F4-H: Optimal Design and Use of Advanced Structural Materials to Mitigate Explosive and Impact Threats

Abstract — The initial focus of this mitigation effort was to conduct studies that aimed to understand the response of conventional and novel materials and structures to shock loads (internal or external) with or without a high temperature environment. The ultimate goal was the development of materials and structures that can mitigate blast conditions. The major focus is an investigation of the effectiveness of coating technologies for structural protection during a blast, including the integration of multi-layered systems with varied densities. The initial phase of work included the hybrid base material development and characterization. This included the development of an optimized randomly distributed reinforced polyurea coating system for reduced fragmentation and enhanced blast and impact protection. System selection for evaluation in reinforced concrete panel and barrier systems was then initiated. Concurrently the system was evaluated for wider application to multi-hazard use in strengthening reinforced concrete elements for flexure, shear and axial loading. Current work is looking at the integration into and effectiveness for systems with ultra-high performance concrete.

I. PARTICIPANTS

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II. PROJECT OVERVIEW AND SIGNIFICANCE

This project contributed to the mitigation area of the ALERT program. The foremost research effort goal was to develop new materials and coating technologies for civil defense against explosives related attacks. The aim of this research was to harden barrier and wall systems in order to reduce injury from attack and to prevent loss of human life caused by significant fragmentation. A secondary evaluation was to explore the multi-hazard potential of the material. To date, it has been evaluated for general strengthening potential in addition to blast mitigation.
III. RESEARCH AND EDUCATION ACTIVITY

A. State-of-the-Art and Technical Approach

The simplest and often most inexpensive blast mitigation technique is the use of large standoff distance between the blast and the structure to be protected. Unfortunately, standoff is not available in most civil environments because a blast attack was not anticipated when these structures were designed and constructed. A method to achieve a modicum of blast protection is to place a barrier that enforces standoff distance and provides some shadowing effects close to the side of the barrier away from the blast. Such barriers also increase the available response time to the threat. Most barriers utilize standard engineering materials such as steel and concrete, and are poorly designed by those who do not understand how to consider the two most important factors in blast – pressure and impulse – that should be modified to create effective blast protection. Barriers also become part of the fragmentation hazard during a close-in blast because their materials are not arranged to minimize spallation.

Material advances in High Performance Concrete (HPC), High-Strength Concrete (HSC), Self-Consolidating Concrete (SCC), and Ultra-High-Strength Concrete (UHSC) have occurred in recent years. One limitation to these material developments is their lack of ductile behavior and the lack of constitutive data for these materials when they are under very high strain rates. In many cases, strength levels have improved dramatically, but there has been a corresponding decrease in material ductility, which results in concerns for the use of these materials in seismic and blast-resistant applications. Limitations on understanding the ultra-high strain rate behavior (for example, the shock Hugoniot) of advanced materials has severely limited researchers’ ability to produce high fidelity computational models of these materials under blast loading. This project has advanced the state-of-the-art by investigating and developing systems that provided a higher level of blast mitigation with reduced fragmentation, and by contributing to the understanding of data necessary for true constitutive models. The state-of-knowledge has also been advanced on the utilization of coating technologies utilized for blast hardening and mitigation with and without discrete fibers. The development of strengthened polyurea coating systems to date has demonstrated a multi-hazard retrofit material suitable for at-risk aging infrastructure in terms of general strengthening and blast mitigation. The blast testing for this work has been completed. New studies have been initiated using ultra-high performance concrete (UHPC) as a mitigation material.

B. Major Contributions

The contributions under ALERT funding to date have included the development of a novel discrete fiber reinforced polyurea (DFRP) coating technology that can be applied to at risk reinforced concrete (RC) structures or new RC structures for improved blast mitigation by Prof. Myers Graduate Students N. Carey, C. Greene, and A. Wulfers. The system behavior has been validated with both experimental testing and through numerical studies. Static load testing of RC members has also demonstrated the applicability of the system for general flexural and shear strengthening. This provides added benefits of the system for multi-hazard applications. More sustainable cost competitive hybrid systems using high-volume fly ash have also been studied under the work by A. Wulfers. This multi-layered system with varied density has been investigated and completed by A. Wulfers. The system he examined consisted of a panel with a base layer of a steel fiber reinforced concrete and a cement-wood-fiber-fly-ash layer. Technology transfer of all work through publications, technical reports, and technical presentations is further described in the Documentation section of this report. Current on-going studies by J. Willey are examining the effectiveness of using ultra-high performance concrete (UHPC) as a mitigation system in both solid and hybrid layer systems. This work is in process.

There are several efforts partially funded by ALERT under the guidance of Prof. Baird. Graduate Student P. Mulligan completed his research effort into the development of improved Explosively-Formed Penetrator (EFP) test devices in order to more effectively test hybrid blast mitigation and armor concepts. The effort
involved the variation of five different physical EFP parameters in order to determine each parameter’s effect on device performance. Mulligan successfully defended his thesis on this topic in the Spring 2011 semester, and was awarded his MS degree in May 2011. Graduate Student L. Bookout worked to extend P. Mulligan’s research into the evaluation of high-strength and high-performance concrete resistance to EFP penetration/damage. Computational modeling, test stand construction, prototyping, and research blast tests were completed in the Spring 2011 semester at the Missouri S&T Experimental Mine facility, and Bookout successfully defended her thesis on this topic in the Fall 2011 semester, and was awarded her MS degree in December 2011. Graduate student C. Baumgart is currently doing research to develop barriers with blast mitigation capabilities. Several forms of media are being investigated and selected based on characteristics such as availability, price, hardness, density etc. to fill cavities inside of a concrete form. By using a multi-layered system with varied densities to mitigate a blast wave more efficiently the thickness, weight and price of blast barriers will be reduced. If the project is successful it is possible that the required standoff distance between a building and an IED will be reduced, thus creating a safer working environment for buildings that cannot afford the currently required standoff distances. A design of experiment method is being used to optimize the results of this research. Testing will commence as soon as the design of experiment is finished and products are ordered.

C. Scholarly Findings and Results

Discrete Fiber - Reinforced Polymer (DFRP) Systems for Infrastructure Strengthening and Blast Mitigation: During this reporting period, the work undertaken by PhD student N.L. Carey was completed. Her work under the guidance of Prof. J. Myers consisted of four related studies, namely: 1. the development and characterization of different DFRP systems for infrastructure strengthening and blast retrofit, 2. the behavior of hybrid, plain, and steel fiber-reinforced concrete panels coated with various polyurea and DFRP systems under blast loading, 3. an analytical investigation conducted using the explicit finite element program LS-DYNA [1, 2] to model panel and coating response under blast loading, and 4. an internal equilibrium mechanics based model developed to predict the flexural capacity of reinforced concrete beams strengthened with various DFRP systems.

Previous annual ALERT reporting presented findings on the topical areas of 1, 2 and 3 mentioned above. The following will present a brief summary of the internal equilibrium modeling using the DFRP system and parametric studies on application to hardening infrastructure systems. An internal force equilibrium approach was applied to determine the nominal flexural strength of DFRP-strengthened concrete beams. Figure 1 illustrates the internal strain and stress distribution for a rectangular section under flexure. In order to estimate the additional capacity provided by the DFRP systems, the coating was assumed to carry a tensile force \( T_p \) in addition to the tensile steel reinforcement contribution \( T_s \). The cross-sectional area of the coating below the neutral axis was used to calculate the contribution of the DFRP systems. The coating tensile force \( T_p \) was assumed to act at a distance between the extreme tension fiber and the center of gravity of the strengthening system, \( y' \). The moment capacity of the section was
determined using the force equilibrium method by equating the compressive and tensile forces.

The developed model was evaluated using available experimental results from the study by Greene and Myers (2010) that investigated flexural and shear behavior of reinforced concrete members strengthened with DFRP systems. Work undertaken by Greene and Myers indicated that the polyurea coating systems provided additional flexural reinforcement resulting in an increase in ultimate capacity. During Greene and Myers’s (2010) experimental work, five rectangular doubly reinforced concrete beams were fabricated and tested in a four-point loading test setup to evaluate flexural behavior of each member. Four beams were coated on the bottom/tension face and sides with 3.2 mm (⅛ in.) plain polyurea or DFRP systems. Beam cross-section and material properties from the Greene and Myers’s (2010) work were used in this study to predict flexural capacity of reinforced concrete beams strengthened with various DFRP systems using internal force equilibrium approach.

The ratio of experimental over theoretical capacity was used to compare the results. The ratio greater or equal to one indicates that the method closely predicts the flexural capacity of RC beams strengthened with various DFRP systems. The model over-predicted the capacity for beam #4 due to variable coating thickness (approx. ± 1.5 mm (1/16 in.)) throughout the member. As shown in Figure 2, the data point for beam B is plotted below the line. The values above the line in Figure 2 represent conservative results.

A parametric analysis was conducted using previously developed and validated model and material characterization results of the various polyureas and DFRP systems from a fiber length optimization study by Carey and Myers (2011) in order to evaluate the flexural behavior of reinforced concrete (RC) beams strengthened with DFRP systems and determine their suitability for flexural retrofit of typical FRP strengthened candidate bridges which has the added blast mitigation enhancements.

The work concluded that the method allows for a wide variety of coating systems and beam geometries to be modeled to determine the most desirable alternative solution. The parametric analysis was conducted using an internal force equilibrium approach and material characterization results of the various DFRP systems to evaluate an increase in flexural capacity due to strengthening systems. The effect on ultimate capacity of fiber volume fraction and coating thickness was evaluated within the parametric study. It was concluded that as the coating thickness increased the contribution of the strengthening increased as illustrated in Fig 3. The DFRP B systems with fiber volume fraction ranging from 4 to 5.2% demonstrated the highest contribution to the flexural capacity ranging from 14 to 16% for a 1.91 cm (¾ in.) thick coating and 19 to 21% for a coating thickness of 2.54 cm (1 in.). These new DFRP systems are advantageous when lower increase in strength is required and can provide blast mitigation attributes.

Use of High Volume Fly Ash Wood Fiber and Polyurea Layers for Blast Mitigation: This project extended research done undertaken by Carey and Myers (2011) to develop and characterize an e-glass discrete
fibre-reinforced polyurea (DFRP) system for infrastructure applications. Carey then recommended two polyurea systems (A and B) be further examined. These polyurea systems were then applied to plain reinforced concrete and steel fiber reinforced concrete panels (SFRC) and it was found that the SFRC panels sustained less overall damage.

For this project SFRC was used as the base layer in combination with the DFRP systems. In addition to the DFRP and SFRC a high-volume fly ash-wood fiber (FA-WF) material was added to act as a sacrificial layer on the panels. The FA-WF is a material that has been under development at Missouri University of Science and Technology (Missouri S&T). These panels were then tested with explosives at the Missouri S&T Mine Facility. The panels were compared visually and analytically. The visual observations were used to compare dramatic differences in the panels, while more analytical means, like residual deflections and estimated mass loss allows panels with very similar damage to be compared. After comparing the results significantly less damage was observed in the hybrid panels that contained a foam-gap and a DFRP layer. Results from this study will be used to evaluate alternative construction methods and coating systems to protect at-risk structures and their inhabitants.

This study consisted of the blast testing of 13 composite concrete panels. Testing consisted of two 1.4 kg (3 lb) charges of an RDX based C-4 explosive at two different stand-off distances on 13 composite concrete panels. The objective of this research was to determine the performance of FA-WF in combination with SFRC and E-glass DFRP at resisting blast damage. The following is the findings, conclusions and further recommendations drawn from this investigation:

- The sacrificial high volume fly ash-wood fiber (FA-WF) material provided an improvement over no additional layer. The 1-H, 2-H panels saw less significant residual deflections and cracking after the first blast event than the SFRC-3.5 panel.
- The control panels with the FA-WF layer (1-H and 2-H) did not perform as well as the SFRC-5.5 panel. This indicates that an additional 50 mm (2 in) of SFRC is a more effective way resisting blast damage compared to a sacrificial layer alone.
- An investigation considering cost would be useful. The additional 50 mm (2 in) of SFRC proved to be better at resisting blast than 50 mm (2 in) of FA-WF. However, the FA-WF material is significantly less expensive than the SFRC material so if cost was considered it may find that FA-WF is a more cost effective way to resist blast. However, the FA-WF may also present some aesthetic concerns for architects.
- An investigation comparing using SFRC and FA-WF as a retrofitting layer would allow for a better comparison between the two materials. In the SFRC-5.5 panel, one lift of 140 mm (5.5 in) is not comparative to two separate lifts, which is present in the hybrid panels.
- The foam-gap significantly reduced the damage in the base layer. The foam-gaps present some issues though, they create a large amount of fragments on the blast side of the panel that may contribute to damage and injuries experienced outside the structure, although it is unlikely the fragmented pieces will cause significant damage beyond the blast wave effects to humans. Another related issue is that if a missile or two blast events are used the impact of the missile or first blast event is likely to reduce the sacrificial layer to rubble exposing the base layer.

For more in depth details, see the report by Myers and Wulfers (2012).

**Development of Improved Explosively-Formed Penetrator (EFP) Test Devices:** During this reporting period, Graduate Student P. Mulligan completed his study of the effects of EFP design variables on the EFP performance against protective structures, and Graduate Student L. Bookout continued Mulligan’s work by studying the performance of optimized EFPs against concrete structures. Mulligan and Bookout presented their findings at the American Physical Society’s 17th Biennial International Conference on Shock Compression of Condensed Matter in Chicago at the end of June 2011. Each presentation was well received, and each student was asked to contribute a paper to the conference proceedings.
Mulligan’s work concerned the effects of variations of select physical parameters on an EFP’s performance against hardened structures. The resulting design parameters allowed us to produce a standardized improvised EFP to use in testing these structures. Mulligan performed modeling of these variables, and then estimated the effects of changes in those variables through use of a modified Gurney equation to predict the projectile velocities. He then verified the models via experimental testing of actual improvised EFPs at the Missouri S&T Experimental Mine Facility. He was also able to use shock hydrodynamics to describe target material performance upon impact of the projectiles.

Bookout then used Mulligan’s standardized EFP design and the modeling predictions to evaluate those predictions in actual tests against additional target materials, namely basic steel-reinforced concrete. Bookout also utilized five different existing penetration evaluation methodologies from the literature to predict projectile performance; she found that only one of those methodologies was a good predictor in the target configuration she utilized. As an aside, she was able to design a unique capture method to retrieve undamaged projectiles; it was necessary to have several of those projectiles in order to gather the physical data necessary to use the penetration prediction methodologies (Fig. 4 shows an exemplar projectile).

Our intent is to utilize the results of Bookout’s work in order to develop a better shock Hugoniot for high-strength concrete materials under the impact of EFP and shaped charge devices. This additional understanding is required in order to better model the performance of such target materials in coupled computational fluid dynamics/computational structural dynamics codes.

During this reporting period, Graduate Student P. Mulligan began his investigation into the physical phenomena that govern underwater explosive lensing. Mulligan’s work examines how multiple small explosive charges can be positioned so the shock waves from the detonation of the charges work to seal a pipe. Thus, one direct product of the work is to provide an efficient use of explosives as a viable means to seal leaking oil pipelines inaccessible to other means of closure. The work is not limited to this application, however; a better understanding of the dynamics of shock manipulation under water will contribute to measures designed to protect shore facilities, shallow water infrastructure, and shipping. Mulligan’s experimental design includes underwater testing as well as above water testing to examine the converging shock waves in various media, and the effects of the Bjerknes Force of the gas bubble generated by an underwater blast.

In addition, P. Mulligan and L. Bookout examined the forces imparted on a projectile due to the material selection of various soft recovery methods. Their work analyzed the forces two different soft-recovery methods impart on the projectiles collected. The first method utilized three-polyethylene water barrels placed “end-to-end” horizontally, providing 2.6 meters (9 feet) of water to stop the projectile. The second method was a modification of the soft-recovery method utilized in “Soft-Recovery of Explosively Formed Penetrators” by Lambert and Pope [1]. This method utilizes a series of several materials with an increasing density gradient, placed end-to-end over 14.3 meters (47 feet) to stop the projectile. This investigation was done to provide researchers with the means of predicting the forces imparted on a projectile collected from the recovery method.

**Education Activities**

A new experimental course entitled CE-ArchE 301, entitled Structural Masonry Design, was approved by the campus curriculum committee and offered at Missouri S&T for the Fall 2011 semester taught by Prof. Myers. The course included approximately 3 weeks of material examining membrane (i.e. coating) retrofit and hard-
ening systems to enhance the blast and hazard mitigation of wall and barrier systems. The membrane and hybrid systems and discussed design approach has been an outcome of the ALERT funded research.

In the Spring of 2012, Prof Myers offered a revised version of CE-ArchE 374 entitled Infrastructure Strengthening with Composites, at Missouri S&T. This course included updated materials on membrane systems and hardening of reinforced concrete (RC) systems based upon the work undertaken in the ALERT program. This will translate the new hybrid design techniques to a new generation of structural engineers for hardening and mitigation.

IV. FUTURE PLANS

A. Scholarly Activities

The immediate on-going and future plans include blast testing UHPC panels under the remaining YR 4 funding, completing data analysis for these tests, and the final reporting as described below.

Ultra-High Performance Concrete (UHPC) Material in Hybrid Systems: Ultra-High Performance Concrete (UHPC) such as those produced with reactive powder concrete (RPC), with compressive strength 4 to 5 times stronger than conventional concrete, exhibit exceptional energy absorption capacity and resistance to fragmentation, making it ideal for structural and non-structural components that need to perform under explosive, impact or shock loads. The flexural toughness of UHPCs enhanced with fine steel fibers is greater than 200 times that of conventional fiber reinforced concrete. Previous blast test results have highlighted the large increase in resistance of UHPC when compared with RC panels of the equivalent size. The results recorded large deformations of UHPC panels with little or no fragmentation. Previous tests using panels were found to develop a hinge capable of higher rotations than RC members, making them significantly more ductile. However, there are certain trade-offs in the use of UHPC for blast mitigation; namely the material’s very high material unit costs.

For this cost effectiveness reason a hybrid approach will be taken in this investigation to optimize the use of UHPC for blast mitigation in combination with the previous successes in the ALERT blast mitigation hybrid studies at Missouri S&T. Evaluation in the development of the system will include both cost and mitigation effectiveness. Selected materials based on this combination will undergo blast testing at the Missouri University of Science & Technology (Missouri S&T) Experimental Mine Facility.

To extend the work in the extreme impulse/high strain rate evaluations area, the research team proposes to investigate the impact shock/structural dynamics required for hydrocode extension to high-strength and novel cementitious materials under development [3].

B. Education Activities

During the Fall 2012 semester, Prof. Baird will offer a new graduate level course at Missouri S&T, Mining 411. This course encompasses explosives safety, design of experiments, statistical techniques, and energetic material risk assessment/risk management.

The new in-residence Explosives Engineering MS degree program recently approved for implementation by the Department of Mining and Nuclear Engineering at Missouri S&T continued to gather momentum. In addition to Prof. Baird’s four MS students who were awarded this degree in the previous academic year, two more students are slated to achieve the degree during the coming year.

V. RELEVANCE AND TRANSITION

The program review assessed the relevance of Thrust F4 at the “high” level, and we continue to transition
the results of our research to government and industry. At the present time, no commercial transitions have happened. However, with the successful development of hybrid systems and coating techniques for enhanced blast protection and reduced fragmentation due to blast potential, commercial applications may develop. Line-X Protective Coatings Corporation from Columbia, Missouri, collaboratively worked with Missouri S&T in the polyurea formulation and specimen coating development. If the DFRP system is determined to be patentable as a result of further investigation, the Intellectual Property agreement is in place to be exercised.

VI. LEVERAGING OF RESOURCES

A US Department of Transportation Graduate Assistantship in Areas of National Need (GAANN) award was leveraged to support PhD student Natalia Carey at Missouri under the guidance of Prof. John J. Myers to support the ALERT program. MS Student, Anthony Wulfers has received a prestigious Chancellor’s Fellowship at Missouri S&T to help support his tuition and fees.

VII. DOCUMENTATION

Several reports with affiliated publications have been developed and are currently in process. Publications report the findings of the discrete fiber polyurea coupon studies developed and studied for application to reinforced concrete (RC) systems for hazard mitigation evaluation as well as flexural and shear strengthening effects of the DFRP system on RC. Numerical results have been submitted for conference and journal publication as well as presented at the 2012 CICE Conference in Rome, Italy. Two technical reports have been completed based upon the dissertation and thesis reports of N.L. Carey and A. Wulfers.

Three publications and associated conference presentations regarding high strain-rate effects in RC barrier materials resulted from the past two years’ research into impact testing of these materials. Additionally, one presentation has been submitted for conference presentation in the area of explosive shock manipulation under water.

A. Technology Transfer: Technical Publications


B. Technology Transfer: Technical Reports


C. Technology Transfer: Technical Presentations and Poster Sessions


D. Seminars, Workshops, and Short Courses

Four workshops presented to local, Missouri State, and Federal law enforcement personnel by Prof. Baird on “Explosives-Related Threats, Recognition, and Awareness.”

VIII. REFERENCES

