

DEVELOPMENT OF NEW PROTECTIVE SOLUTIONS TO COUNTER EMERGING AND ADAPTIVE THREATS

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ABSTRACT

As a part of its Survivability and Protective Structures research area, the U.S. Army Engineer Research and Development Center (ERDC) is conducting several parallel research initiatives focused on the development of new protective capabilities which meet warfighter operational constraints and provide protection from emerging and increasingly severe threats. Utilizing a combination of micro and macroscale material research, advanced computational methods, and physical experimentation to validate protective structural systems, ERDC is providing advanced solutions to warfighter needs. This paper presents ERDC's research efforts in multiscale material development and characterization, advanced computational methods for high-deformation/high-strain rate events, and lightweight, low logistics protective structural systems.

1. INTRODUCTION

The rapidly changing operational environment faced by U.S. warfighters has placed a keen focus on the need for adaptable physical force protection measures which can be tailored in the field in response to dynamic conditions. Adaptation requirements take many forms, including needs for 1) geometric adaptations to meet scenario-dictated configuration requirements, 2) functional adaptations to meet operationally-dictated use requirements, and 3) performance adaptations to meet a changing array of threats ranging from small arms fire to vehicle-borne improvised explosive devices (VBIEDs). Coupled with requirements for logistics minimization, speed in deployment, and rapid system recovery, new paradigms are evolving for the physical force protection community. It has been shown that the most common approaches to protective construction, generally based on the use of high-mass structures such as reinforced concrete barriers and earthen revetments, are not fully suitable to address these paradigm shifts. In scenarios such as short-dwell outside-the-wire construction projects, contingency outposts, and rapidly emplaced check points, common labor- and lift-intensive approaches are not feasible. As a result, the user community has identified the need for new classes of protective structures which

make use of advanced materials developed using state-of-the-art research methods to provide protective capabilities for use in a wide array of challenging conditions.

This need for advanced protective structures has not only been necessitated by the Soldiers' operational and functional requirements, but also by the adaptive nature of the threat environment. As protective solutions have been developed and fielded by the military research, development, and acquisition community, enemy threats have also adapted as a means to counter these new protective techniques. The emergence of new and increasingly severe threats—such as large-caliber rockets, increasingly severe improvised explosive devices (IEDs), and explosively formed penetrators (EFPs)—has accentuated the warfighters' need for new physical protective systems. These systems must make use of novel materials and structures which can be adapted and upgraded in order to mitigate the current threats as well as address those which may emerge in the future.

As a result of these evolutionary challenges, new research in multiple thrust areas is required to develop the necessary protective solutions. One primary area of research focus must be on the development of new and advanced protective materials, not merely in a phenomenological sense, but in a way that the materials' response and failure mechanisms at subscale levels are better understood. In turn, the enhanced understanding of subscale material performance under certain conditions, such as impact and penetration events, can be used to enhance macroscale material behavior and optimize performance through material tailoring and design. Additionally, research must focus on advanced computational capabilities so that first-principles based approaches are extended to better understand and model material performance at fundamental length scales. With better modeling capabilities to simulate material response such as microstructure fracture and failure, computational bridging techniques can be used to scale upward and better simulate overall material response in penetration and shock events—leading to improved design and analysis capabilities in the computational environment. Lastly, advancements made through this materials and computational research must be assimilated into novel

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protective systems which are capable of providing the necessary protection in a manner consistent with changing operational requirements and threats.

In response to the warfighters' evolving needs, the U.S. Army Engineer Research and Development Center (ERDC) has maintained focus on the development of protective solutions which meet logistical and operational requirements while providing protection from an array of changing threats. Recognizing the need for state-of-the-art research to address these challenges, through its 6.2 Adaptive Protection program (FY07 to FY08) ERDC began coupled research in the areas of multiscale materials studies and advanced computational methods for high-rate, high-damage events. Transitioning into its 6.2/6.3 DEFeat of Emerging and Adaptive Threats (DEFEAT) Army Technology Objective – Demonstration (ATO-D) in FY09, the computational and materials research efforts will be continued in order to further advance development in these areas. In combination with the Adaptive Protection research effort, from FY05 to FY07 ERDC conducted research under the Modular Protective System (MPS) for Future Force Assets ATO. Products of the MPS ATO included a lightweight, all man-portable protective structure, which was fielded to forces in Iraq at conclusion of the program.

The remainder of this paper discusses recent ERDC efforts in the three above-mentioned research areas. First, a description of research within the area of multiscale material development and characterization is presented. This is followed by discussion of ERDC's new Computational Protection Testbed research effort, which focuses on the development and application of new computational techniques for modeling and simulation of multiscale, high-rate, high-damage events. Lastly, discussion is given to ERDC's MPS developmental effort, which typifies the type of new force protection capabilities that are required to address emerging warfighter needs.

2. MULTISCALE MATERIAL DEVELOPMENT AND CHARACTERIZATION

With respect to multiscale material studies, ERDC has focused effort in two major research categories. The first is focused on multiscale material development, with primary efforts targeted at advanced development of cementitious materials and Portland cement based composites for use as improved structure armoring materials. Through studies of constitutive material components at scales of 100 μm or less, researchers are investigating the interactions between material phases and effects of these interactions on the material's plastic and hardened states. In the plastic state, research is leading to improved knowledge regarding water demands in terms

of workability and hydration reactions, which leads to improved constructability with the materials as well as higher performance in the hardened state. Microscale studies of the hardened materials have revealed insight into weaknesses that result from material interfaces, which in turn can lead to reduced toughness and compressive strength at the macroscale material level. By tailoring the constitutive components so that weakened interface conditions are not created, researchers have been able to increase material strength and toughness. This has occurred through better selection of constitutive material components based on their chemical and mechanical interactions.

As an example of multiscale material development, a recent ERDC study focused on the influence of various fine aggregate types on strength and variability of a certain ultra-high performance concrete (UHPC) mixture proportion that may be used for protective construction. The study was conducted as part of a program to establish an experimental material design with maximized strength and minimized variability for use in subsequent weapons' effects experiments and numerical model validation. Utilizing typical concrete sand, foundry sand, manufactured sand and materials such as aluminum oxide (Al_2O_3) and silicon carbide (SiC), moderate variability was found in plastic material parameters such as wetting time and flow, as well as in the materials' hardened compressive strength. Utilizing scanning electron microscopy to study the materials' hardened microstructure, it was found that certain materials such as the SiC potentially formed weak interfaces with the hydration product calcium silicate hydrate (C-S-H), while other materials such as the foundry sand formed much more uniform bond surfaces. Micrographs of the SiC and foundry sand mixes are shown in Figures 1 and 2. As a result of the study, the foundry sand was identified as the most desirable aggregate for further use in the experimental material characterization and modeling.

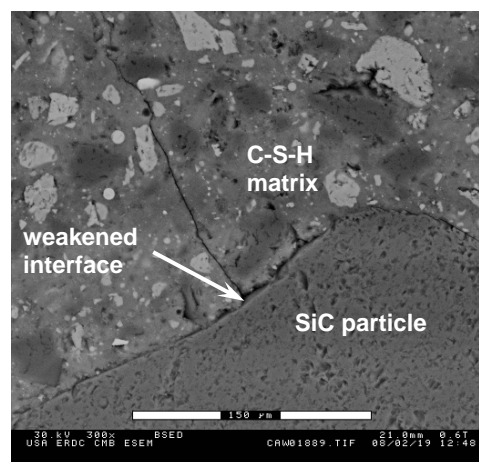


Figure 1. Scanning electron micrograph of hardened UHPC containing SiC aggregate (300x magnification)

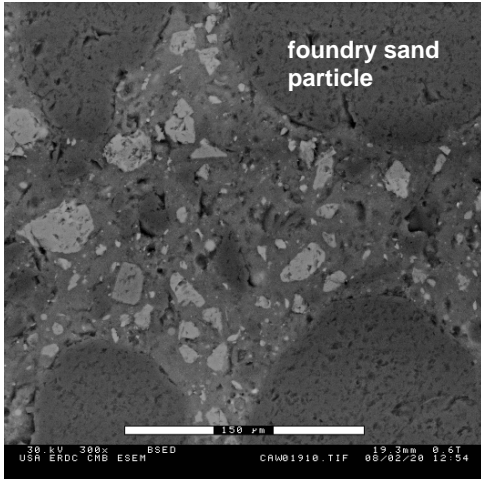


Figure 2. Scanning electron micrograph of hardened UHPC containing foundry sand (300x magnification)

In addition to multiscale material development, ERDC is also focusing research effort toward characterization of material subscale properties for use in multiscale computational methods. Because most state-of-practice approaches to computational methods are based on phenomenological material models, constitutive descriptions are most often based on macroscale material properties such as unconfined compressive strength, tri-axial and hydrostatic stress/strain path response, tensile strength, and fracture toughness, as determined by standard cylinder, cube and beam tests. However, to support multiscale computational capabilities, material properties at subscale resolution must also be quantified to provide the appropriate constitutive descriptions for the computational methods.

With respect to subscale material characterization (i.e. mm and below), significant challenges currently exist in the experimental techniques available for use. With increasing resolution in scale, limits exist with respect to both equipment capabilities and testing procedures. Furthermore, in some instances additional research is required simply to determine which material properties have the greatest influence on a certain subscale response based on the mode of failure or damage at the scale of interest.

An example of the challenges associated with multiscale material characterization is found in a multiscale study ERDC is conducting with fiber-reinforced, UHPC materials. The materials are formed from a blend of fine aggregates, Portland cement and pozzolanic materials that implements particle packing technology, minimization of hydration water, and alternative curing techniques to obtain elevated unconfined compressive strengths ranging from 20,000 psi to 40,000 psi. As should be expected for high

compressive strength cementitious materials, low fracture toughness is also a characteristic trait, which is partially offset by the inclusion of short, randomly distributed steel or glass reinforcement fibers (approx 1-in. length, 0.03-in. diameter).

As a first step in progression of scale refinement, the cementitious matrix and reinforcement fibers can be considered as two distinct material components, and therefore their interaction must be described to better understand overall material performance at the macroscale level. Considering interaction of these two material components and the potential modes of response and failure between them, the questions are subsequently posed as to which material properties most significantly influence their interaction, and furthermore, how are these properties quantified experimentally. For example, during simple pullout failure of a single fiber strand from the cementitious matrix, depending on the fiber type and its chemical bond to the matrix failure may occur along the surface of the fiber, indicating that chemical bond strength is a primary governing factor, or failure may occur within the cementitious matrix, indicating that its mechanical failure characteristics govern response. Therefore, both of these characteristics must be quantified to accurately develop a microstructure constitutive model, which presents certain challenges for experimental equipment and procedures, even at this relatively simple level of scale refinement. Then considering that in reality the cementitious matrix structure consists of a non-homogeneous substructure at the interface layer with the fiber, determination of basic material properties in this area such as compressive, tensile and shear strength present even greater challenges.

With the foregoing discussion focused on basic considerations associated with multiscale quantification of the matrix/fiber interaction for a single fiber in the high-strength concrete material, challenges associated with accurate characterization of material traits are significantly increased by potential interaction between multiple fibers and the simultaneous failure modes which may occur and interact. Furthermore, consideration of material properties under dynamic conditions during impact and penetration events—which forms the basis of ERDC’s research objectives—extends the material research requirements into entirely new areas requiring state-of-the-art experimental and analytical approaches to gather the necessary characteristic data.

In order to address the challenges associated with multiscale material characterization, ERDC has teamed with researchers at the University of Michigan Advanced Civil Engineering Materials Research Laboratory (Professor V.C. Li) and North Carolina A&T (Professor Sameer Hamoush) to conduct multiscale experimental studies on the fiber-reinforced UHPC materials. The

collaborative efforts will utilize experimental techniques at a variety of refinement scales, ranging from single-fiber pull tests (static and dynamic) to nanoindentation and electron microscopy, to better understand and characterize material response in support of constitutive models at the necessary scales.

3. COMPUTATIONAL PROTECTION TESTBED

In conjunction with multiscale material research, ERDC is focusing research on development of advanced computational capabilities which can be used to improve the analysis and design of protective systems under impact and shock loading. In accordance with the goal of establishing a numerical experimentation arena for modeling material and system performance, the program has been labeled as a Computational Protection Testbed. Within this testbed, two distinct objectives have been established, which include 1) development of new computational methods that enhance the current state-of-practice capabilities in high strain rate, large deformation modeling, and 2) use of these methods in conjunction with ERDC's material and protective structures experimental research to provide enhanced protective systems that meet the warfighters' challenging needs.

With respect to new numerical methods, ERDC is conducting collaborative research with Professor J.S. Chen at the University of California, Los Angeles (UCLA) focused on the development of new numerical techniques for meshless, multiscale modeling and simulation. The focus on meshless methods is driven by the well known difficulties associated with use of the finite element method (FEM) to model large deformation/damage events, which include numerical instability due to mesh deformation, mass conservation versus element erosion during model breakup, and the lack of random fracture growth capability due to the structured element mesh, just to name a few. However, because meshless methods are not dependent on a fixed mesh structure that must be defined a priori, they are much more capable of simulating events which involve extensive material fracture, failure and breakup.

With the UCLA Department of Civil and Environmental Engineering, Professor Chen has led state-of-the-art research in a novel meshfree technique labeled the reproducing kernel particle method (RKPM) (Liu, Ju and Zhang 1995, Chen et al. 1996), and is now collaborating with ERDC for further development. Fundamental to the RKPM technique is field variable approximation utilizing kernel-based interpolation functions instead of the regular mesh-structured approach utilized in the finite element method. Expressed in a discrete form, the basic reproducing kernel approximation

function (as an approximation function in the Galerkin method) is given in the following equation.

$$u(x) = \sum_{I=1}^{NP} C(x; x - x_I) \Phi_a(x - x_I) d_I \quad (1)$$

In equation 1, $u(x)$ = the field variable approximation, $C(x; x - x_I)$ = correction function, $\Phi_a(x - x_I)$ = kernel function (similar to FE shape function) with support size "a", d_I = approximation coefficients, and NP = number of discrete points in domain. The correction function defines the order of consistency and enrichment in the approximation, while the kernel function defines the continuity and locality of the approximation. The kernel function and correction function combine to form the kernel-based approximation function, analogous to the FE shape function, $N_I(x)$.

In comparison to the common FEM approximation shown in Equation 2, analogy between the RKPM method and FE method is seen, where the RKPM approximation is written over the kernel domain and the FE approximation is written over the structured element domain ($N_I(x)$ = FE interpolation function and u_I = field variable at node I).

$$u(x) = \sum_{I=1}^N \Psi_I(x) u_I \quad (2)$$

Although the RKPM and FEM approximation formulations are similar in form, the distinct advantage provided by the meshfree approach is that computational nodes are related through the kernel support area, instead of through the element-based nodal connectivity used in the FEM. As a result, problems associated with mesh distortion and entanglement are alleviated, as nodes within the kernel are free to move relative to each other without generating numerical instabilities. An example of a kernel support area is shown in Figure 3, where the field variable approximation at node I is determined by the neighboring nodes with their kernels covering node I . Also shown in Figure 3 is a typical continuous RKPM shape function, which is derived from the product of the RKPM kernel and correction functions. Other shape function forms can be used as well, such as discontinuous box functions, or piecewise hat functions, dependent upon modeling objectives.

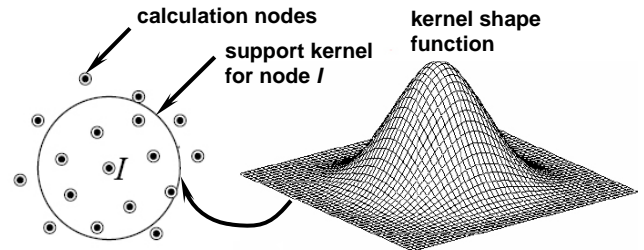


Figure 3. RKPM support kernel and shape function (Chen, 2006 seminar on multiscale meshless methods)

Lagrangian and so-called semi-Lagrangian formulations of the RKPM have been developed for application to various types of problems. In the Lagrangian formulation, the support for a given node remains constant in material coordinates, such that all nodes contained within the kernel remain constant through the calculation (resulting in distortion of the kernel). However, in the semi-Lagrangian formulation the kernel follows the base-node I , but supporting nodes are allowed to convect in and out of the supporting kernel. As a result, an additional convection term is required in solution of the governing equations, but extreme material distortion is most easily supported through this approach.

Another distinct advantage of the RKPM approach for impact and damage problems is the simplicity of discretization refinement. With the appropriate adjustment for mass conservation in the system and shape function reconstruction, in the RKPM approach nodes can be adaptively inserted where finer model resolution is required (such as in crack formation areas), without being encumbered with the compatibility requirements associated with FEM. An example of adaptive nodal refinement at the tip of a propagating crack is shown in Figure 4. In this case, nodes are adaptively inserted and removed at the crack tip to track its growth while minimizing computational expense associated with the finer discretization.

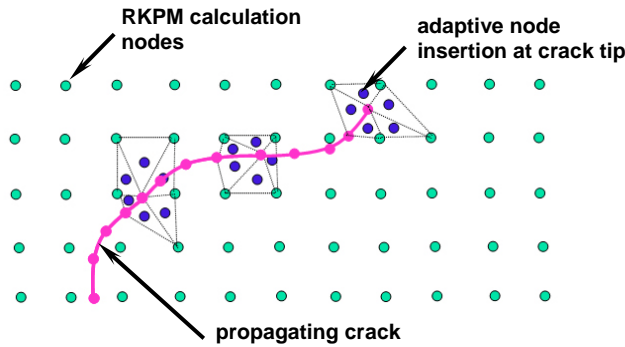


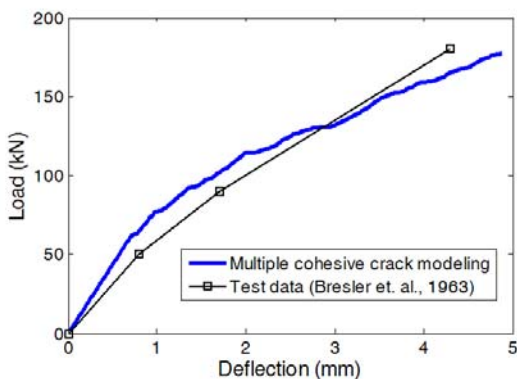
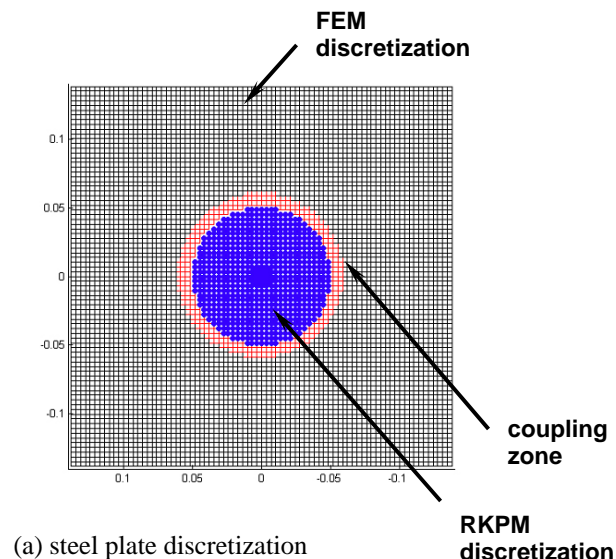
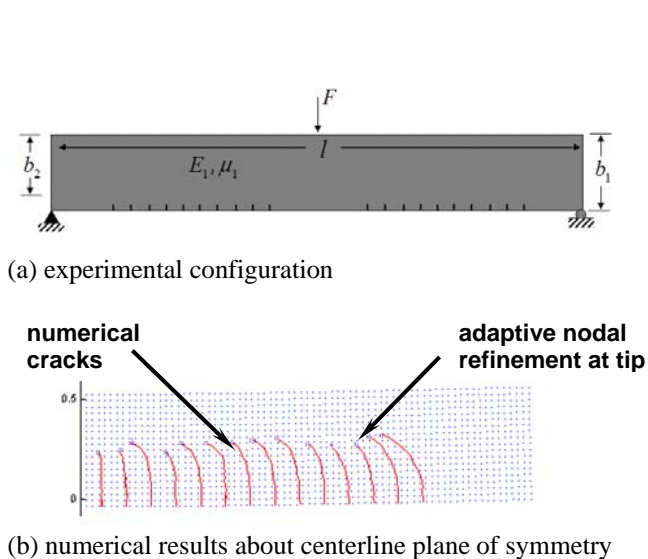
Figure 4. RKPM adaptive spatial refinement during crack growth (Chen, Guan and Hu, 2008 in-progress review)

With respect to development of the RKPM approach for application to shock, impact and penetration problems, numerical method development has focused on several areas in order to enhance performance for the problems of interest. Included in these research areas have been development of time domain sub-cycling algorithms to improve computational efficiency in problems with significant wave velocity gradients, automatic support size adjustment (i.e. kernel size) to accommodate extreme material motion and damage, and improved frictional contact algorithms for particle interaction. Development in each of these areas has led to enhanced capability of

the RKPM approach to accurately and efficiently model high strain rate and high deformation gradient events.

In addition to enhancement of the meshfree formulation, research efforts have also focused on development and inclusion of multiscale techniques to capture the influence of fine-scale material phenomena on macroscale material response. Research is being conducted in two areas to couple multiscale modeling capabilities with the parallel RKPM developments. One approach is based on the application of an interactive or adaptive hierarchical multiscale modeling technique, where mesoscale models are invoked to calculate material response in high damage zones, while macroscale constitutive models are used to calculate response in areas which experience low deformation gradients. The second approach considered utilizes a non-interactive approach to capture fine scale effects on macroscale response. In this case, fine scale numerical models are used to develop microstructure-based constitutive models for different forms of response, which are translated to the macroscale in the form of homogenized material laws. The homogenized, microstructure-based material laws are then applied to the macroscale model for calculation of global material response. For bridging between scales, an asymptotic expansion technique coupled with an energy based variational formulation is used.

Specific multiscale research focus has been given to the development of concrete dynamic crack growth models which will be applied to the meshfree, multiscale formulation through use of a representative volume element (RVE) approach. Within the RVE, the cohesive law is applied to crack growth, and utilizing a variational statement on energy conservation the crack size and direction can be calculated. This provides significant advantage over classic FEM approaches, because crack length and direction can be calculated and propagated naturally, without influence from a background mesh structure. Preliminary numerical experiments have been conducted to benchmark the cohesive law crack growth model implementation against experimental results. Compared against a beam flexure experiment in Figure 5, the cohesive law technique with adaptive refinement in the meshfree formulation accurately modeled the material response.



(c) comparison between numerical and experimental results

Figure 5. Beam flexure experiment, comparison between numerical and experimental results
(Hu and Chen, 2008 in-progress review)

Because the research objective of the Computational Protection Testbed is to develop advanced numerical techniques to model protective structure performance in events such as impact and penetration, preliminary numerical experiments have also been conducted to simulate projectile penetration events. Shown in Figure 6, a coupled FEM/RKPM model was used to replicate an ERDC conducted thin-plate (steel) penetration experiment. Shown is the coupled FEM/RKPM discretization, where the meshfree method was used in the vicinity of the projectile impact point and conventional finite elements were used in low deformation gradient areas beyond. Results indicated reasonable agreement between the numerical and physical experiments.

Figure 6. RKPM penetration simulation
(Chen, Guan and Hu, 2008 in-progress review)

4. NOVEL PROTECTIVE STRUCTURES

As a result of changing operational and functional requirements, high-mass, logistically expensive materials such as soil and concrete do not fully satisfy the force protection requirements for U.S. military forces operating in the contingency and expeditionary environments. Rather, based on evolving constraints new protective capabilities are required that combine reduced mass and volume with increased performance characteristics in a manner that can be adapted to changing conditions. In recognition of this shift in protective structure applications, ERDC has recently completed a three-year, 6.2 level ATO research program focused on the development of new protection structures which are better aligned with the current battlefield environment. The program, Modular Protective Systems for Future Force Assets, concluded in FY07 with the successful demonstration of a Spiral 1.0 protective structural system capable of withstanding a range of direct, indirect, shoulder fired rocket and bare charge threats. These

protective capabilities were developed and experimentally validated through numerous experimental activities.

The MPS, shown in Figure 7, provides the warfighter with a material solution for rapidly deployed and recovered physical protection. Spiral 1.0 of MPS consists of a lightweight space frame and composite armor panels that were validated for protection against a wide range of threat munitions. The system was designed such that all components are one or two-man portable, and require no construction assets to emplace an 8-ft-tall protective wall. Protection is provided by a multi-layered armor panel system, therefore protection levels can be tailored by the user based on threats in the area and available resources. One of these armor panels, based on the UHPC material, was a resulting development from ERDC's parallel materials research efforts. The protective potential from a high compressive strength, commercially producible cement based armor panel was recognized by ERDC and capitalized upon to achieve a cost effective armor solution.

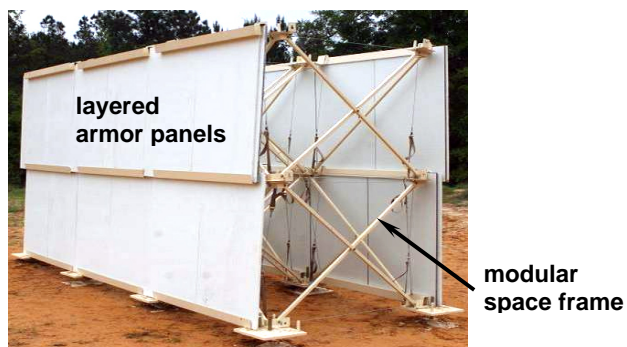


Figure 7. Modular protective system and components

Several developmental iterations were necessary before the final armor panel design was selected through combined material development and ballistic experimentation. As a part of the experimental process, the performance of new panel configurations were evaluated with Fragment Simulating Projectiles (FSPs) to quantify their ballistic protection performance. Throughout this process, focus was given to minimization of areal density and cost, while maximizing manufacturability, durability, and ballistic resistance. FSPs were chosen to serve as the ballistic index since one of the expected applications of MPS was indirect fire protection. The FSP mass and velocity were chosen to represent a reasonable design fragment generated by the indirect fire threats of interest in the CENTCOM AOR. These FSP experiments served as an excellent rapid developmental procedure to eliminate low performance armor designs without incurring the cost and time required to perform a field experiment. Furthermore, results of the laboratory controlled FSP experiments will

provide validation data for modeling efforts conducted within the Computational Protection Testbed.

In addition to laboratory experiments, the MPS was validated through numerous field experiments to fully mitigate the fragmentation effects of foreign fragmentation rounds. Furthermore, numerous bare charge experiments were conducted to assess structural stability under blast loading. In all cases, the MPS performed well, and provided multi-hit protection capability against these severe blast and fragmentation threats. Finally, when augmented with a screening system the MPS has been shown to provide protection from certain shoulder-fired rocket threats. Additional research is planned, such that a validated screening system can be incorporated into the standard MPS fielding kit. Experimental validation of the MPS performance when exposed to indirect fire and bare charge effects is shown in Figures 8 and 9.



Figure 8. MPS performance validation experiment, indirect fire threat.



Figure 9. MPS performance validation experiment, bare charge threat.

Development of the Spiral 1.0 MPS concluded at the end of FY07, and Class IV National Stock Numbers (NSNs) were assigned for the individual components. Additionally, an NSN was established for a kit containing all the necessary components to construct an 8-ft-tall, 5-ft-wide, 10-ft-long protective wall. In the same approximate time frame, an Operational Needs Statement (ONS) was generated by forward forces, stating the need for a lightweight physical protection system. In response to the ONS, the U.S. Army Rapid Equipping Force (REF) supported initial fielding of the MPS system. The U.S. Army Test and Evaluation Command assisted with the fielding effort by rapidly conducting a Capabilities and Limitations assessment and a safety and human factors evaluation for the system. The REF initiative was conducted in Spring 2008, with materials fielded to an operational area in the CENCOM AOR. Response from forces using the system has been positive, with additional materials requested for use.

In conjunction with the REF fielding initiative, ERDC has also been engaged by the Office of Naval Research and the Naval Expeditionary Combat Command (NECC) to develop Spiral 2.0 of the MPS, tailored to meet the expeditionary needs of naval combat forces (FY08 to FY10 ONR Rapid Technology Transition project). Focus of the Spiral 2.0 effort is on enhanced expediency of wall construction and investigation of increased armor performance, and at successful completion of the project the Spiral 2.0 development is expected to be incorporated as a standard component in the NECC and Navy Seabee force protection tool kit.

5. SUMMARY AND CONCLUSIONS

In response to warfighter needs in an adapting threat environment, the U.S. Army Engineer Research and Development Center has focused multiple research areas towards the collaborative development of advanced protective structures. Coupling subscale material development and characterization research with the development and application of new computational methods for high-rate, high-damage events, ERDC expects to generate higher performing materials and structures through increased understanding of fine-scale material phenomena and its impact on macroscale material response.

With regard to the material development and characterization research area, investigations have led to the successful development of a UHPC armor material for use in protective structures. Furthermore, through collaborative research under a Cooperative Research and Development Agreement with the United States Gypsum Company, the UHPC armor panel has been tailored to facilitate production line manufacturing, making the

product readily available for warfighter use. Through expansion of these UHPC accomplishments, and working in conjunction with leading cement composite researchers such as V.C. Li at the University of Michigan, it is expected that further enhancement of these protective materials' performance will be obtained. Additionally, this research will lead to better understanding of the materials' fundamental response and failure mechanisms across a range of length scales, allowing researchers to support constitutive models used in computational research as well as develop improved armor materials based on improved first-principles approaches.

In conjunction with material focused research, ERDC continues to focus significant effort on the development of new numerical methods for weapons' effects and dynamic response modeling. Research to-date has shown that new meshless methods, such as RKPM, can provide significantly enhanced computational capabilities over the current state-of-practice approaches employing conventional finite element procedures and other particle techniques. Furthermore, coupled multiscale modeling techniques will further enhance computational capabilities for warfighter applications. Through the use of validated multiscale models, researchers will be able to utilize numerical methods to design and analyze material performance based on improved first-principles approaches, which will result in a more efficient development process as well as enhanced material performance based on substructure material design.

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