# THRUST F4
## BLAST MITIGATION

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*Work on the F4-I project was completed in Year 4; therefore, a yearly project report is no longer included.*
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 completed during this reporting period 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. Most recently completed are the studies by J. Willey, which examined the effectiveness of using ultra-high performance concrete (UHPC) as a mitigation system in both solid and hybrid layer systems. This work is summarized under Section C.

There are several completed 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. The media being considered includes but is not limited to steel grit, pumice, various types of sand and foam. By using a multilayered 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

Use of Ultra-High Performance Concrete for Blast Mitigation: This project extended research done by Myers and Carey (2012) and Myers and Wulfers (2012) to investigate various structural panels and coating systems to mitigate blast threats. Myers and Carey (2012) characterized discrete fiber-reinforced polyurea (DFRP) systems that were applied to plain reinforced concrete and steel fiber reinforced concrete (SFRC) panels. The results showed that the SFRC panels sustained less damage. Myers and Wulfers (2012) extended this work by applying the coating systems recommended by Myers and Carey to panels with a fly-ash wood-fiber (FA-WF) sacrificial layer, as well as panels with an internal foam gap. The results showed increased performance with the hybrid panels.

For this research, the goal was to investigate if a UHPC panel of equal or lesser thickness would achieve improved or equal performance, as well as what effect the fiber content had on mitigation performance. Minimal work has been done in this area with UHPC, so the results of this research will add valuable data to the field of blast mitigation. The panels underwent blast testing at the Missouri S&T Experimental Mine, and were compared both visually and analytically. Visual observations were used to compare significant differences in damage, while analytical methods such as residual deflection and mass loss were used to compare panels with similar damage. This study should be used as an initial report to provide a conceptual understanding of the material and how it performs under blast loading. With the results of this study in mind, the research could be built upon and expanded.

This study consisted of testing 6 UHPC panels. Two (2) panel thicknesses and three (3) fiber contents were investigated. The charge weight and standoff distances varied during testing depending on the behavior being studied. All charges were a RDX based C-4 explosive. The objective was to determine the performance of UHPC for blast mitigation, study the spalling behavior of the material under blast loading, and comment on how well the current design software (CEDAW and ConWEP) predict damage for this type of material. The following are the preliminary findings, conclusions, and further recommendations drawn from this investigation.

- UHPC panels with fibers performed significantly better than plain UHPC without fiber.
- An increase in fiber content provided increased blast mitigation performance.
- Upon UHPC panel failure, little to no spalling or fragmentation behavior is observed, which is beneficial
for providing protective structural wall systems in an at-risk building.

- ConWEP does not predict spalling or breaching behavior of this material well.
- CEDAW predicts damage levels for UHPC with fibers fairly accurately, but does not predict behavior well for plain UHPC panels.
- UHPC panels should be studied with a continuous mesh reinforcement to improve performance of plain UHPC, as well as improve shock performance of fibrous UHPC.
- UHPC may not be the most cost effective way to mitigate blast events, and a cost study should be conducted.

For more in depth information, please see the coming report by Willey and Myers (2013).

**Use of Ultra-High Performance Concrete for Impact Resistance:** This project extended research done by Gliha and Volz and Keener and Volz to investigate carbon fiber reinforced concrete panels under impact loading. The results showed that the carbon-fiber reinforced panels out performed normal reinforced concrete panels for impact resistance.

For this research, the goal was to investigate if a UHPC panel of equal thickness would achieve equal or improved performance. The panels were tested at the Missouri S&T Structural Engineering Research Laboratory (SERL), and were compared both visually and analytically.

This study consisted of testing two (2) UHPC panels. One (1) plain UHPC panel with no fiber, and one (1) UHPC panel with 6% fiber were investigated. The impact weight was 50 pounds, and the drop height gradually increased until failure of the specimen. The objective was to determine the crack height, and failure height of the specimens, and compare their performance. The following are the preliminary findings, conclusions, and further recommendations drawn from this investigation.

- UHPC panels with fibers performed significantly better than plain UHPC without fiber.
- The plain UHPC panel performed the same as a unreinforced normal concrete panel.
- The fibers were effective at bridging cracks in the concrete to continue to provide impact resistance.
- UHPC panels should be studied with a continuous mesh reinforcement to improve performance of plain UHPC.

For more in depth information, please see the coming report by Willey and Myers (2013).

**Education Activities**

A new experimental course entitled CE-ArchE 301, entitled Structural Masonry Design, was approved by the campus curriculum committee and initially 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 hardening 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. It was once again offered in the Fall of 2012.

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.

In the Fall 2012 semester, Prof. Baird offered a new graduate level course at Missouri S&T, Mining 411. This course encompassed explosives safety, design of experiments, statistical techniques, and energetic material risk assessment/risk management.
IV. FUTURE PLANS

A. Scholarly Activities

The scholarly work undertaken by Missouri S&T has concluded with the expenditure of the remaining YR 4 funding.

B. Education Activities

The new in-residence Explosives Engineering MS degree program was previously approved and has been implemented at Missouri S&T. This new program development will continue as a degree option at Missouri S&T.

V. RELEVANCE AND TRANSITION

The program investigators continue to transition the results of our research to government and industry. However, at the present time, no commercial transitions or patents have occurred.

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 Students, Anthony Wulfers and Julie Willey have received a prestigious Chancellor’s Fellowship at Missouri S&T to help support their tuition and fees.

VII. PROJECT DOCUMENTATION AND DELIVERABLES

Several reports with affiliated publications have been developed and are currently in process. The following is a summary.

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
