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Controlling the Load Distribution in High-Strength Materials Army Science Planning and Strategy Meeting (ASPSM)

by Christopher Hoppel, David Stepp, Richard Becker, Michael Bakas, Lionel Vargas-Gonzalez, Andrew Tonge, and Mark Tschopp

NOTICES

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14. ABSTRACT

Future Army capabilities require understanding and controlling the physics associated with material fracture and failure from applied loads, a mechanical behavior relevant to many problems within Army systems, ranging from bolted joints to armor, and one that impacts Soldier lethality and survivability. To address this, the US Army Combat Capabilities Development Command Army Research Laboratory held an Army Science Planning and Strategy Meeting (ASPSM) on Controlling the Load Distribution in High-Strength Materials in December 2020. Participants presented and discussed material concepts for redistributing localized loading and delay or preventing failure due to impact in granular media, lattice structures, and emerging composite architectures. Leveraging the research's inherently interdisciplinary nature (material science, experimental and computational mechanics, machine learning, and computer science), participants identified a need for developing numerical techniques to model the constitutive response of these materials, including mechanical behavior under large deformations, fracture, and failure. Machine learning algorithms can offer some advantages in speed and accuracy by integrating into the data-driven design strategy, but their application needs to be validated by experimental data or physics-based models. A research strategy focused on these principles will produce systems and equipment for the future Soldier with an enhanced capability for mitigating stresses generated from impact or other sources.

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1. Introduction

The US Army has a significant interest in controlling material fracture and failure, given that this behavior governs the performance limits for both lethality and protection. In terminal ballistic processes, both the projectile and armor system undergo deformation, fracture, and failure during the penetration process; the response is dependent on the fracture process as well as the behavior of the material post fracture. Composite armors in helmets, torso armor, and vehicle armor are designed to distribute momentum and energy, deform, delaminate, and eventually stop a projectile during the penetration process.

The failure process is controlled by the material structure; structures that enable materials to absorb significant energy or distribute the momentum while failing gracefully will have advantages over brittle material systems under high rates of loading. Recent research has demonstrated that tailoring the structure of hard granular materials to induce interactions during the failure process (i.e., the shear jamming phenomenon) shows promise in spreading locally high-impact loads over a broader area (O'Hern et al. 2014; Behringer and Chakraborty 2018; Wang et al. 2019; Carlevaro et al. 2020). Metamaterial concepts (Injeti et al. 2019) and lattice structural designs (Tian et al. 2020) offer the potential of lightweight structures that enable the redirection or spreading of highly localized loading. Material mechanisms that spread out peak loads have the potential to revolutionize the design of armors and other structures designed to withstand high local loading (i.e., bolted or riveted joints).

The Army held an Army Science Planning and Strategy Meeting (ASPSM) to address technical gaps in our ability to design materials for force, momentum, and energy distribution at high loads and loading rates. The purpose of the workshop was to probe the state of the art and theoretical limits, and establish goals for future research. Section 2 of this report summarizes the outcomes from the workshop, built around the notes from the nine breakout sessions. Section 3 of the report recommends an approach for future research in this area.

2. Workshop Results

The ASPSM on Controlling Load Distribution in High-Strength Materials was held December 7, 9, and 11, 2020, as three afternoon video conferences. The attendees for the workshop are listed in Appendix A, and the agenda for the workshop is given in Appendix B. During the first day (December 7), each attendee was allocated 2 min to introduce themselves and their interest in this research area. Appendix C of this report contains the introductory slides. After the introductory session, the attendees were divided into three breakout sessions. During the second day (December 9), leaders from the first set of breakout sessions briefed the workshop on their findings. The first breakout briefing was followed by a keynote presentation by LTC (Ret) Dr Thomas "Bull" Holland on "Pasteur's Quadrant and the Phases of War". The second set of three breakout sessions were held after the keynote address. On Friday, December 11, the leaders of the second set of breakout sessions reported their findings to the workshop, and the group broke into a third set of three breakout sessions, which then reported their findings to the workshop at the end of that day. The following section captures the information reported from the nine breakout sessions at the workshop.

2.1 Breakout Sessions A and B on Monday, December 7: Government Research Needs

Workshop attendees were broken into three groups (A, B, and C) by the workshop organizers. Groups A and B were formed from government attendees. Each group was asked the following:

- *Identify the near-, mid-, and long-term Army mission requirements that could be met with potential capabilities that could emerge from breakthrough research in controlling the load distribution in high-strength materials.*

Group A defined the timeframes such that the near term was defined as for technologies that could be fielded in 2028, the mid term was defined as 2035, and the far term was defined as after 2045. Both groups identified armor as a research area with an enduring requirement for materials that could more effectively distribute loading. In the near term, the focus will be on improving vehicle and body armors, which are generally constrained by their weight, space, and allowable deformation. In the mid and far terms, the groups believe that armor requirements will change with an increase in autonomous systems on the battlefields. Armor will be needed to protect autonomous systems, which may significantly change the protection requirements. In addition, autonomous systems may provide protection for Soldiers. These armors may not have the same space and deflection requirements, which could open the aperture to consider other material options. In the mid to far terms, other threats, such as directed-energy threats, may become more prevalent on the battlefield and could create additional armor requirements.

Other potential applications of load-redistributing materials included point contacts, bolted joints (or any other applications where loading could be highly localized), gun barrels, and recoil systems to mitigate the large shock for firing weapon systems. In these applications, the materials are designed to spread localized loading out over space and time to delay the fracture and failure of materials. The group also discussed that some applications will require systems that focus the loading, such as in penetrating mechanisms and hypersonic weapons.

2.1.1 Near-Term Science and Technology Challenges

In the near term, science and technology programs can improve the performance of load-distributing programs by working in the areas of processing technologies, experimental methods, computational models, and optimization tools.

Research in processing technology should strive to create microstructures that induce the desired properties (or mechanisms) in materials by identifying the critical processing variables, identifying new processing mechanisms, and minimizing processing-related defects.

In experimental mechanics, critical experiments are needed to characterize materials of interest. These experiments include standardizing high-strain-rate experiments for relevant material systems, and identifying the relationships between relatively easily measured static properties and high-strain-rate behavior. One of the areas discussed was the relationship between material hardness and fracture toughness. For armor applications, research focused on understanding the load distribution throughout the penetration process is required.

Improvements in computational models that more accurately simulate high-rate loading conditions leading to material damage, as well as the behavior of damaged material, need to be developed. This includes enhanced modeling of the interfaces between material systems, including how these interfaces affect wave propagation. Improvements in the ability to model reinforced concrete are needed to account for the behavior of the reinforcement bars that are essential to the failure process. In ceramics, new methods for modeling the response and flow of damaged material, including under confined conditions, are necessary. Composite materials require improved modeling tools to describe the behavior of damaged and delaminated composite materials undergoing large deformations.

There was also some discussion focused on deflection concepts. Armors can deflect a projectile, particularly in impacts at high obliquity, by providing a path of lower resistance (Jauhari 1970). An example of this is a composite material helmet where the projectile travels around the delaminated zone. The workshop discussion centered on how multiscale architectures could be designed to passively affect bullet ricochet. The group also discussed whether active mechanisms or asymmetric loading could redirect a bullet.

2.1.2 Mid-Term Research Challenges

In the mid-term timeframe, science and technology programs can improve the performance of load-distributing programs by working in the areas of material science, experimental methods, computational models, and optimization tools.

In material science, research is needed to define the ideal materials and structures for load redistribution. This will include research in operative deformation and failure mechanisms in materials to achieve load redistribution. Material systems can be designed to employ additive manufacturing (AM) processes. Predictive material constitutive models and processing methods will need to be developed. The vision is that in the mid term, researchers will be able to design ideal materials, computationally model their performance, and then build them using rapid manufacturing techniques.

Material interfaces should be improved to obtain the necessary wave propagation properties for promoting key mechanisms while keeping optimal full-scale structural properties. Graded interfaces may allow more effective wave transmission and damage tolerance. Material mechanisms will be developed to guide the path for distribution of loading and eventual fracture and failure paths. This will include developing topologic mechanisms that redistribute loading, such as auxetic materials (materials with a negative Poisson's ratio).

Experimental methods that characterize high-rate deformation mechanisms are required. This will include enhanced diagnostic methods to detect, measure, and quantify the effects of material phase changes during high-rate deformation.

Computational models with representative volume elements based on wave propagation to capture the high-rate response of materials need to be developed. Currently, typical micromechanical unit cell models treat the small volume as deforming homogeneously. This does not capture the effects of a wave moving through the unit cell. This is important for capturing shock entropy and not smearing out wave fronts. These computation models will also incorporate improved methods for capturing the behavior of failed materials.

In the mid term, the group identified machine learning (ML) as a tool that could help identify promising materials. The ML algorithms identified would rely on high-throughput experiments and diagnostics to capture important aspects of the deformation. There was some concern that ML algorithms would require substantial development to capture the finer differences in armor systems. The ML techniques employed should incorporate the relevant physical behavior and capture the high-rate phenomena. As computational models more accurately depict behavior of constituent phases, there will be an opportunity for ML techniques to assist in identifying topologic configurations that promote load spreading.

2.1.3 Far-Term Research Challenges

Many of the concepts discussed in Sections 2.1.1 and 2.1.2 will probably extend into the far-term timeframe. However, there were several additional research topics that were identified for the far term. In this timeframe, the group identified AM techniques that can make materials with an improved structure for load redistribution. This will require research in the techniques, methods, and materials available for AM and the mechanics of materials to identify desired structural properties. Many current AM processes are limited by the materials that can be used and the properties that can be achieved. AM could also be utilized to achieve seamless graded structures. While current armor systems employ gradation through layers of material, these layers are often adhesively bonded together. The adhesive bonds are a discontinuity in material properties, and often an initiation point for damage and wave reflection in the armor system.

In the far term, numerical methods should be improved to better account for the fracture and failure of materials. Current numerical methods are based on finite size volumes in which properties are uniform and are effective at modeling the stresses and strains of intact material. These numerical methods are limited in their ability to model the response of damaged material. Computational techniques are also needed to directly link the material microstructure to its continuum response.

2.2 Breakout Session C on Monday, December 7: Research Opportunities

Group C was formed with attendees from academia and was asked the following:

- *Identify which of your research interests could potentially intersect in a "convergence" with complementary research from other academics to impact our ability to control load distribution in high-strength materials.*

The group identified that a goal of tailoring a material system response for a particular application like ballistics would require an optimization framework. This would be built around constrained minimization: what system minimizes potential damage or energy transfer with a mass below some maximum threshold? The group discussion focused on the challenges. For instance, why has there not been a significant breakthrough in this space? They recognized that this is an incredibly difficult problem, with highly nonlinear phenomena spanning temporal and spatial scales with many uncertainties. These problems are likely over-constrained, preventing optimization methods from being effective.

In material science, Group C recognized the need for research in architected materials, multiphase material systems, materials that can exhibit phase changes in response to applied loads, adaptive material systems, and reactive material systems. There was interest in a retrospective on self-healing materials: what factors have limited the application of self-healing systems that have been available for over 20 years?

Research in material science will need to be supported by theoretical and computational innovations: there is a need for advances in nonlinear optimization, multiscale methods in the face of localization, alternative theoretical frameworks that might make the optimization problem tractable, and computational algorithms that trade precision for efficiency.

Manufacturing science is an essential part of the approach as research in material science and computational mechanics should be informed by what can realistically be fabricated at scale.

These approaches should also leverage the significant investments being made in ML, data-driven techniques, and manifold learning. We should collect much more data from experiments and find a way to make that data open and shareable. There is interest in rethinking experiments for the microstructure of anisotropic materials, capturing localization effects and providing information that can help construct hierarchical models of structure to response.

Much of the prior work in this space has been deterministic in nature. Including stochastic components and thinking about the response in terms of distributions could help regularize the problem.

2.3 Breakout Sessions on Wednesday, December 9: Research Convergences

During the first day of the workshop, the organizers ran a poll for the participants with the following question:

- *From the 2-min presentations you saw and/or heard, who are the top individuals with whom your research interests might form a "convergence" that could enable new scientific discovery and breakthroughs for controlling load distribution in high-strength materials (~1–3)?*

Based on the response to this question, the workshop was broken into three groups of seven or eight people for the breakout sessions on Wednesday, December 9. All three groups contained a mixture of government and academic members. All three groups were asked to address the following three questions:

1. *Identify the most promising opportunities to advance controlling load distribution in materials (i.e., based on the Monday Group C out-brief and beyond)?*
2. *Identify key barriers to demonstrating desired capabilities (i.e., based on the Monday Group A and B out-briefs and beyond)?*
3. *Identify specific research convergences that must occur to begin to overcome those barriers?*

2.3.1 December 9 Group A Results

Group A identified three classes of materials that offer opportunities to control load distribution in brittle materials: complex or disordered materials, granular materials, and hierarchical engineered materials.

Complex and disordered materials offer the potential of spreading applied loading through multiphase complexion, complex arrangements, and large contrasts in impedance. The key barriers to designing complex and disordered materials include challenges in processing disparate materials, testing standards, and optimization tools. While processing science is rapidly improving in terms of fidelity and range, AM introduces new phases and interfaces/interphases that are not well understood and can dominate the material response. Testing standards are needed that provide quantitative understanding of the material structure. This should include information on the thermodynamics of the material and the relationships between the material structure and the mechanical properties. For the design of this material class, objective functions that are well behaved and sensitive to the material properties are needed to optimize complex properties and behaviors.

To take advantage of the promise of granular systems, we need improvements in processing science, material science, testing standards, and engineering design. In processing science, AM processes are needed to design granular systems with secondary phases. For example, laser fusion additive manufacture can be used to trap powders in closed regions. There is also interest in engineered particles that can interact through physical or chemical processes during flow. In testing standards, granular materials will require relevant 3-D dynamic characterization techniques to capture their interactions and flow that can be altered by changing particle shape and size distributions as well as composition.

The design of hierarchical materials requires improvements in engineering design tools and advanced materials characterization, enabling the exploitation of nonlinearities at material interfaces, the design of discrete material systems with complex interactions (e.g., chainmail, interlocking structures), and reconfigurable systems.

All of these material classes face barriers to obtaining, analyzing, and exploiting the relevant data. For instance, training ML techniques can be a barrier in terms of not having the necessary data to generalize well. ML can be limited in accuracy compared to finite element analysis methods, since the underlying physics is often not incorporated. Sparse data from experimental measurements may also be a concern in terms of ingesting this into the ML algorithms. Current techniques also require enhanced understanding to bridge material length scales (e.g., the microstructural tests relevant to full-scale experiments). High-throughput experiments are needed with rapid assessment of full-scale experimental data. Finally, if large amounts of application-relevant data can be obtained, security concerns will limit what data can be shared with the extramural research community.

Group A identified several specific research convergences that must occur to overcome the barriers. To make progress within these interdisciplinary areas, computational mechanics researchers need to work with 1) digital graphics designers and computer scientists, to enhance visualization of the results, 2) systems (optimization) engineers, to develop reduced-order (RO) models for optimization, 3) geological scientists (in granular materials), to understand energy management of granular systems and materials with disparate phases, and 4) reactive chemistry experts, to understand novel means for trapping and dissipating energy.

2.3.2 December 9 Group B Results

Group B identified the following opportunities to advance the ability to control the load distribution in materials:

- *Get away from materials that go through damage localization like shear banding*
  - Multiphase materials provide new opportunities.
  - Disordered structure can be exploited for robustly evolving failure response during continued loading.
  - Dynamic Poisson's ratio for control of load transmission
- *Spread out the load over space and time*
  - Slow down loading rates (increase delta t); granular materials can reduce the wave speed by a factor of 6.

  - Spread out loads (reduce delta P), propagating jamming fronts in granular media.
- *Explore granular materials*
  - Frictional interfaces define performance.
  - Friction is a fairly rate-independent mechanism for dry grains (unless they change structurally), but can be made rate-dependent by design when interstitial media are included.
  - Heterogeneous granular systems have a small speed of sound compared to homogeneous materials (metals), thus are easily pushed into supersonic regime.
  - Encapsulated granular materials can provide damage zone constraints.
- *Control the friction mechanisms in granular media*
  - Control the nanometer-scale phenomena that control friction.
- *Consider a metal truss structure, using an architected material structure to distribute loading*
- *Explore amorphous materials*
  - Glassy film lines will give a crack tortuosity.

Key barriers to demonstrating the desired capabilities were identified in experimental techniques, computational methods, material science, and optimization. Enhanced experimental techniques are needed for the following:

- Characterize the response of granular systems across a wider spectrum of deformation speeds.
- Understand the deformation and failure of materials beyond the averaged load curves.
- Understand and control stress fluctuations and their dependence on particle properties.
- Capture the thermal response in high-rate loading experiments.

In computational methods, constitutive models are needed to describe the response of granular media with more attention paid to complex grain-to-grain interfaces. Computational methods are also needed to capture the properties that govern how materials interact during complex flow processes.

In material sciences, advancements are needed to understand the root mechanisms that control friction. This includes the chemical composition of the material and the role of geometry across the size scale. A research challenge for the materials science community is to change the coefficient of friction beyond coulombic friction.

Optimization frameworks will require greater amounts of data for optimization. Verification of these data is a challenge to using them. The diagnostic data are also sparse at the timescales of greatest interest to the research community. These frameworks also require canonical models that can be shared and effectively describe the problems that the community wants to optimize.

Group B identified the following research communities that must converge to overcome these barriers:

- Granular media community: materials, architectures
- Materials science: metallurgy, ceramics, polymers, glass
- Mechanics and mechanisms: multi-physics experiments
- Manufacturing science: additive and otherwise
- ML
- Multi-objective optimization and expertise to synthesize the results

These researchers will need to be able to draw connections between constitutive properties and the operative mechanisms in multiphase systems.

2.3.3 December 9 Group C Results

Group C identified that novel mechanisms and promising opportunities to push the state of the art for controlling load distribution in materials primarily centered on the key themes of *anisotropy* and *heterogeneity*. These opportunities included the following areas:

- Multiscale material design
    - Nanoscale, microscale, and mesoscale material mixtures and chemistries (ceramic/metal, ceramic/ceramic, ceramic/polymer)
    - Mimicking of biological structures (nacre, dentin/enamel) for improved structural toughness and new mechanisms
- Impedance matching/mismatching

    - Enhance or retard the transmission of stress waves through Z tuning (tuning the through-the-thickness wave propagation properties)
- Anisotropic constitutive material properties
    - Orthogonal anisotropy, such as stiff reinforcement phases
    - Topological mechanical materials with varying modes of stiffness
- Self-organizing materials
    - J-hooking in granular media (Iskander et al. 2015)
    - Reorganization to enable durability for subsequent events
- Phase transformations/viscoelastic effects
    - Phase transformations, glass transitions, and so on, for volumetric expansion and deflection mechanisms
- Macroscopic deflection mechanisms
    - Layering techniques to dissipate energy at interfaces and spread loading over a larger area
    - Spaced armor concepts to deflect incoming projectiles
- Adaptive/responsive materials
    - Similar to phase-change mechanisms, but recoverable
    - Materials that can change materials properties (stiffness, hardness) during impact
- Granular media–based frictional methods
    - Beds with optimized granule shape, distribution, compliance, and elastic properties
    - We can learn a lot from what nature tells us from geological events to help inform in this area

Group C identified several barriers to demonstrating the desired capabilities. These included a lack of understanding of means for more effective load distribution. This understanding should include the material system of interest, the properties, and the scales of the problems. The problems can be bounded when the fundamental physical limitations can be established. There are gaps in the knowledge in how to translate the understanding from quasi-static mechanics to high-rate events. Material properties need to be measured at the right loading rates to obtain useful information, especially about the dynamic mechanisms that govern the response. Large models that incorporate the physics at much smaller scales are needed, bridging the physics of shock loading from the nanoscale through the macroscale.

The major convergences that must occur to address these barriers include exploring dynamic processes and wave propagation at multiple length scales. Opportunities exist to understand the effects of wave propagation in materials from communities outside of mechanics, materials, and physics. These include the following:

- Converging ideas of materials and system-level design concepts to drive the manufacturing science state of the art and enable implementation of the notional concepts
- Artificial intelligence and ML techniques combined with mechanical experiments and modeling/simulation to enable high-throughput experimentation and cut through vast materials trade spaces at low cost/time
- Opportunities to encourage researchers in other areas (such as those in the granular media and metamaterial communities) to partner in wave propagation research

2.4 Breakout Sessions on Friday, December 11: Opportunities for New Discovery

On Friday, December 11, the workshop was broken into three groups of seven or eight people based on their research interests (all three groups contained a mixture of government and academic members). All three groups were asked to address the following question:

- *Identify specific opportunities of marrying/converging the following scientific goals to enable significant new scientific discovery for controlling load distribution in materials:*
    - *Designing composite materials/topologies for load mitigation*
    - *Advancing numerical simulation methods and optimization tools to better address highly dynamic loading conditions*
    - *Characterizing/exploiting relevant mechanisms that occur under highly dynamic loading conditions*

2.4.1 December 11 Group A Results

Group A identified the following opportunities:

- Merging the areas of mechanics and materials design with computer graphics or computer science; this allows researchers to treat materials as systems and recognize that materials become components that are part of the system.
  - Graphics might provide approaches for reducing the problems of complexity by giving approaches for fast-running forward solutions.
  - Granular materials could be coupled with interesting nonlinear or active bulk properties.
  - Use hybrid or hierarchical materials with increasing complexity.
  - Use RO models and back out the real physics in complex systems
  - Use ML to fit parameters for computer graphics engines using very sparse experiments.
  - Use AM, ML, and automated testing to simulate systems of interest.
- Data-driven design methods to accelerate discovery
  - Develop methods to evaluate and potentially adapt human ideas in the machine-design loop.

Group A identified the following data was needed for design for load redistribution:

- Large strain data on soft materials
- Granular material: Transient data are missing, the heterogeneous nature of data is needed, and field data (continuum-level response) rather than localized or point data are needed, as well as stress (fluctuation) data resolved with time.
- Percolation theory connection to loading rate, load path, and particle shape
- The ability to do more with the data from the experiments that we can do today
- Full-field 3-D data capture (even better if it is through the bulk); can answer questions about localization
- A single experiment that interrogates all of the loading directions to get a full stiffness tensor

- Manipulation of the force chains to prevent the formation of chains that are too strong will promote the formation of many lower intensity force chains
- Two-phase materials for improved system properties

Group A also identified the need for critical experiments where data could be augmented with advanced diagnostic techniques (i.e., transient full-field data). Responsive materials need to be designed to work in the appropriate timescales. These depend on the desired mechanism and the applied loading.

2.4.2 December 11 Group B Results

Group B selected four promising areas where collaborative research would enable significant new scientific discovery for controlling load distribution in materials:

- Granular media models
    - Dynamic particle interactions
    - High-rate thermodynamics of particles (from the tribology field)
    - Synchrotron experiments to establish the physics of granular media flow
- Emerging composites
    - Ceramics, metals, and polymers
    - Macro- and microscale design
    - Processing science
    - Exploiting material nanoscale effects
- Multi-phase structural optimization
    - Nonlinear optimization problems
- Constitutive material modeling
    - Nonlinear response of topological models

2.4.3 December 11 Group C Results

Group C recognized that impact problems require many disciplines to work together seamlessly; these include material science, experimental and computational mechanics, and ML. Researchers will not make progress by running down their own lane in isolation, but need to engage other researchers. They identified four areas for progress in this area:

1. Establishing experiments to fabricate promising types of model systems using phenomenological or empirical understanding (quasi-static response behavior) and exploring the space of these systems and variables (lattice sizes, spacing, powder size, etc.) to build knowledge of the dynamic behavior space:

    a. Understanding manufacturing constraints (this restricts the design space, which makes the problem easier at the moment) greater or equal to *a fourth bullet* beyond the materials, simulation, and characterization.

    b. Continue to push manufacturing capabilities for improved refinement and abilities for multiscale, multi-material structures.

2. Establishing a clear definition of the variables and physics necessary/ identifying the requirements to define the problem and help guide the ability to make informed decisions on identifying where to operate (which materials, scale, etc.).

3. Bounding problems (closed loops) to generate payoffs in improving materials and mechanisms:

    c. Focuses on single variables/parameters with few control variables and understanding the effect of that one parameter in a closed testing loop, generating knowledge, then focusing on next step.

    d. Provides tight coupling between simulations and experiments as well as fast-turnaround analysis of experimental and computational data.

    e. Simplifies problems to evaluate promising technologies.

4. Developing better means/new mechanisms for continued engagement between academia and government to encourage free exchange, access to knowledge, and mitigate "competitiveness" between research groups:

    f. Need to discuss if Multidisciplinary University Research Initiatives (MURIs) are still the right mechanism. Other ideas include the addition of joint faculty appointments and graduate student internships.

3. Research Strategy

Material systems such as granular media materials, lattice structures, reactive/phase changing materials, and emerging composite material architectures offer the opportunity to redistribute localized loading, which can significantly/substantially delay or mitigate the effects of failure due to impact loading. This broad class of mechanisms and materials meets the future needs of the Army. Research in these areas is inherently interdisciplinary. Developing the necessary mechanisms, materials and design tools requires expertise in material science, experimental and computational mechanics, processing science, and computer science. The following areas were frequently brought up as both technical challenges and opportunities for significant impact on materials that can redistribute load.

3.1 Canonical Models

The workshop participants identified that canonical models are still not able to capture all of the mechanisms that are needed for developing these new material systems. There is a need to develop numerical techniques to model the constitutive response of these materials—including the behavior under large deformations, fracture, and failure—while at the same time recognizing that some applications might benefit from simpler, focused models that still capture the necessary and relevant physics. This development includes new numerical methods developed to better address the behavior of the evolving material comminution. The ability to describe the underlying material physics governing the transition between different mechanisms during the failure process is not just critical to modeling these materials, but also to using these models to discover/engineer new materials and material systems.

3.2 Machine Learning

The workshop participants identified that ML has a number of advantages, but also must be cautiously integrated into the pipeline for these materials. ML is often discussed as an emerging tool that helps to accelerate the progress of research by helping users process and understand massive amounts of data. Like many research tools or instruments, ML depends on the ability of the developer/user. The success of integrating ML algorithms depends on selecting the optimal ML models, using the right techniques and processes to train the model and its hyperparameters, and validating that the model generalizes well within the input space defined. This seems simple in concept, and has even been made more accessible than ever with open-source tools, but it still requires some skill and some care. ML is very useful for defining mathematical functions that map input parameters to output parameters via any number of different algorithms, from linear/logistic regression, to kernel-based methods, to various neural network architectures. The ML algorithms generalize well throughout the parameter space *when the parameter space is well characterized*. An example discussed in the workshop was how ML can help enable the selection of AM build (input) parameters to maximize (output) responses such as the build quality and part throughput. The predictions from ML algorithms can be used for various different uses, from utilizing in optimization methods, to inserting in physics-based constitutive models, to coupling with numerical solvers.

ML is currently being used in a number of different ways in similar areas to those discussed within this workshop. For instance, ML algorithms (Gaussian process regression, in this case) have been used to bridge scales within hierarchical multiscale models for materials (Leiter et al. 2018), providing an important connection between material microstructure and component-scale performance. ML algorithms have also been of great value for image data sets (e.g., convolutional neural networks), using computed tomography or serial sectioning data to predict key microstructural features for mesoscale simulations. As the volume and quality of material data increase, the need for novel algorithms to automate how we process and reduce these data will also increase. ML algorithms are already being used to accelerate data reduction tasks like analyzing X-ray and image data from ballistic experiments.

Another potential use of ML for materials research within the Army is preprocessing unformatted or natural data into a format that is more easily consumed and processed by machines, such as in natural language processing. The classic set of algorithms for this are neural network sequence models like recurrent neural networks, gated recurrent units, and long/short-term memory, which do not have to be applied to text. These have recently been used to generate rapid ML algorithms that represent how "sequences" of strain within materials can be used to predict yield surfaces.

There should be some caution to buying into the promise of ML as the only critical path to some of these applications. ML algorithms require data to train! These models cannot create responses without data, since the physics are not incorporated into the model architecture, but rather are learned through the data that it is given. So, if there are not sufficient data stemming from experiments or constitutive models for a particular physical process (e.g., dynamic fragmentation of ceramics under simultaneous pressure and shear), then it is likely that ML algorithms trained only on data in adjacent parameter spaces (or no data at all) will not solve that problem. If there are sparse data within a domain, this may not be sufficient for more complex ML architectures (with more nonlinearity); furthermore, simpler ML models (linear models, kernel-based models) may not be sufficient to capture the details of nonlinear behavior. If the predictions desired are outside of the parameter space that the ML model is trained on, then it may perform poorly, despite the fact that the ML model performed well on the (withheld) test data set used to evaluate its performance—this is where the ability to quantify uncertainty in ML models is important. These gaps are actively being pursued within the ML community by subject-matter experts.

The good, the bad, and the ugly of ML models—at a minimum, the Army must maintain sufficient expertise in ML that it can identify tasks that are well suited to take advantage of existing ML capabilities and identify new ML-based capabilities to bring into the lab. Developing internal subject-matter experts in ML is needed to expand how ML is incorporated into a broad range of Army problems. ML is an emerging cross-disciplinary tool where the Army will greatly benefit from enhanced internal expertise and communication.

3.3 Additive Manufacturing

The workshop participants identified that AM will be an instrumental tool for realizing and fabricating many of the proposed solutions herein. The underlying assumption is that AM techniques will be capable of fabricating the designs. While exploring future load redistribution concepts should not be limited by current technology, current AM technology will not meet these needs, especially for metals and ceramics. AM is prone to significant processing flaws, the impact of which are magnified in the precisely engineered hierarchical concepts being proposed. These flaws have many origins including material evaporation, incompletely melted powder, and localized stresses due to shrinkage due to rapid heating and cooling. Given the key role of this technology toward realizing many of the concepts being proposed, one aspect of the future research strategy should be to develop solutions for these issues. Potential directions for future work can include developing feedstock materials designed for consistent printing, qualification and standards for the printing process, and alternative non-thermal techniques.

3.4 Data and High-Throughput Experimentation

The workshop participants identified that data from high-throughput experimentation and modeling can be advantageous in engaging with expertise in basic research within the academic community. The challenge here for research on Army-specific problems is the limited application-specific data that can be shared due to security concerns. This slows the research process because metrics for success are often poorly defined, and academic researchers do not know the full picture with respect to the performance of these materials, sometimes even the boundary conditions, and the Army's needs. This goes against the research strategy of application-driven research described in *Pasteur's Quadrant* (Stokes 1997) and by LTC (Ret.) Dr Holland during the workshop keynote address.

3.5 Final Recommendations

The authors of this report recommend a mixture of approaches to overcome the barrier dividing academic research from Army needs. The first recommendation is developing high-fidelity "open source" canonical models—ones where physical configurations and experimental results can be readily shared between government researchers and academia. For example, a sphere impact experiment can be executed and analyzed in an open forum. These open problems allow ideas to be developed jointly, while providing a forum to demonstrate novel approaches at the intersection of processing science, experimental and computational mechanics, and ML. Students supported under this research program could work on these computational tools and readily transition their research skills to more applied problems through internships at secure institutions.

The second recommendation is to provide mechanisms for engagement with external partners (i.e., strongly couple controlled research needs and academic research programs). Researchers should meet regularly with partners to discuss opportunities and results. Materials, experimental and computational techniques, and models should be shared, as appropriate, throughout the research process, allowing evaluation of novel materials and real-time feedback. Mechanisms such as faculty/student internships and research sabbaticals should be encouraged throughout the program.

The third recommendation is related to talent management for the organization and our partners (i.e., how do we bring partners into the controlled research area space). One mechanism is partnering with external investigators who hold clearances and can work in controlled research areas. Another mechanism would be hiring these investigators through internal staffing mechanisms. Aside from directly relying upon expertise of full-time equivalent staff scientists, this approach leverages the partner's knowledge of the research and their network of colleagues.

4. Conclusion

Recent research has shown great promise in the science of granular media materials, lattice structures, reactive materials, and emerging composites. By developing the mechanical response and tailoring the structure of these materials, they can display unique behavior during the failure process, spreading out highly localized loading over space and time. These novel materials have the potential to revolutionize the design of structures subjected to localized impact loading such as armor.

The ASPSM on Controlling the Load Distribution in High-Strength Materials recommends developing both basic and applied research programs to exploit the potential of this broad class of mechanisms and materials that distribute dynamic loads. This research will be interdisciplinary; it represents the convergence of expertise in material science, experimental and computational mechanics, processing science, and computer science. ML algorithms should be incorporated and integrated into the data-driven design component of these materials, as applicable. This research strategy will produce enhanced capability for load distribution in Army equipment that will benefit the future Soldier.

5. References

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Appendix A. List of Attendees

Name	Position	Organization
Michael Bakas	Army Research Office (ARO) Synthesis and Processing Program Manager	ARL-ARO
Richard Becker	ARL Research Fellow	ARL, Weapons and Materials Research Directorate (WMRD)
Brad Boyce	Distinguished Member of the Technical Staff	Sandia National Laboratories
Giuseppe Buscarnera	Associate Professor of Civil and Environmental Engineering	Northwestern University
Dan Cole	ARO Program Manager	ARL-ARO
Kent Danielson	Engineering Systems and Materials Division, DOD High-Performance Computing Modernization Program	US Army Engineer Research and Development Center
Chiara Daraio	Professor of Mechanical Engineering and Applied Physics	California Institute of Technology
John Dolbow	Professor of Mechanical Engineering and Materials Science	Duke University
Denise Ford	ARO Solid Mechanics Program Manager	ARL, Army Research Office
Christopher Hoppel	Program Manager, Physics of Soldier Protection	ARL, WMRD
Heinrich Jaeger	Sewell Avery Distinguished Service Professor, Department of Physics	University of Chicago
Ken Kamrin	Professor of Mechanical Engineering	Massachusetts Institute of Technology (MIT)
Sinan Keten	Associate Professor of Mechanical Engineering and Civil and Environmental Engineering	Northwestern University
Mike LaFiandra	Deputy Chief Scientist, ARL	ARL
Jerry LaSalvia	Team Lead, Synthesis and Processing	ARL, WMRD
Adam Rawlett	Senior Research Scientist (ST) Materials Science	ARL, WMRD
Scott Schoenfeld	Senior Research Scientist (ST) Terminal Ballistics; Chief Scientist, WMRD	ARL, WMRD
Christopher Schuh	Danae and Vasilis Salapatas Professor in Metallurgy	MIT
Joshua Socolar	Professor of Physics	Duke University
Dave Stepp	Chief Scientist, ARO	ARL-ARO
Ravi Thyagarajan	Chief Scientist, US Army Futures Command (AFC)	AFC Headquarters Science and Technology
Andrew Tonge	Physics of Soldier Protection	ARL, WMRD
Mark Tschopp	Regional Lead, ARL Central	ARL Central
Lorenzo Valdevit	Professor of Mechanical and Aerospace Engineering	University of California, Irvine
Lionel Vargas-Gonzalez	Deputy Program Manager, Physics of Soldier Protection	ARL, WMRD
Haydn Wadley	Edgar Starke Professor of Materials Science and Engineering	University of Virginia

Appendix B. Workshop Agenda

Controlling the Load Distribution in High Strength Materials

Army Science Planning and Strategy Meeting (ASPSM)

All times are Eastern Standard Time.

Workshop Agenda

Monday, December 7 – Day 1

1230 Virtual Room Opens

1300 Introduce Workshop and Goals (Hoppel, Stepp)

1320 Introduce Participants (each participant is allowed up to 2 min and 1 slide to introduce themselves and their interest in this research area)

1430 Breakout Session 1: What are the greatest opportunities for controlling load distribution in high-strength materials?
- A: Academic Partners 1 (Partners will be assigned prior to check-in)
- B: Academic Partners 2
- C: Government Attendees

1700 Adjourn

Wednesday, December 9 – Day 2

1230 Virtual Room Opens

1300 Day 1 Summary, Day 2 Objectives (Stepp, Hoppel)

1315 Breakout Session 1 Leaders Report out to Group

1415 Keynote Presentation: LTC (Ret) Dr Bull Holland "Pasteur's Quadrant and the Phases of War"

1500 Breakout Session 2

1700 Adjourn

Friday, December 11 – Day 3

1230 Virtual Room Opens

1300 Day 2 Summary, Day 3 Objectives (Stepp, Hoppel)

1315 Breakout Session 2 Leaders Report out to Group

1430 Breakout Session 3

1615 Breakout Session 3 Report Out

1700 Adjourn

Appendix C. Introductory Slides

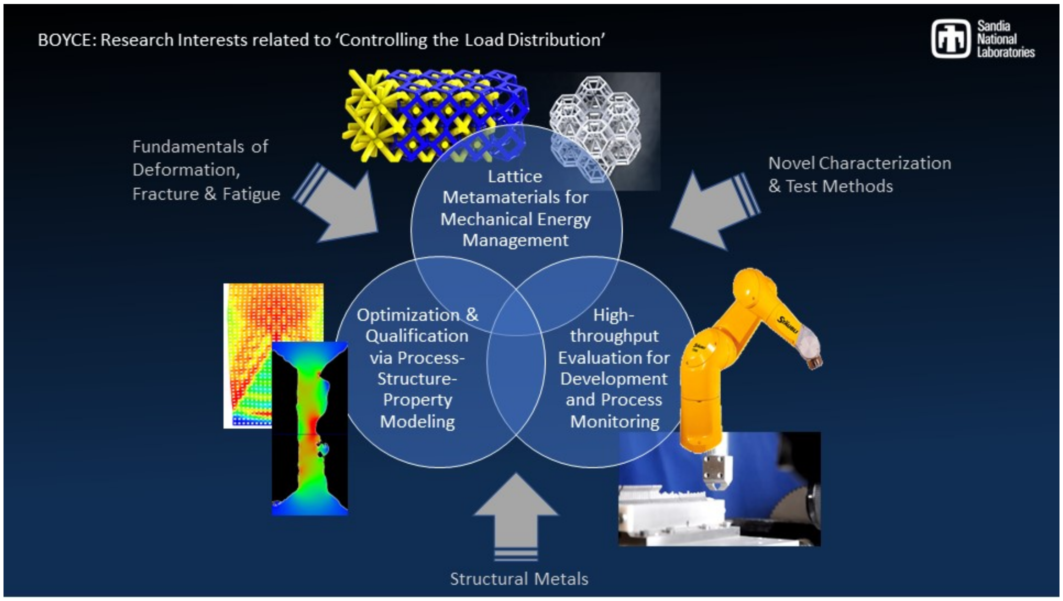

Fig. C-1 Introductory slide from Dr Brad Boyce

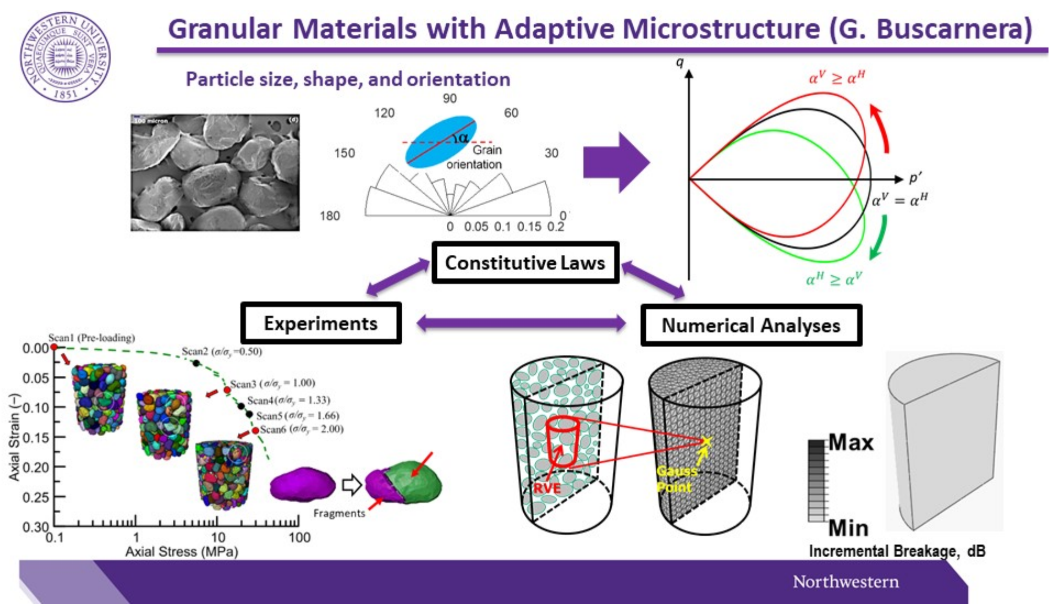

Fig. C-2 Introductory slide from Dr Giuseppe Buscarnera

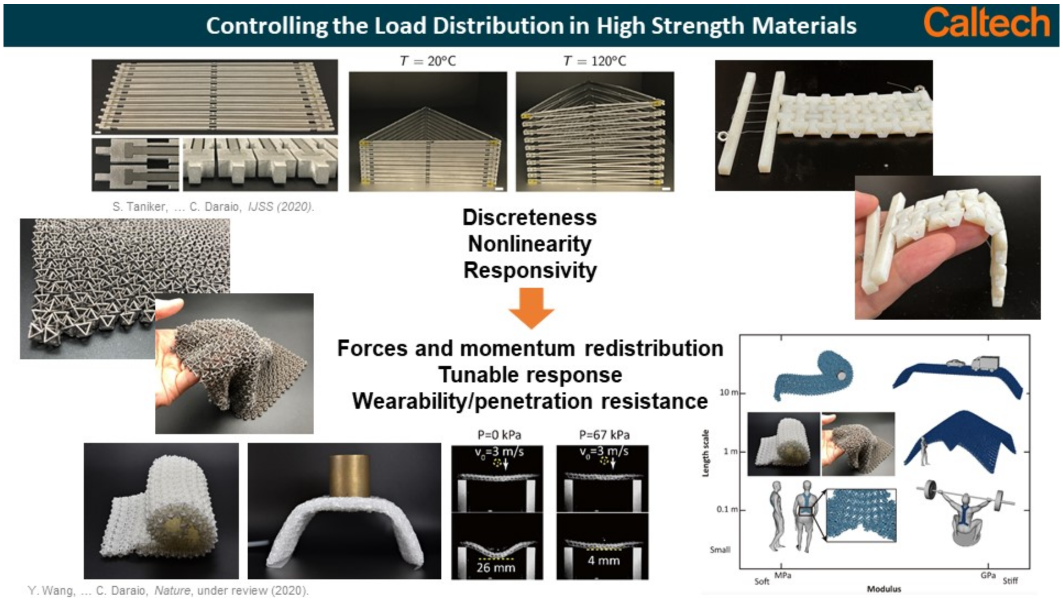

Fig. C-3 Introductory slide from Professor Chiara Daraio

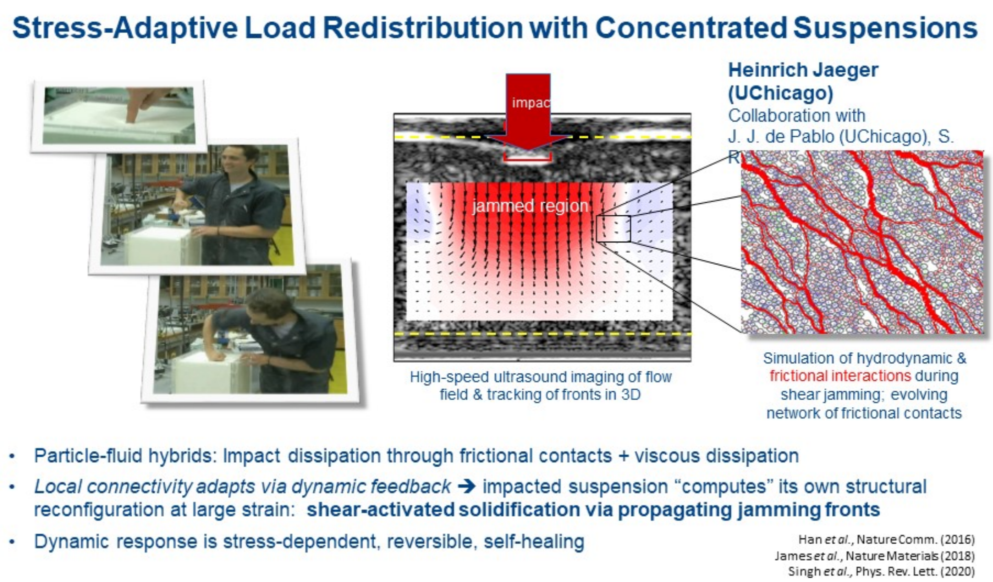

Fig. C-4 Introductory slide from Professor Heinrich Jaeger

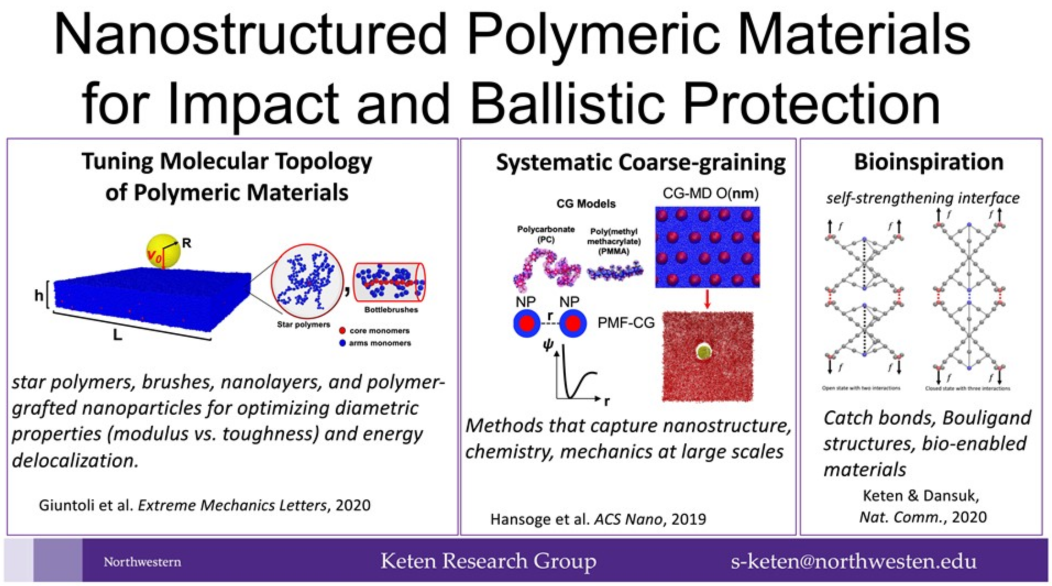

Fig. C-5 Introductory slide from Dr Sinan Keten

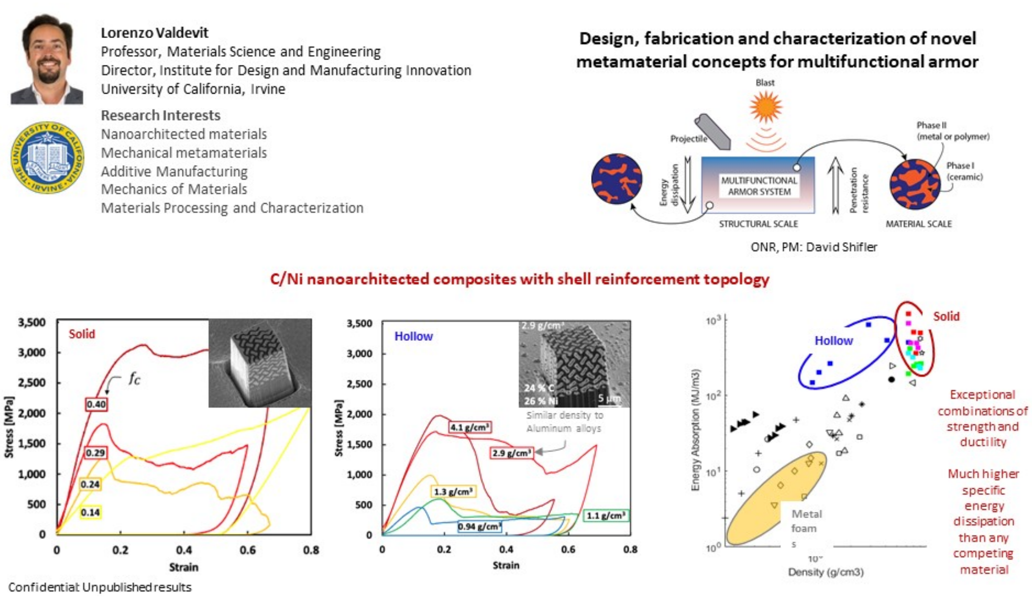

Fig. C-6 Introductory slide from Professor Lorenzo Valdevit

Fig. C-7 Introductory slide from Dr Denise Ford

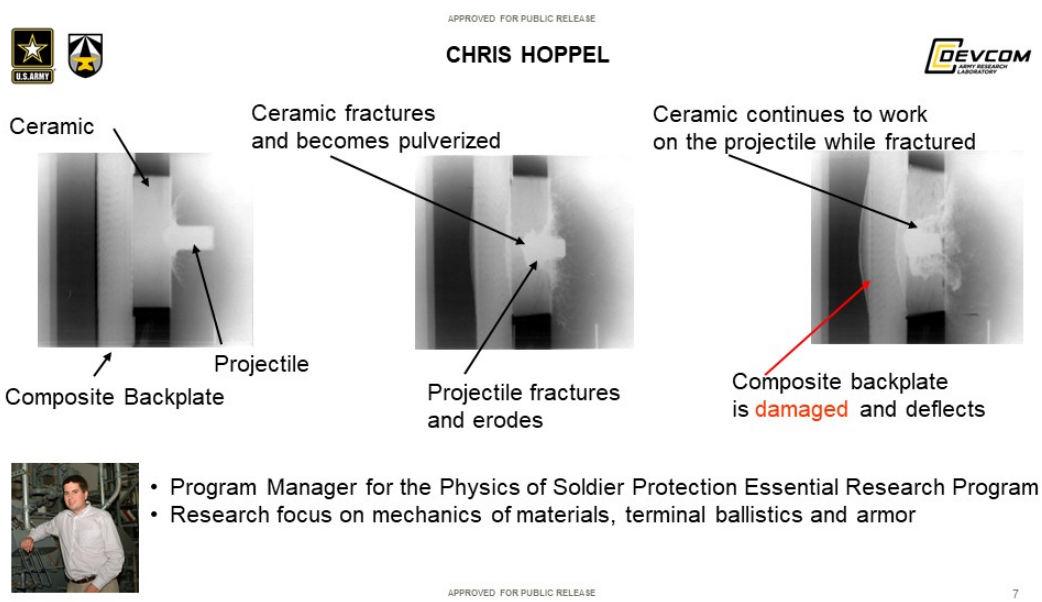

Fig. C-8 Introductory slide from Dr Christopher Hoppel

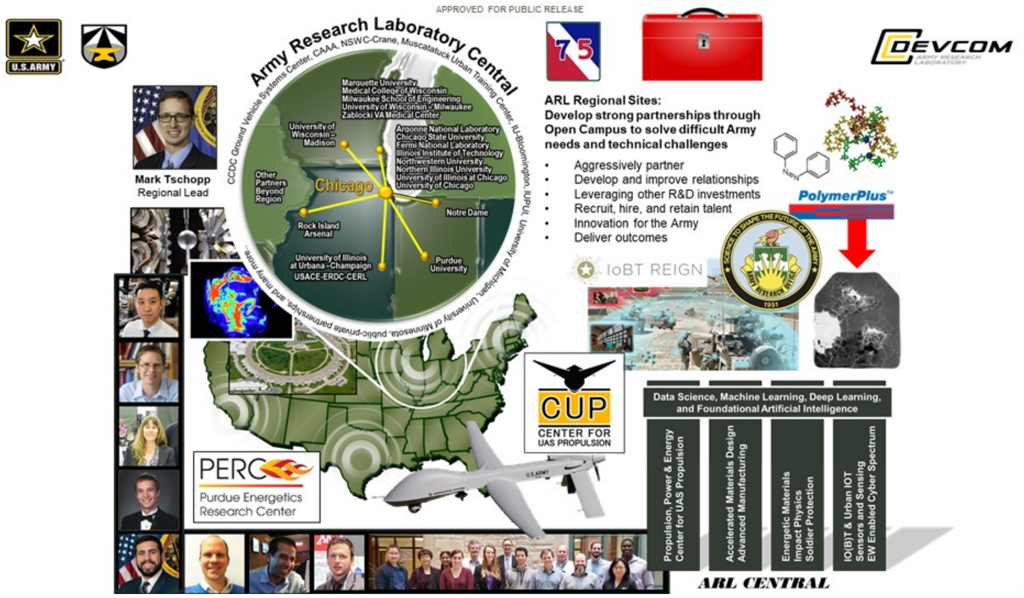

Fig. C-9 Introductory slide from Dr Mark Tschopp

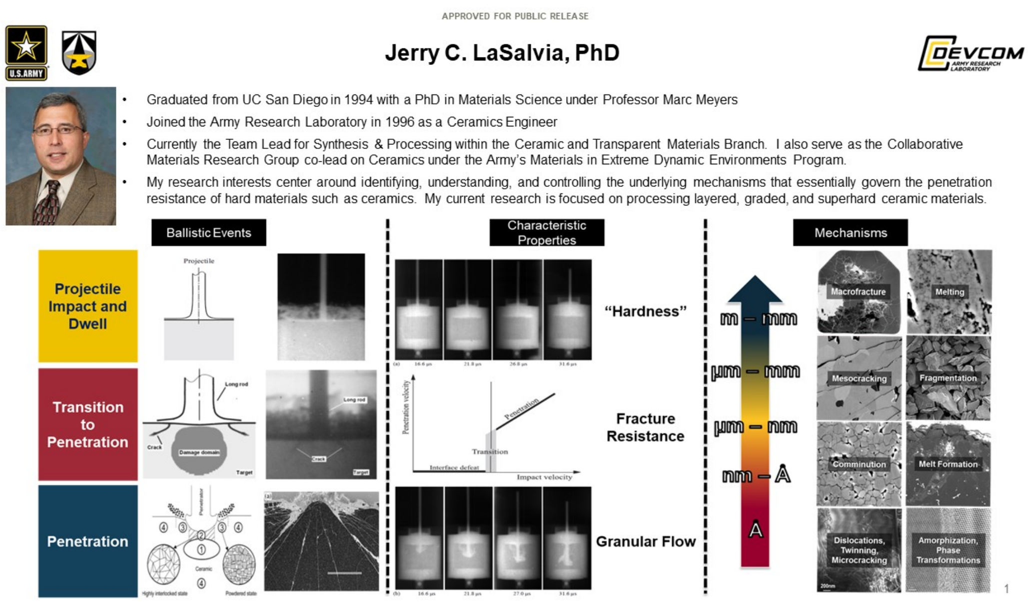

Fig. C-10 Introductory slide from Dr Jerry LaSalvia

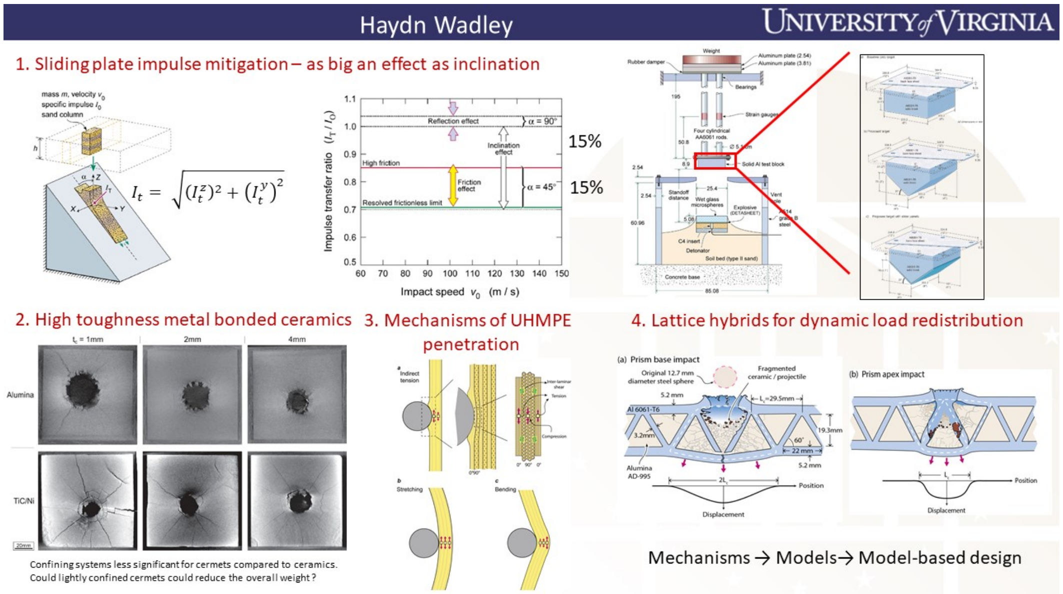

Fig. C-11 Introductory slide from Professor Haydn Wadley

List of Symbols, Abbreviations, and Acronyms

3-D	three-dimensional
AFC	US Army Futures Command
AM	additive manufacturing
ARL	Army Research Laboratory
ARO	Army Research Office
ASA(ALT)	Secretary of the Army for Acquisition, Logistics, and Technology
ASPSM	Army Science Planning and Strategy Meeting
DOD	Department of Defense
MIT	Massachusetts Institute of Technology
ML	machine learning
RO	reduced-order
WMRD	Weapons and Materials Research Directorate

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J IVANCIK

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