the composite beam. The experiment is performed on a modified Kolsky compression bar platform by impacting the specimen installed at the incident bar end onto a static indenter at a constant velocity. The load on the indenter is directly measured by a load cell to replace the transmission bar, whilst the deflection of the composite beam is determined by stress wave passing the strain gauges on the incident bar surface. During loading, synchrotron X-ray penetrates the specimen from side and recognizes damage-related features developed inside composite. The X-rays with the damage information are then transferred to the visible light by a scintillator, magnified by a 5X objective lens and finally projected to the high-speed camera for imaging. Composites investigated are unidirectional and cross-ply S-2 glass fiber reinforced two matrix systems as commercialized SC-15 and newly developed ductile TGDDM-Jeffamine® D230 matrix modified by monoamine functionalized partially reacted substructures (mPRS), respectively. The experimental technique is revealed to have micrometer resolution to identify the crack initiation at 20-μm scale level within 200 ns and damage-related features down to 10 μm scale, such as fiber/matrix transverse debonding, fiber bridging. Moreover, it is capable of tracking the damage evolution inside and between individual plies of laminated composites.

The Parametrically Homogenized Continuum Damage Mechanics (PHCDM) models, validated by the above experimental observations, are developed to provide more quantitative information such as local stress and strain distributions, damage evolution, and detailed microscopic failure behaviors. In PHCDM models, the macroscopic constitutive laws are entirely based on micromechanical responses, therefore, the effects of microscopic information can be explicitly incorporated into the constitutive parameters through representative aggregated microstructural parameters (RAMPs). This multi-scale modeling scheme enables material-by-design from microscopic level while being computationally efficient for structure level analysis.



Crack initiation in a unidirectional GFRC with fibers in 0°

Dynamic failure of a unidirectional GFRC with fibers in 90°

Dynamic failure of a $[0°_{12}/90°_{12}]$ composite laminate

Figure 8: Real-time damage characterization for GFRCs. (a) Schematic of the experimental setup; (b) Dynamic failure of various GFRCs; (c) PHCDM prediction for damage in a unidirectional 90° GFRC beam along longitudinal direction.

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3. Gao J., Lim B. H., Zhai X., Nie Y., Kedir N., Chen W., Failure behaviors of single high-performance fibers under transverse dynamic cut. International Journal of Impact Engineering, 2020, 144:103660.

4. Zhang X., O'Brien D. J., Ghosh S., Parametrically homogenized continuum damage mechanics (PHCDM) models for composites from micromechanical analysis, Computer Methods in Applied Mechanics and Engineering, 2019, 346: 456-485.

5. Gao J., Palmese G. R., Highly ductile epoxy systems obtained by network topology modification using partially reacted substructures, Polymer (in review).

Multi-scale Finite Element Modeling of Ballistic Impact Damage in a Woven Composite

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High velocity impact on a plain weave composite target causes damage across multiple length scales. Macroscale transverse deformation wave and stress wave propagation lead to mesoscale fracture within and between interwoven fiber tows, called transverse cracking (TC) and tow-tow delamination (TTD) cracking respectively. Mesoscale fracture is composed of rate-dependent microscale fiber-matrix interface debonding and matrix plasticity and fracture. Further, atomic scale mechanisms govern these microscale behaviors. A multiscale modeling approach incorporating input from lower length scale models into a meso-mechanical finite element model (FEM), which includes mesoscale progressive damage and failure, enables prediction of the ballistic limit (V_BL) of macroscale composite targets.

The phenomenological cohesive zone model (CZM) is used to model TCs and TTD cracks in continuum fiber-matrix composite tows with cohesive zones placed across and between tows based on experimental observations. These continuum tows are woven together into a meso-mechanical FEM subjected to ballistic impact. CZMs use traction-separation laws (TSL) to describe the energy of fracture by relating the tractions inhibiting fracture as a function of the separation distance between incipient fracture surfaces. Micro-mechanical FEMs are being developed to predict mixed-mode TSLs for meso-mechanical models. Micro-mechanical models include rate-dependent matrix plasticity and fiber-matrix interface debonding from experimental data and lower length scale modeling. These models are used to compute the energy per unit area of fracture from which the TSLs are derived.

Continuum FEMs without resolved meso-architecture do not adequately predict V_BL. Incorporating mesoscale woven tows and matrix improves V_BL prediction. Including mesoscale damage mechanisms such as TTD cracks further improves V_BL prediction. This accurate prediction of V_BL enables the materials-by-design approach to improving ballistic performance in composite targets by incorporating lower length scale material behavior and mechanics into ballistic impact scale models.

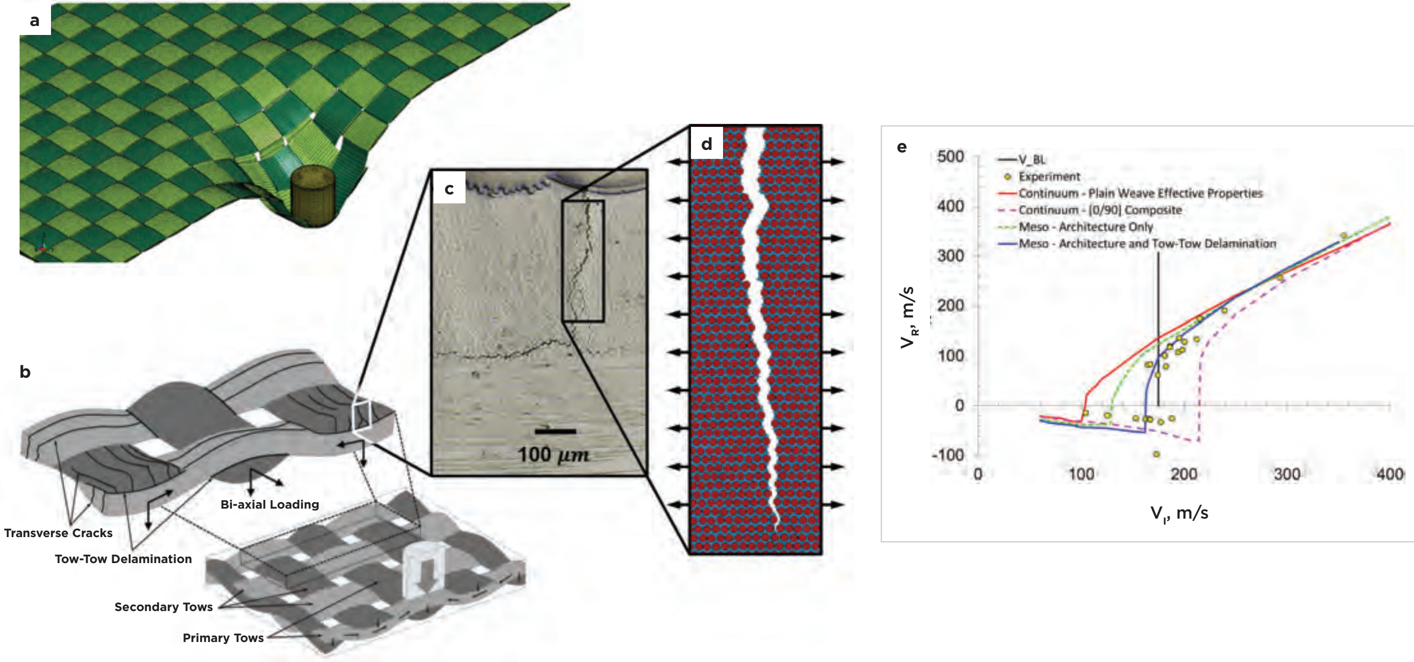


Figure 9: Ballistic impact on a single-layer, plain weave, glass/epoxy composite represented by a mesoscale finite element model (a) and by a schematic illustrating meso-architecture and experimentally observed mesoscale damage (b), which is further illustrated with a post-experiment photomicrograph of a horizontal tow-tow delamination crack and a vertical transverse crack (c), which is simulated with a micromechanical model (d) to determine cohesive zone model parameters for the mesoscale model (a). This approach enables improved prediction of ballistic limit (V_BL) compared with continuum models (e).

PROF. WAYNE CHEN

Reilly Professor of Aeronautics and Astronautics & Materials Engineering; Associate Dean for Research and Innovation; Professor of Mechanical Engineering (by courtesy), Purdue University

MEDE Area of Research:
Real-time damage visualization in composites

> "MEDE is an excellent bridge connecting my research group to the broader community of armor materials by design. It provides a stimulating, collaborative, and organized environment for people from atomistic simulation to armor testing to work together and generate innovative solutions."

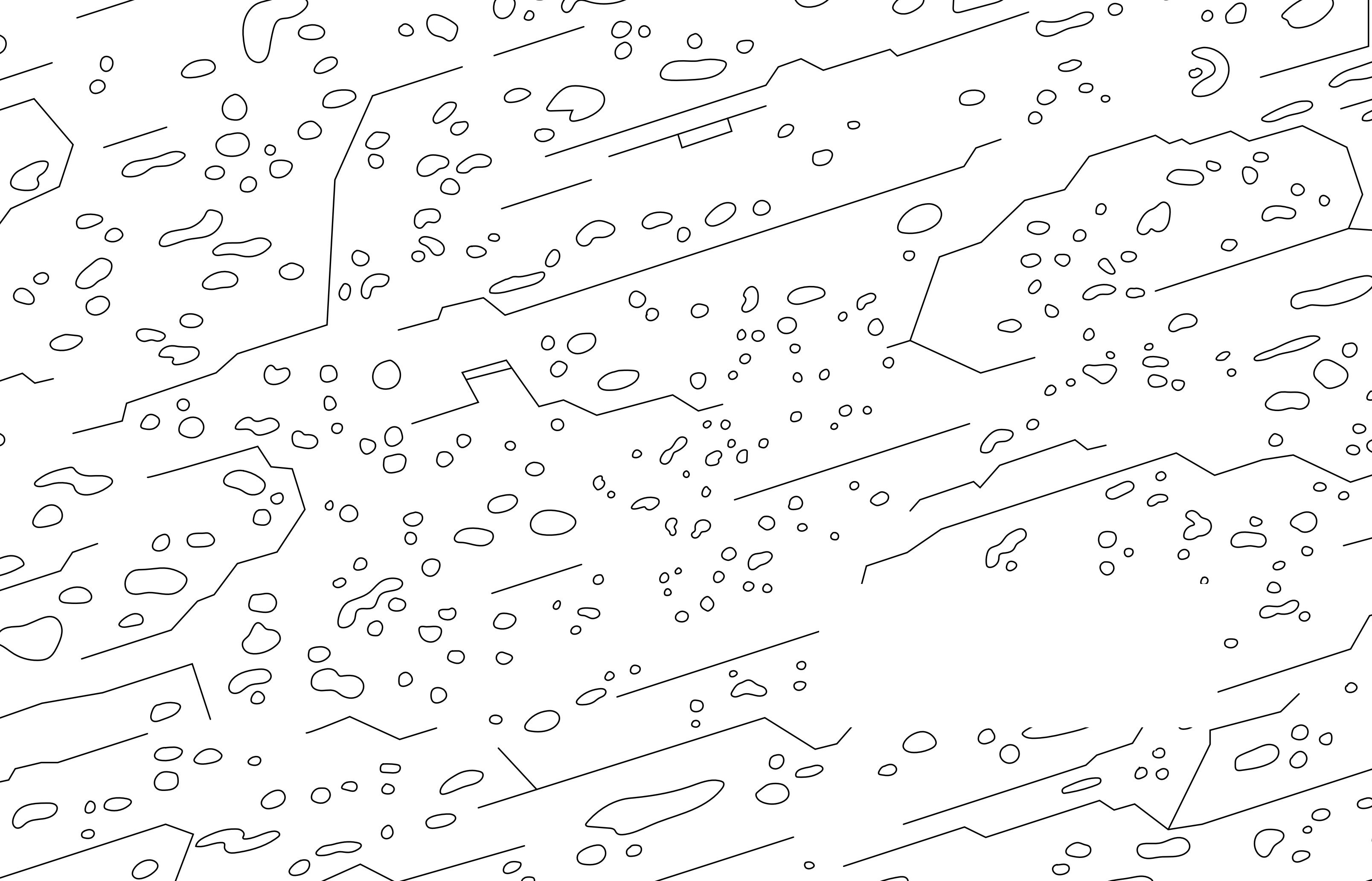
MR. JINLING GAO

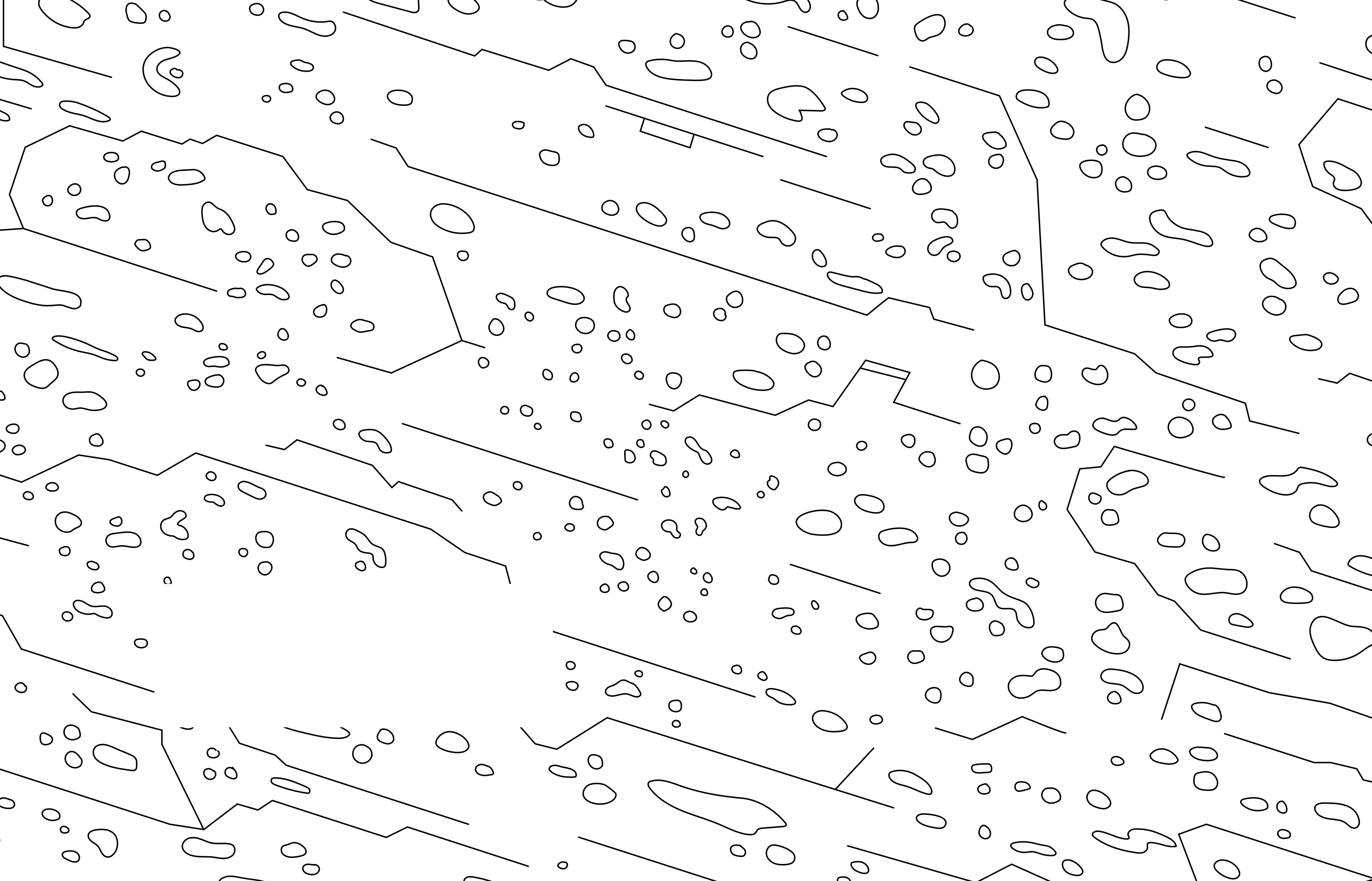
Graduate Research Assistant, Purdue University

MEDE Area of Research:
Real-time damage visualization in composites

"The MEDE program has allowed me to delve into the microscale damage detection in composite materials under dynamic loading through various visualization techniques. I have been fortunate to be part of the Composites Collaborative Materials Research Group, collaborating and exchanging ideas with researchers from leading universities and Army Research Laboratory, and seeking different approaches to solve challenging problems in composite fields. These collaborations and data sharing have been significantly beneficial to young researchers like me to expand the understanding on composites."

Artistic rendering of magnesium as seen through a transmission electron microscope.





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CCDC ARL Lead - Dr. Jeffrey Lloyd

Metals CMRG

Note: photo taken in 2019

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CONSORTIUM RESEARCH TASKS

- A Reduced-order Basis for High-throughput Microstructure-property Screening of Magnesium Alloys (Joshi, Univ. of Houston)
- Effects of Solute Atoms and Precipitates on Deformation and Twinning Response in MgAl Alloys (Kimberley, NMT)
- High Strain Rate Characterization, Thermal Softening and Spallation of Mg and the New CMRG Alloys (Ramesh, JHU)
- Mesoscale Model of Dynamic Deformation of Magnesium (Bhattacharya, Caltech)
- Microstructural Influences on Spall Void Nucleation (Hufnagel, JHU)
- Optimal Size, Shape, Spacing, and Orientation of Grains, Twins, and Second-phase Particles for Enhanced Mg Spall Resistance and Ballistic Performance (Wilkerson, Texas A&M)
- Partnered Research Initiative (Sankar, Xu, and Yarmolenko, NC A&T)
- Physically-informed Machine Learning For Material Deformations (Stuart and Bhattacharya, Caltech)
- Processing and Characterization of Novel Mg Alloys (Weihs, Hufnagel, and Kecskes, JHU)
- The Interplay of Recrystallization and Precipitation During Mg Alloy Processing (Kochmann, ETH Zürich)
- The Role of Vacancy Generation During Deformation Induced Nanoprecipitation in Mg Alloys (Falk, JHU)

Uncertainty Quantification

Dr. Xingsheng Sun	Dr. Burigede Liu	Prof. Kaushik Bhattacharya	Prof. Michael Ortiz
California Institute of Technology	*California Institute of Technology*	*California Institute of Technology*	*California Institute of Technology*

How does the natural variability of material behavior affect ballistic response? How do uncertainties at the small scale affect the performance at the large scale?

While real materials have natural variability, they are described in engineering with deterministic models with fixed parameters. This can have profound consequences in situations where one has to certify the outcome as in ballistic protection. Dr. Xingsheng Sun and Professor Michael Ortiz have developed a new framework to quantify how variability in material behavior affects the overall ballistic response. Key to their work is Levi's concentration of measures inequality which provides rigorous bounds on the uncertainty and therefore can be used in the certification. Unlike previous work, this approach does not require an a priori knowledge of the statistics of material uncertainty. Further, their computational approach is modular and can be used as a "wrapper" around existing approaches. They have demonstrated this work on magnesium, and have transitioned it to the CCDC Army Research Laboratory.

A key aspect of the materials-by-design approach is the recognition that properties of real materials are the result of complex multiscale phenomena. Therefore, materials are commonly described by a cascade of models where analysis at one scale informs models at a higher scale. However, there are uncertainties at each scale and this affects the overall behavior. Sun and Ortiz, in collaboration with Dr. Burigede Liu and Professor Kaushik Bhattacharya, have developed a framework to understand how these uncertainties propagate through the multiscale framework as illustrated in the corresponding figure. Crucially, the method only requires analysis of each scale which is computationally feasible and then uses the rigorous McDiarmid's inequality to estimate the overall system uncertainty. Further, the approach provides the sensitivity of the system response to parameters at each scale. This is critical for materials-by-design because it informs what aspect of the material has to be changed to improve overall system performance. The approach has been demonstrated on the ballistic response of magnesium plates starting from the single crystal response, as depicted in the corresponding figure.

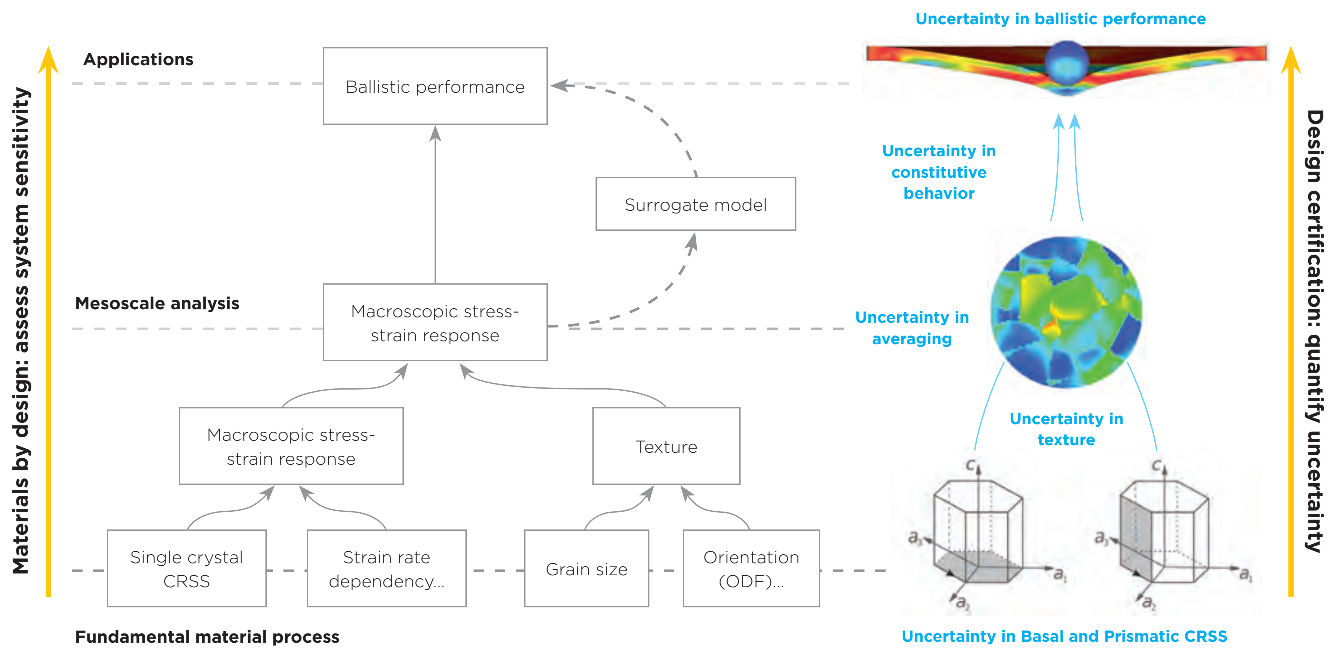


Figure 10: Multiscale uncertainty quantification and material by design of polycrystalline magnesium: from single crystal properties to ballistic performance.

Fabrication of Novel Mg Alloys and their Deformation Processing via Confined and Differential Speed Rolling

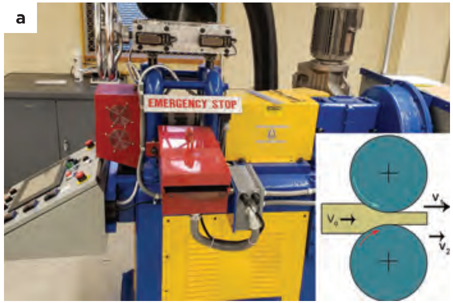
Prof. Jagannathan Sankar *NC A&T State University*	**Dr. Zhigang Xu** *NC A&T State University*	**Dr. Sergey Yarmolenko** *NC A&T State University*	**Prof. Qiuming Wei** *UNC Charlotte*
Dr. Laszlo Kecskes *Johns Hopkins University*	**Prof. Tim Weihs** *Johns Hopkins University*	**Prof. Todd Hufnagel** *Johns Hopkins University*	**Dr. Jeffrey Lloyd** *CCDC Army Research Laboratory*

Since 2018, NC A&T has been the sole supplier of customized magnesium (Mg) alloys to the MEDE program with the required materials quantity, quality, and turn-around time. Since joining the larger MEDE consortium, NC A&T developed a state-of-the-art melting/casting system to meet the requirement for severe plastic deformation processing (via Equal Channel Angular Extrusion [ECAE]) studies at JHU and ARL. Using our process innovation acumen, we are able to cast multiple-batches of bars and plates of Mg-Al and Mg-Zn-Ca alloys and continue to support the material needs of JHU for ECAE processing. We are not only meeting the continuing needs of the ECAE process studies, but also making additional Mg alloy casts for extrusion and differential speed rolling (DSR) studies at NC A&T, as well as for confined rolling studies at UNCC. To minimize the impurity amount (less than 100 ppm), a specially designed procedure of extended dwelling at reduced temperatures before casting was developed and verified with detailed SEM/EDS analyses, combined with other characterization techniques including high-resolution CT scans and μ-XRF mapping. The results show that the number of impurities was reduced by a factor of two compared to our initial effort and by a factor of 5 compared to commercial vendors. Moreover, the impurity type, size, and spatial distribution data produced by microscopic characterization studies will be used as input variables in modelling studies of material performance.

NC A&T has made significant progress in studies of the effects of rolling parameters, such as roller speed ratio, rolling temperature, thickness reduction rate on the dynamic recrystallization (DRX) and texture evolution of Mg alloys under DSR conditions, as well as in determination of their mechanical performance of Mg-Al alloys. It was found that DSR has better grain refining capability over conventional rolling (CR). Different DRX behaviors of the Mg-9Al and Mg-6Al alloys were discovered after rolling. DSR also reduced in-plane tensile plastic anisotropy for Mg-6Al alloy compared to that with CR. Systematic rolling studies will provide sets of microstructures which will help to better understand deformation mechanisms in extreme dynamic environments. These microstructures will be mapped out under carefully designed experiments that correlate the microstructure from the atomistic to continuum level with the dynamic mechanical behavior under controlled conditions. NC A&T has also set up a state-of-the-art electron backscatter diffraction (EBSD) system and is utilizing it in the study of deformation and dynamic recrystallization in Mg alloys processed by different rolling technologies at NC A&T and UNCC, as well as by ECAE at JHU.

EBSD has been used not only to provide orientation information of each individual grain, but also to reveal geometrically necessary dislocations (GND) along the grain boundaries and inside the grains as well. Our study of the effect of strain on the efficiency of DRX at elevated temperature shows that GND maps will be very valuable in the optimization of processing parameters.

Figure 11: Photograph of the NC A&T differential speed rolling (DSR) system. It can process a plate up to 1″ thick × 6″ wide with a maximum speed ratio of 2. This system is one of a few in the USA and will contribute to improvement in processing capability within the MEDE program; b) tensile stress-strain curves of the rolled Mg-6Al alloy plates in the rolling (RD), transverse (TD), and 45°-RD directions for the plates processed with CR and DSR.



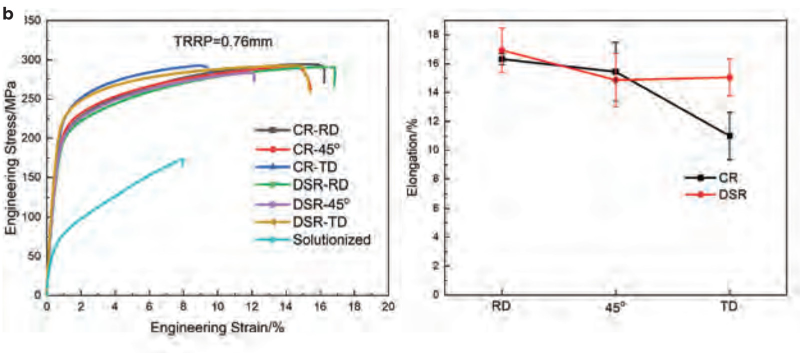
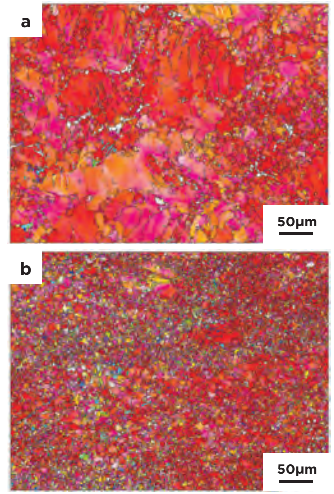


Figure 12: Inverse pole figure maps for Mg-9Al processed with a) CR and b) DSR with a speed ratio of 2. All of the rolling experiments were conducted at 400°C, 0.76-mm reduction/pass, and ~50% total thickness reduction.



PROF. JUSTIN WILKERSON

Assistant Professor, Dept. of Mechanical Engineering, Texas A&M University

MEDE Area of Research:
Optimal Size, Shape, Spacing, and Orientation of Grains, Twins, and Second-phase Particles for Enhanced Mg Spall Resistance and Ballistic Performance

> "The MEDE program has afforded me the opportunity to work on a number of fundamental problems whose solutions have real-world implications for the Soldier. The sustained, collaborative nature of MEDE is the vehicle that best enables me to bring visibility to my work and translate it into real-world applications."

DR. SURAJ RAVINDRAN

Postdoctoral Scholar, California Institute of Technology

MEDE Area of Research: *Dynamic strength of magnesium and its alloys at extreme pressures*

"My research investigates the interplay between pressure and strain rate on the strength of magnesium and its alloys, which helps in developing and validating material models for impact related applications. MEDE program has provided me with a unique opportunity to expand my knowledge by collaborating with interdisciplinary material modeling and processing groups."

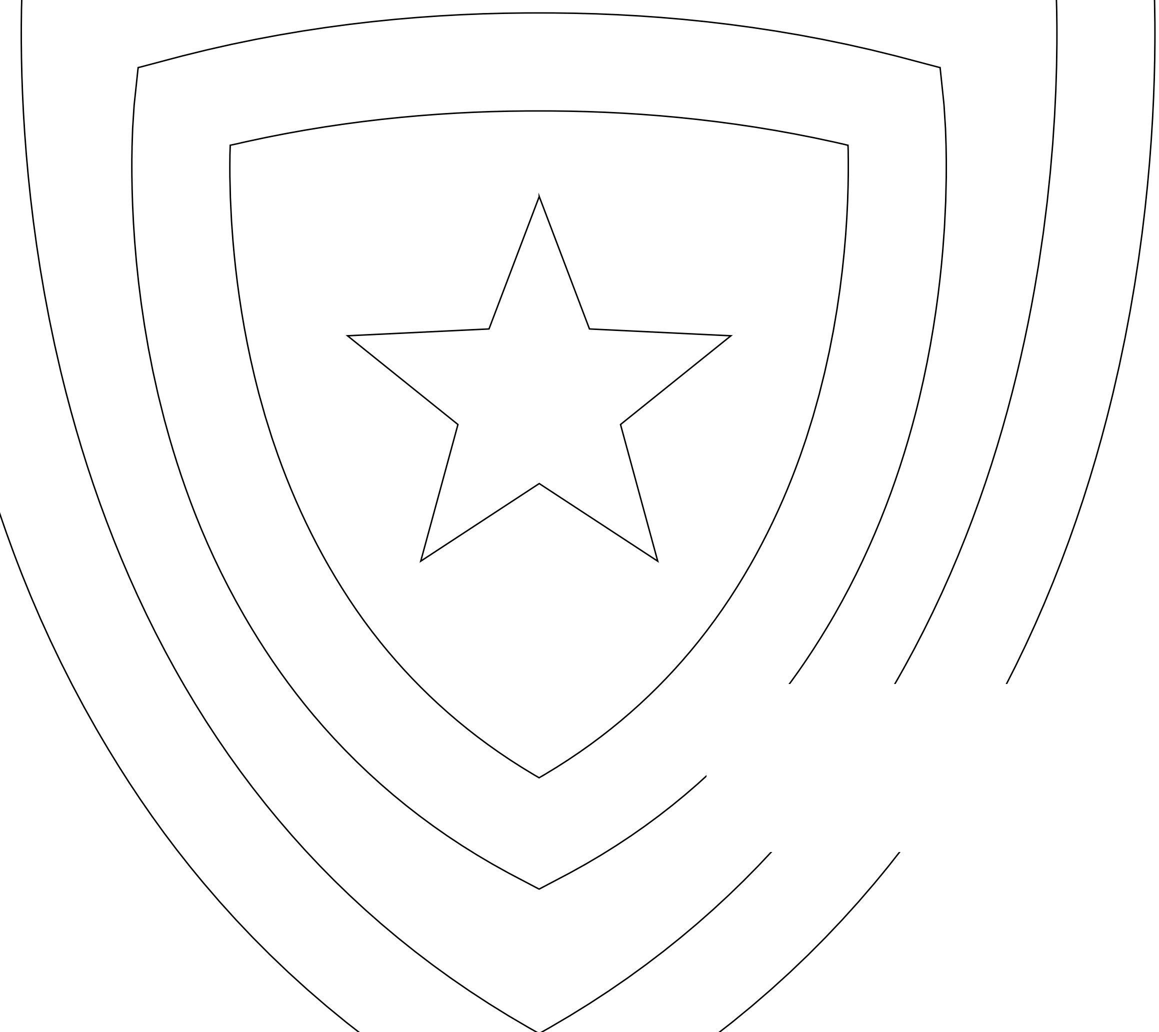
DR. DANIEL MAGAGNOSC

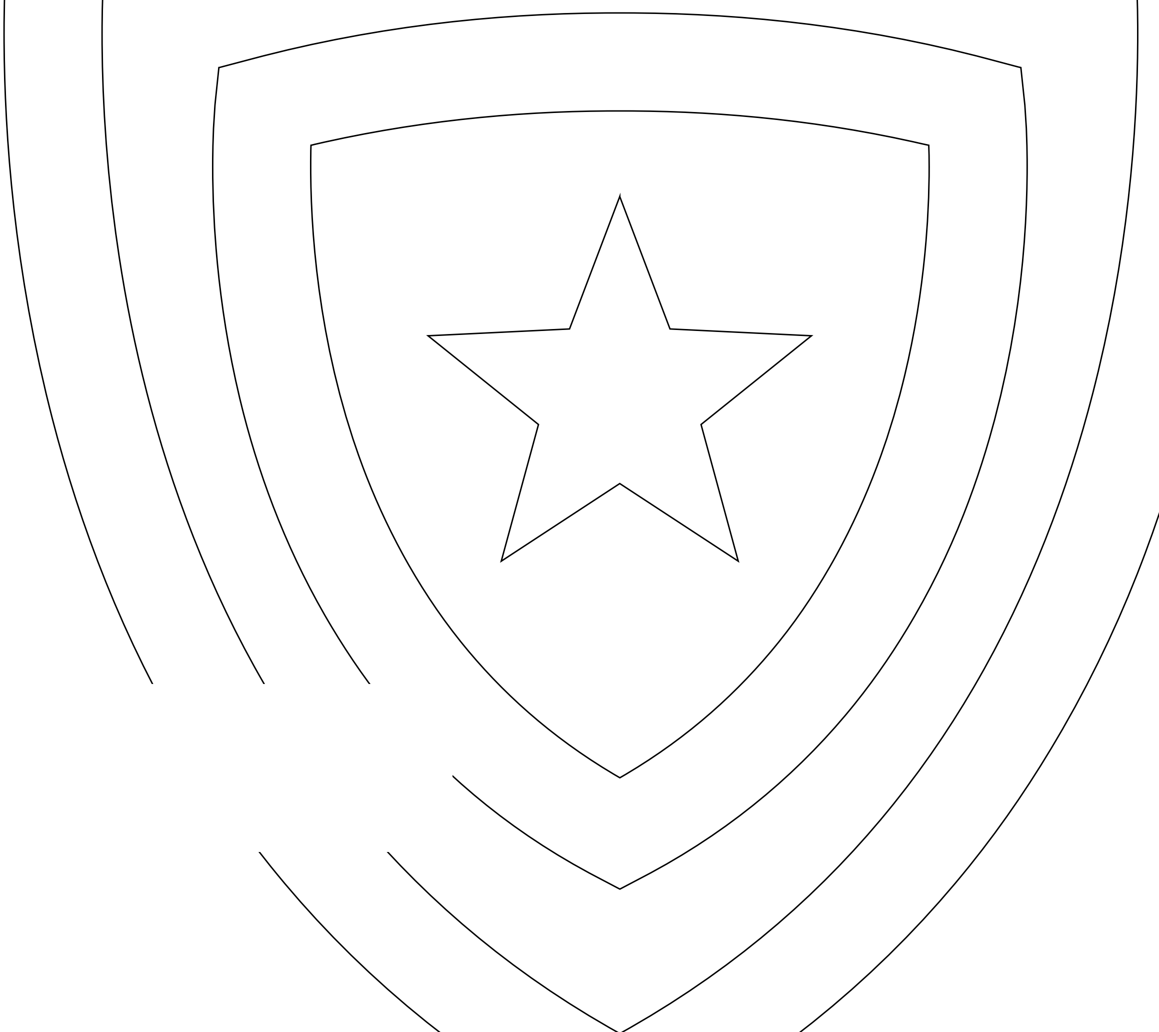
Materials Engineer, CCDC Army Research Laboratory

MEDE Area of Research: *Pre-twinned Mg alloys for controlled fracture*

"Working with the MEDE program provides me access to leading experts on Mg processing and deformation. Being able to quickly share results and receive feedback has accelerated the discovery process. The breadth of experimental methods available within MEDE has also been a large benefit. This allowed me to quickly explore unique loading conditions that are critical to understanding fracture during impact."

The CMEDE shield symbolizes the protection and the strong collaboration found within the MEDE program.





INTEGRATIVE AND COLLABORATIVE TOOLS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Dr. Brian Schuster


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Prof. K.T. Ramesh, JHU

Dr. Adam Sierakowski, JHU

SELECT CCDC ARL COLLABORATORS

Dr. Richard Becker

Dr. William Mattson

Dr. Betsy Rice

Dr. Brian Schuster

INTEGRATIVE RESEARCH ACTIVITIES

- Collaborative Research Administrative Environment and Data Library (Sierakowski and Walker, JHU)
- MEDE Data Science Cloud (Elbert, JHU)

Incorporating the UMAT Material Model Interface into the EPIC Code

Charles A. Gerlach
Southwest Research Institute

There is a strong desire to ease the process of getting complex material models (developed by others) into computer codes used by the Department of Defense. The MEDE program realized this need and funded Southwest Research Institute (SwRI) to incorporate an interface into the Elastic-Plastic Impact Computations (EPIC) code such to ease the process of using newly developed material models in EPIC[1]. SwRI incorporated the user material (UMAT) interface into EPIC which allows material models to be easily used within the EPIC framework. This interface is a standard, developed by Abaqus, and requires very few changes to the model if the interface standard is adhered to.

After incorporation of the UMAT interface a thorough checkout was performed to verify the interface was incorporated correctly. The verification used the Tonge-Ramesh (TR) ceramic model[2] because this model is included in the native EPIC code[3] and there is also a UMAT interface version of the TR model. This allows for a direct comparison of model results; one using the model native in EPIC that has been thoroughly checked and the other using the UMAT interface.

Figure 13 presents a comparison of a single 3D hexahedral element simultaneously subjected to shear and tension (shown on the left) and to shear and compression (shown on the right). Artificial viscosity has been turned off. The results using the TR model through the UMAT interface are shown with black dots and the results using the TR model native in EPIC are shown with the red lines; the two results overlay confirming the UMAT interface is incorporated correctly.

Figure 14 presents a ballistic impact computation of a steel cylinder impacting a boron carbide plate backed by an aluminum plate at 1000 m/s. The computed result on the top uses the TR ceramic model native in EPIC and the result on the bottom uses the UMAT interface; the computed results are nearly identical (the slight differences are a result of temperature which is treated differently between the native model and the UMAT model). This new capability provides the MEDE material model developers with an efficient and simple procedure for using these new models in EPIC. Towards this end, we continue to develop more effective ways to capture and analyze the large, diverse data commonplace in materials today. Direct collaboration with MEDE investigators creates new ways to maximize the impact of their data.

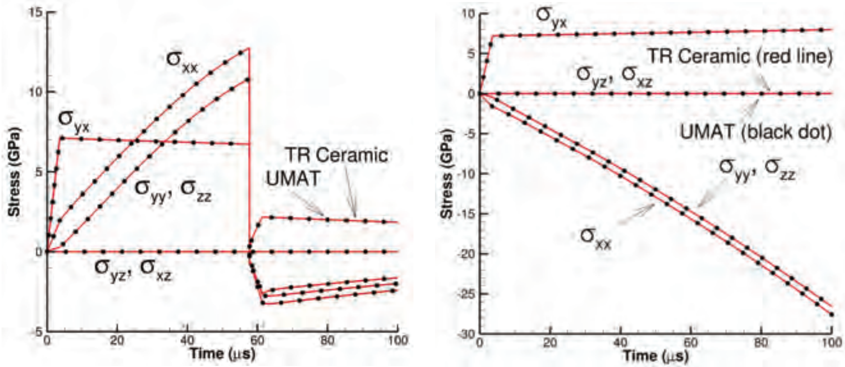


Figure 13: Single element comparison between the TR Ceramic model native in EPIC, and the same model compiled through the UMAT interface. Combination of shear and tension is shown on the left and a combination of shear and compression is shown on the right.

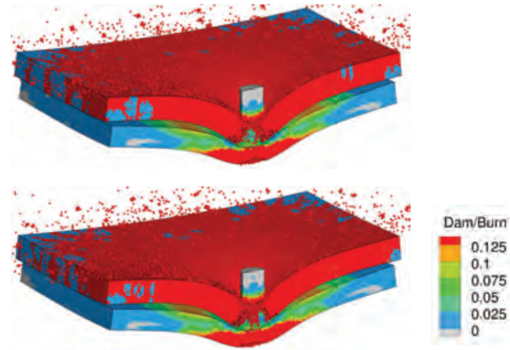


Figure 14: A tool-steel cylinder impacting a boron carbide plate backed by an aluminum plate. The computed result using the TR model native in EPIC is shown on the top and the result using the UMAT interface is shown on the bottom.

References

1. C. A. Gerlach, "Incorporating the UMAT material model interface into the EPIC code", SwRI Technical Report 18.17637.07, May, 2018.

2. A. L. Tonge, "A unified framework which uses multi-scale microstructure information for modeling dynamic failure in brittle materials," PhD thesis, The Johns Hopkins University, 2014.

3. T. J. Holmquist, C. A. Gerlach, and G. R. Johnson, "Incorporating the Tonge-Ramesh (TR) ceramic model into the EPIC code", SwRI Technical Report 18.17637.03, October, 2015.

ADDITIONAL COLLABORATIVE ACTIVITIES

Collaborative Research Administration Environment and Data Library (Craedl)

Contributed by: Dr. Adam Sierakowski

Beyond its primary scientific mission, the CMEDE consortium faces three key challenges:

1. Managing the research efforts of hundreds of researchers distributed across the country;
2. Sharing large data sets across institutional boundaries; and
3. Igniting collaborative efforts through data discovery.

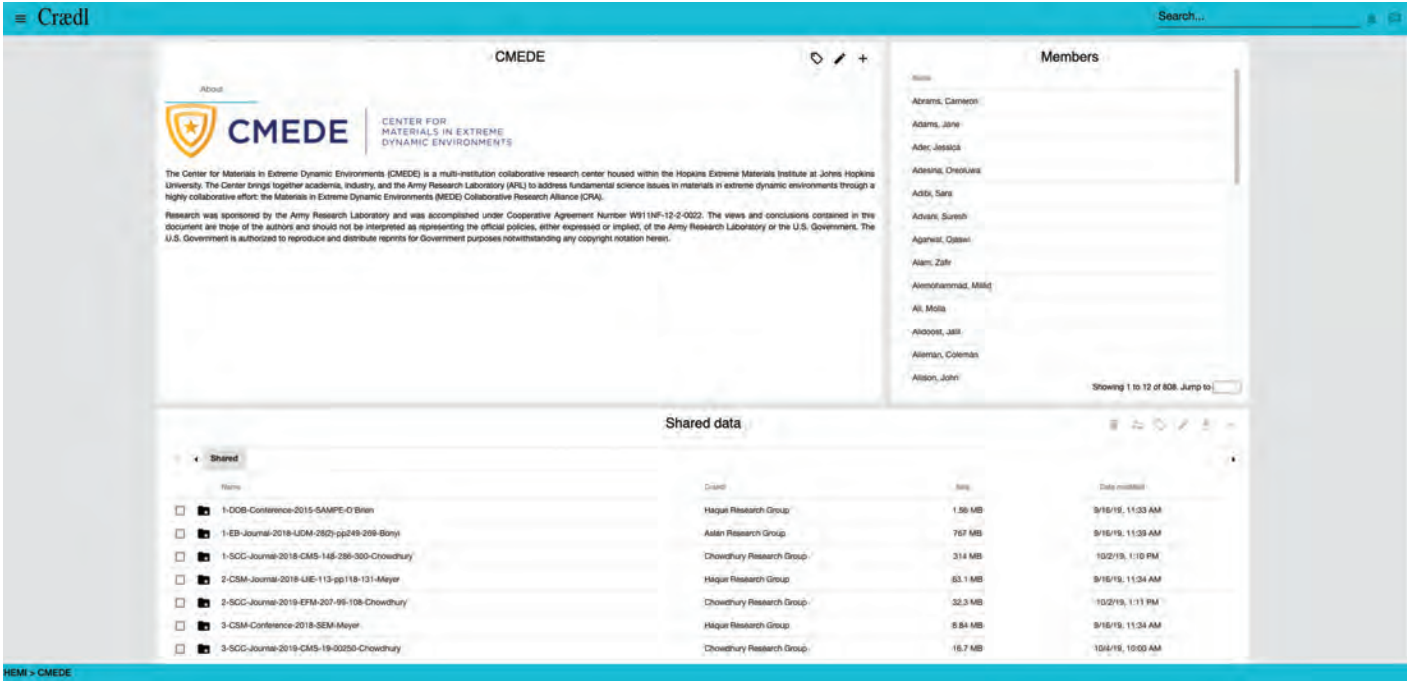
Craedl, the Collaborative Research Administration Environment and Data Library, is a tool being developed to overcome these challenges. Accessible at https://craedl.org/institute/hemi, Craedl provides a secure environment for CMEDE affiliates to store their data, share it with collaborators, and search the data shared by other affiliates.

Craedl balances structure and flexibility, enabling researchers to incorporate it directly into their workflow. By doing so, researchers can take advantage of Craedl's automatic metadata population capabilities to document their work in small increments over the life of a project. This metadata—the data that describes the data—is crucially important because it facilitates searching, which prevents data from getting lost and helps colleagues discover otherwise hidden data. Importantly, the researcher maintains complete control over his or her data: All of a researcher's data remains private unless explicitly shared with a collaborator, at which time the data becomes visible to the collaborator's searches. Further, Craedl enhances the short- and long-term operations of research groups by providing discussion boards and other group management tools that assist in the documentation of the work.

Researchers log in to Craedl using the credentials of their home institution or using their email address. Craedl organizes the network of CMEDE researchers by tracking their grants, projects, data, publications, and presentations to assist in the management of CMEDE's distributed research groups. Craedl facilitates the sharing of data sets large and small (up to tens of terabytes) and is currently underpinned by a 284TB file storage system.

Cræd l

Collaborative Research Administration Environment and Data Library



In addition to supporting the sharing, archival, and discovery of research data, Craedl helps manage CMEDE's collaborative efforts.

CCDC ARL Open Campus

The MEDE CRA embraces the CCDC ARL Open Campus Initiative. The highly collaborative nature of the MEDE program intrinsically supports consortium members working side by side with CCDC ARL scientists and engineers. In addition to taking advantage of CCDC ARL's laboratories at Aberdeen Proving Ground in Maryland, CRA members frequently utilize facilities at other MEDE consortium locations. Johns Hopkins University, Rutgers University, and the University of Delaware each have dedicated space for CCDC ARL researchers. This promotes the building of a science and technology ecosystem that encourages groundbreaking advances in basic and applied research areas of relevance to the Army.

Collaboration with the MEDE Programme

Contributed by: Chris Hawkins MPhys MIMMM – UK Lead for MSA/MEDE interaction

The Dstl Materials for Strategic Advantage (MSA) Programme is funded by the UK Ministry of Defence and undertakes innovative materials research that will enable Front Line Commands to deliver future defence platforms and capabilities. MSA delivers across a breadth of materials technologies and continues to have a strong focus on materials for physical protection for the dismounted soldier and land vehicles.

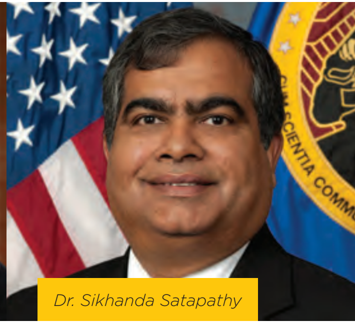
A strong cohort of PhD students is now established looking at topics including laser sintering of ceramics, novel routes for ceramic manufacture and understanding ballistic interfaces. Imperial College London, in collaboration with Johns Hopkins, are using microstructural models developed for armour ceramics in partnership with Oxford University, and now implemented in commercial finite element code, to simulate the large deformation of Dyneema® at multiple scales. In addition, Oxford and Lehigh Universities, together have been studying ceramic grain boundary strength.

Despite the challenges of the current global pandemic, collaboration continues between UK and US universities through the multitude of video and teleconferencing platforms.

The UK MSA Programme anticipate a highly productive ongoing relationship with MEDE, both in terms of Dstl staff meeting and conference participation and the alignment of our respective research activities.

2020 Fall Meeting Plenary Speakers

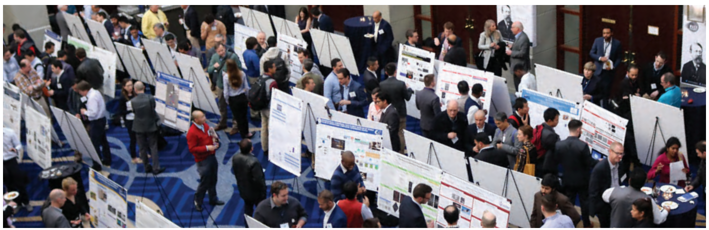

Prof. K.T. Ramesh


Dr. Sikhanda Satapathy


Dr. Adam Rawlett


Dr. Doug Templeton

The MEDE Fall Meeting is an annual, closed event that brings the entire MEDE CRA together for program overviews, collaborative activities and discussion. the event was attended by 130 individuals including special guests from the United Kingdom's Defence Science and Technology Laboratory, the U.S. Army CCDC Army Research Laboratory, the Defense Threat Reduction Agency, the National Institute of Standards and Technology, the U.S. Army CCDC Soldier Center, the U.S. Army Engineer Research and Development Command, the Office of Naval Research, and the National Ground Intelligence Center. Professor K.T. Ramesh (JHU) and Dr. Sikhanda Satapathy (CCDC ARL) led the meeting, which highlighted the research accomplishments for new metallic, ceramic, and composite protection materials, as well as new computational design codes and tools for armor applications.



Mach Conference

The Mach Conference is an annual, open event that showcases the state of the art of multiscale research in materials, with an emphasis on advancing the fundamental science and engineering of materials and structures in extreme environments. MEDE CRA members are significant participants in this event, which shares research discoveries to the broader community. Due to COVID-19, the 2020 Mach Conference was canceled, but the event is scheduled to return in 2021.

RELATED ACADEMIC PROGRAMS

In addition to its research activities, CMEDE runs several academic programs that broaden the scientific impact of the MEDE program.

Traditional

- Short Courses – Intensive, two-day courses taught by a master in his/her field that are co-sponsored by the Hopkins Extreme Materials Institute. Attendees include professionals, researchers, and graduate students from industry, government, national laboratories and academia.
- Lectures and Seminars – CMEDE supports the Enterprise for Multiscale Research of Materials lecture series that helps to educate and promote collaboration across the entire enterprise. Additionally, CMEDE hosts seminars from distinguished experts from scientific fields related to MEDE research.

Dr. Adam Sierakowski introduces new students to the Collaborative Research Administration Environment and Data Library (Craedl).

Internship and Apprenticeships

- Extreme Science Internships (ESI) – The ESI program is a year-round, paid internship program with Morgan State University. ESI provides internal internships at Morgan State to allow students to develop their research skills before participating in an external internship at a MEDE CRA location. ESI has been a highly successful program and serves as a model collaboration for student development.

- Undergraduate Research and Apprenticeship Program (URAP) – URAP provides undergraduate students with an authentic science and engineering research experience alongside university researchers at one of the MEDE university locations. Through this program, students develop skills in Army critical science and engineering research areas to prepare them for the next steps of their educational and professional career. URAP is sponsored by the Army Research Office and is a part of the Army Educational Outreach Program.

- Research and Engineering Apprenticeship Program (REAP) – The Hopkins Extreme Materials Institute (HEMI), parent to CMEDE at Johns Hopkins University, was selected as a host site for REAP. REAP is a summer STEM program that places talented high school students, from groups historically under-represented and underserved, in STEM in research apprenticeships. REAP apprentices work under the direct supervision of a mentor on a hands-on research project. REAP is a part of the Army Educational Outreach Program.

2020 URAP and REAP interns

Other Activities

- HEMI/MICA Extreme Arts Program – The HEMI/MICA Extreme Arts Program is an initiative that brings faculty and students from Johns Hopkins University and the Maryland Institute College of Art (MICA) together to explore unique perspectives on extreme events. The program aims to encourage collaboration among artists and researchers to examine data, interpret outcomes, and translate results from extreme events in new ways. It is our hope that this dialogue will create a stronger community through a shared sense of curiosity and exploration. CMEDE is a significant participant in this program.


2020 Extreme Arts Summer Project Interns Danielle Duplain and Chelsea Conrad.

CMEDE STRATEGIC PARTNERSHIPS

MEDE has established strategic partnerships with several key organizations. These partnerships enable CMEDE to collaborate, leverage resources and broaden its impact to the scientific community.

Subcommittee of the Materials Genome Initiative (SMGI) of the National Science and Technology Council

Center for Composites Materials (CCM)

Army Educational Outreach Program

US Advanced Ceramics Association (USACA)

The Institute for Data Intensive Engineering and Science

Air Force Research Laboratory

Maryland Advanced Research Computing Center (MARCC)

Lightweight Innovations for Tomorrow (LIFT)

Ceramics, Composite and Optical Materials Center (CCOMC)

U.S. Naval Research Laboratory

National Institutes of Standards and Technology

CMEDE LEADERSHIP AND STAFF MEMBERS AT JOHNS HOPKINS UNIVERSITY

CMEDE Leadership

Prof. K.T. Ramesh
Director

Prof. Lori Graham-Brady
Associate Director

Dr. Victor Nakano
Executive Program Director

CMEDE Staff

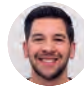
Jessica Ader
Senior Communications Specialist

Bess Bieluczyk
Senior Administrative Coordinator

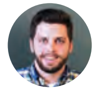
Denise R. Brown
Budget Specialist

Lisa Eklund
Grants and Contracts Manager

Scott McGhee
Senior Administrative Manager



Justin Moreno
Associate Staff Engineer



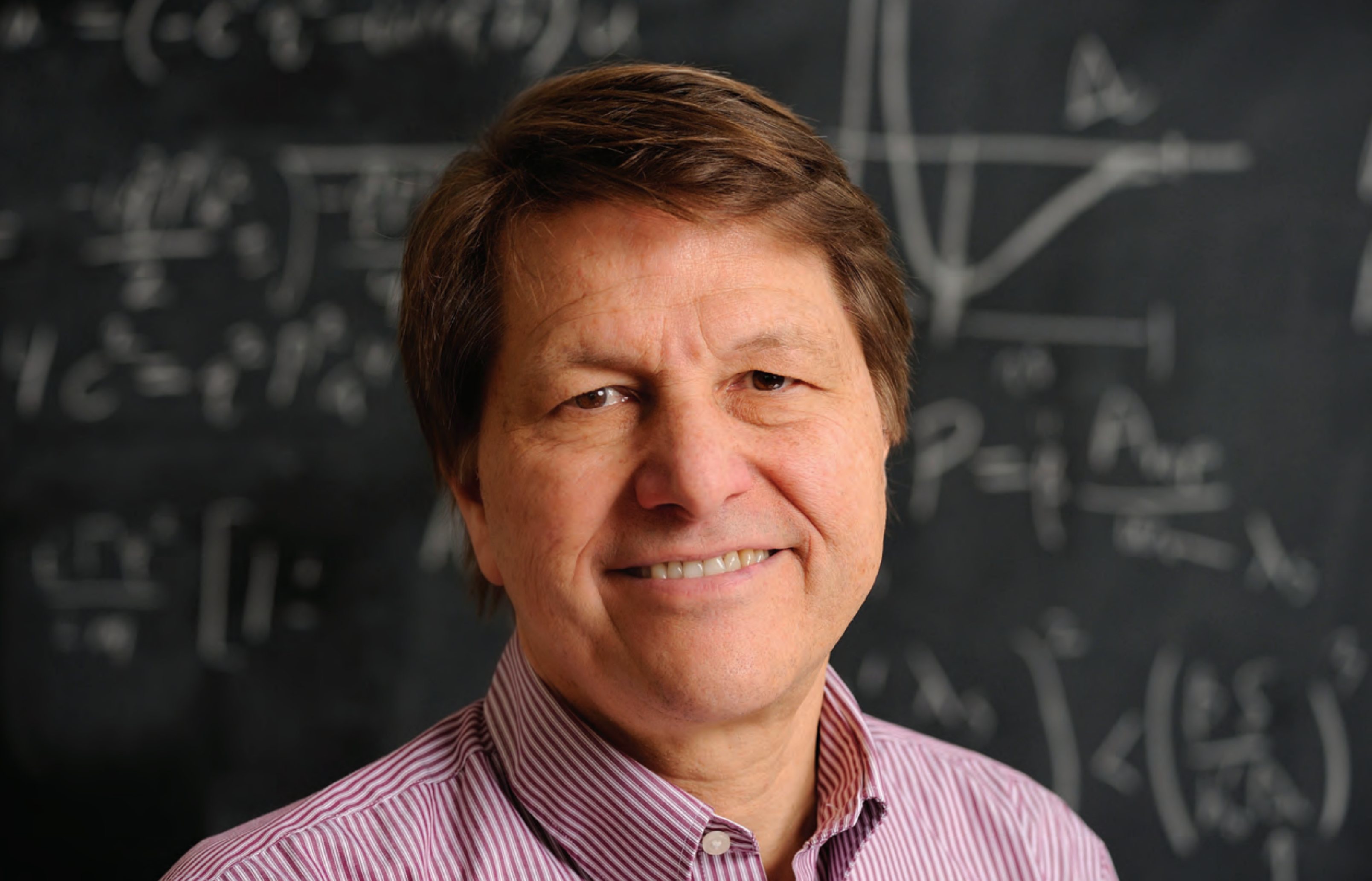
Andrew Proulx
Senior Grants and Contracts Analyst

Matthew Shaeffer
Staff Engineer

Katie Vaught
Senior Administrative Coordinator

ABBREVIATIONS AND ACRONYMS

AEOP	Army Educational Outreach Program
CCDC ARL	U.S. Army Combat Capabilities Development Command Army Research Laboratory
CALTECH	California Institute of Technology
CCM	Center for Composite Materials
CCOMC	Ceramic, Composite and Optical Materials Center
CMC	Consortium Management Committee
CMEDE	Center for Materials in Extreme Dynamic Environments
CMRG	Collaborative Materials Research Group
CTRG	Collaborative Technical Research Group
CRAEDL	Collaborative Research Administration Environment and Data Library
DELAWARE	University of Delaware
DOD	Department of Defense
DREXEL	Drexel University
DSTL	Defence Science and Technology Laboratory
EMRM	Enterprise for Multiscale Research of Materials
ESI	Extreme Science Internship
HEMI	Hopkins Extreme Materials Institute
JHU	Johns Hopkins University
MEDE	Materials in Extreme Dynamic Environments
MEDE CRA	MEDE Collaborative Research Alliance
MGI	Materials Genome Initiative
MICA	Maryland Institute College of Art
MSU	Morgan State University
NC A&T	North Carolina Agricultural & Technical State University
NIST	National Institute of Standards and Technology
NMT	New Mexico Institute of Mining and Technology
PURDUE	Purdue University
REAP	Research in Engineering Apprenticeship Program
RUTGERS	Rutgers University
STEM	Science, Technology, Engineering and Math
UNCC	University of North Carolina at Charlotte
URAP	Undergraduate Research and Apprenticeship Program



IN MEMORIAM: PROF. MARK ROBBINS

Mark O. Robbins, Professor in the Department of Physics and Astronomy at Johns Hopkins University, renowned condensed matter and statistical physicist, member of the HEMI Executive Committee, and member of the MEDE Polymers and Ceramic CMRGs, died unexpectedly on Thursday, August 13, 2020.

Within MEDE, Mark played a dominant role in the modeling aspects of the Polymers CMRG, and more recently in the modeling of granular flow within the Ceramics CMRG. His legacy in the physics of condensed matter is very substantial, and his legacy in terms of the people that he mentored is stronger still.

Mark Robbins grew up in Newton, Massachusetts, and received his BA and MA degrees from Harvard University. He spent a year as a Churchill Fellow at Cambridge University before receiving his PhD from the University of California, Berkeley in 1983. Following a postdoctoral fellowship at Exxon's Corporate Research Science Laboratory in New Jersey, he joined the Department of Physics and Astronomy at Johns Hopkins in 1986.

Mark was a member of the advisory board for the Kavli Institute of Theoretical Physics at the University of California, Santa Barbara and was also on the advisory board of the Boulder School for Condensed Matter and Materials Physics. He became a Fellow of the American Physical Society in 2000 and was awarded a Simons Fellowship in Physics in 2013.

Mark was one of those rare people that you knew you could trust completely, and his combination of clarity of thought and unfailing good humor resolved many a knotty problem at Johns Hopkins. At the University level, he was instrumental in the development of high-performance computing at Johns Hopkins, including in the conception and development of the Maryland Advanced Research Computing Center, which continues to be used by a large number of MEDE researchers. He was also the Associate Director of the Institute for Data Intensive Engineering and Science at Johns Hopkins.

On a research trip to Brazil in 1987, Robbins picked up what he humorously described as a "dangerous habit" of collecting and crossbreeding orchids. He grew a diverse number of the species, and developed new breeds of orchids through experimental crossbreeding techniques. This earned him an Award of Merit from the American Orchid Society. He officially named two of his new orchids after his children, Thomas and Catherine.

He is survived by his wife, Patricia McGuiggan (an associate research professor in the Department of Materials Science and Engineering at Johns Hopkins), and his two children.

HEMI.JHU.EDU/CMEDE

For more information on CMEDE, visit us at: hemi.jhu.edu/cmede,
call us at 410-516-7257 or email us at mede@jhu.edu.

Research was sponsored by the Army Research Laboratory and was accomplished under Cooperative Agreement Number W911NF-12-2-0022. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Army Research Laboratory or the U.S. Government. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation herein.

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