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CHALLENGES IN PROTECTIVE STRUCTURES R&D

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ABSTRACT

Defending society against rapidly evolving types of warfare, such as asymmetric warfare, will remain a challenge, at least through the first half of the 21st century. Technology will continue to play a major role in these efforts, and society must develop appropriate innovative theoretical, numerical, and experimental approaches that will lead to a wide range of solutions. This paper is aimed at highlighting challenges that must be overcome to achieve the required objectives.

1. INTRODUCTION

In today's geopolitical environment, the need to protect both military facilities and civilian populations from attack has not diminished. Furthermore, we have noted with great concern an increasing need to protect civilian populations against terrorism and social/subversive unrest. Unlike the global politically and ideologically motivated conflicts of the past, dominated by well-organized military forces, most of the armed conflicts in the last two decades have been localized and dominated by social, religious, economic, and/or ethnic causes. In many cases, well understood and reasonably predictable military operations have been replaced by much less understood and less predictable activities carried out by determined individuals or small groups that have a wide range of backgrounds and capabilities. They are directed against well-selected targets, and they are aimed at inflicting considerable economic damage and loss of lives. Such activities, despite involving a few individuals or small groups, can have devastating consequences. They can adversely affect national and international stability, and cause worldwide serious economic, social and political damage. Addressing this problem will require a well-planned multilayered approach that strikes a fine balance between assuring a nation's security and maintaining the freedoms that a modern society enjoys. We must develop innovative theoretical, numerical and

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experimental approaches to protect society from a wide range of threats, and must conduct these activities in a well-coordinated collaboration between government, academic, and private organizations. Such technologies are the last layers of defense between society and the threats, after all other layers of defense have failed. They are vital for insuring the safety of people, and the preservation of valuable national assets.

2. CURRENT CAPABILITIES FOR DESIGN OF PROTECTED FACILITES

Protective design is different from typical civilian design approaches, where a code can be followed to achieve well-defined performance and safety requirements. Although there are several resources providing specific information on security measures, protection levels, and structural design and analysis procedures, no single document encompasses the full design process from start to finish. Moreover, there is little standardization between manuals, and no hierarchy between the different resources. Besides, most of the documents are prescriptive and not performance based. Therefore, the designer is required to determine the requirements to ensure physical security and safety by following the design process described in Table 1, and the specific resources might be used to support each step with careful consideration.

For example, both the GSA guideline and the UFC manual for progressive collapse require that a building would not fail due to the removal of a single column. However, this does not ensure that the structure is safe from progressive collapse, since an explosive load might damage more than a single column. Likewise, meeting the requirements set forth by each manual may not ensure the actual physical safety of the occupants. Too much focus is placed on individual components rather than on a holistic perspective of the system. Another complication is that the results from each scenario involving blast can vary so dramatically that the outcome is very difficult to predict, and the corresponding design might not be well defined.

Also, the design needs to be worked through by a team of specialists in several areas, and not confined to a single specialty. Finally, an important aspect to a protective system solution is the presentation to the customer. In order to provide a successful presentation, the team needs to do a case study on the proposed structure based on the customer’s requirements, and present a cause-and-effect sequence that could be addressed. A cost/benefit ratio could be outlined for the various options to enable the rational selection of a solution with an appropriate level of protection.

Table 1. Design Process

Design Step	References
A. Define facility operational performance requirements.	1, 2, 4, 7
B. Establish quality assurance (QA) criteria for analysis, design, and construction work, and assign	8, 12
C. Perform threat, hazard, and risk assessments, and estimate future risk.	1, 7, 13
D. Determine explosive sources, their locations, and magnitudes	1, 2, 5, 7, 11, 13
E. Estimate corresponding loading conditions.	4, 5, 11, 13
F. Establish general siting, facility layout, and design criteria.	1, 2, 3, 7, 11, 12, 13
G. Proportion members for equivalent static loads.	4, 5, 8, 9
H. Compute blast loads on facility more accurately.	4, 5, 11
I. Compute loading from fragments, crater ejecta, ground shock, etc.	5
J. Combine all dynamic loads and perform preliminary dynamic analyses.	4, 11, 5
K. Redesign facility to meet selected criteria estimated loading effects.	4, 5
L. Consider nuclear radiation, EMP, thermal effects, CB, etc., if appropriate.	10
M. Verify design by acceptable methods.	
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3. CURRENT CAPABILITIES FOR ANALYSIS

3.1 Loading Environments

Loading environments produced by conventional explosive devices include fragments and/or debris propelled and engulfed by the blast wave. Blast parameters from bare explosive devices cannot be used to describe the combined blast-fragment-debris environment. A cased explosive device could cause a more severe loading environment than anticipated from a bare explosive charge. The combination of pressure and fragment impulse, as a function of the detonation distance from the target, is another important issue that does not have reliable models at this time, and this topic must be studied.

Also, the loading cannot be determined accurately for cases where explosive charges are placed in contact with, or in close proximity to the target, and for nonstandard explosive devices. The pressure distribution from explosive charges of shapes other than spherical or cylindrical will be considerably different than those obtained from cylindrical or spherical charges, and the information provided in the various design manuals would not apply.

3.2 Structural Response and Material Behavior

Close-in HE detonations and certain nuclear loads may cause structural failures controlled by material properties or by direct shear. At present the understanding of these phenomena is incomplete. The same is true for possible coupled structural responses (e.g., direct shear, flexure and in-plane forces). One must achieve a better understanding of complicated structural dynamic behavior that would lead to improved design methods.

Closed-form solutions for structural response are limited to simple geometries, simple loading and support conditions, and linear materials. Obviously, one might have to resort to explosive tests. However, there is a basic difference between many of the explosive tests and precision tests in a laboratory. Data from typical explosive devices may not provide accurate information for protective architecture considerations. Consequently, it is anticipated that numerical simulations could be used more frequently instead of some experiments. However, data from precision tests are needed for the calibration and validation of the various computer codes. The combination of experiments with continuum mechanics theories to clarify behavior, damage, and transitions between response modes are also urgently needed. There is also a need to obtain constitutive relations for various materials up to very high pressure levels, and to define and better explain strain rate effects. So far, there is confidence in scaled tests (structural concrete systems) as long as real materials can be used; however, it is not clear if smaller scaled tests on typical construction materials (e.g., reinforced concrete) can be justified. When scaled tests are to be performed, more than one scale should be used in order to verify proper behavior, and to account for size effects. Furthermore, there are serious questions about using scaling laws to study breaching and other severe structural responses. Recent studies showed that size effects are coupled with loading rate effects to significantly influence material behavior, and these findings need to be incorporated into advanced computational tools and design recommendations.

4. POLITICAL STRATETAGE NEEDS AND POSSIBLE SOLUTIONS

In light of the known threat environments, previous recommendations must be modified to address both the protection requirements faced by society, including land-, sea-, and air-based systems and facilities, as well as the protection of civilian populations, as follows:

- Expand current defense programs of both short- and long-term research on relevant threat protection.
- Adapt existing technology developed for military use and disseminate it to civilian design professionals through professional organizations and academic curriculums.

- Establish both national and multinational government-academic-industry partnerships whose purpose is to enhance and facilitate the development and implementation of such technologies.

Clearly, a comprehensive approach is required for developing protective technologies, design standards for new construction, guidelines for hardening of facilities and other structural systems. Furthermore, for the approach to be fully comprehensive, it is critical that an effective government-academic-industry partnership is developed to provide an institutional network to foster R&D, training, and technology transfer. Consistent with these recommendations, an integrated and multinational systems approach should be explored seriously. A possible approach is expected to involve a sequence of complementary activities, from basic research through implementation. Such activities should be conducted internationally through national centers for protective technology research and development (NCPTR&D). These centers will direct, coordinate, and be supported by collaborative government, academic, and industry consortia who will perform various parts of the activities mentioned above. National academic support consortia (NASC) should be established to engage in this critical effort through both research and education activities. These NASCs will identify and mobilize faculty members from universities with appropriate scientific and technical capabilities, and lead some of the required R&D.

4. EDUCATION, TRAINING, AND TECHNOLOGY TRANSFER NEEDS

As technology is developed, it transitions to test and evaluation, which determines if the technology is applicable for a given application. After several iterations, such technology is transferred to operational testing for its evaluation under realistic conditions. Upon completion of this evaluation phase, acquisition and operational training occurs. Training for known threats relies on a predetermined course of action. Some adversarial actions might be anticipated and counter measures could be practiced during training. Nevertheless, in various instances, criticism was noted for not anticipating threat evolution and not training for it. This is also a shortcoming of conventional training for first responders; they are trained to respond to the known conditions, and may not be able to respond adequately under different conditions. This must be corrected by educating personnel to understand the possible threats, and the ability of available technology to deal with them. The appropriate people should be able to modify their actions to address such threats intelligently, and hopefully develop preemptive measures. This structured approach does not exist yet in the general field of protection from weapons of mass destruction (WMD). Furthermore, military solutions are often incompatible with civilian modes of operation, and they could also be either too rigid or too expensive to implement in nonmilitary organizations.

Leaving this process to commercial vendors could be another option, but quality controls and costs for commercial technology are frequently controversial. Further, the time available for the training of the appropriate persons (e.g., engineers, security specialists, emergency and rescue operations staff, etc.) is limited, compared to that of military personnel. Appropriate government agencies are expected to address these issues through collaboration with industry and academic institutions, and with other government agencies. Universities will have to be involved more than in merely basic research. They will also have to play an integral role as think tanks, and in transferring the developed knowledge and technology to the end-users. Within many government agencies and their supporting industrial organizations, there is a critical need to attract and/or develop employees with experience in protective science and technology, as the current workforce ages and reaches retirement age. Since the mid-1980s, a gradual decline has taken place in academic protective technology related R&D activities, along with the involvement of academicians in these R&D efforts. As a result, very few eminent academicians in this field are still available in the U.S. Except for the University of Florida that has an academic program and a graduate level certificate dedicated to protective science and technology, no comparable formal engineering training exists at other U.S. universities. The situation is similar in most other developed countries. Therefore, establishing government-academic-industry consortia in various countries, with a mandate to develop new and cost-effective protective technologies, and train current and future engineers and scientists, should be seriously considered.

The University of Florida in the USA has recognized this challenge, and has embarked on an effort to remedy it. The Center for Infrastructure Protection and Physical Security (CIPPS) is heavily involved in R&D on such topics, and they have established a series of five graduate level courses that provide comprehensive training on a broad range of related topics, as follows:

- Introduction to Protective Structures (required of all participants)
- Advanced Protective Structures
- Retrofit Methods for Protective Structures
- Applied Protective Technology
- Impact Engineering

Besides these courses, the Civil and Coastal Engineering (CCE) Department, an academic unit of the Engineering School of Sustainable Infrastructure and Environment (ESSIE), has related activities on protecting from natural disasters (hurricanes, tornadoes, and earthquakes) that enables the research teams to work within a Multi-Hazard Protection framework. Furthermore, CIPPS has established a Critical Infrastructure Protection Certificate (CIPC) program for graduate students with interests in the area of protecting the Nation's critical infrastructure systems against blast, shock, and impact incidents. This is a 9-credit program, compatible with the decision by the College of Engineering (COE) to select the area of security and critical infrastructure protection as one of its focus areas. This Certificate program was formulated to meet the education needs of a diverse group of students, while working within the current CCE curriculum to optimize the delivery of education and faculty resources. Participants in the Critical Infrastructure Protection Certificate program can select three courses from the five courses, but most students involved in related R&D activities take all five courses. The Certificate is awarded to participants upon the completion of their graduate degree studies.

5. RECOMMENDATIONS

Although current design procedures give guidelines on how to enhance the breaching resistance of a facility, it could be impractical to protect against breaching and direct shear effects by conventional means. Alternative construction and/or reinforcement details should be permitted for cases in which reinforcement lacing would be required (lacing of reinforcement is similar to textile weaving). The use of various materials and combinations of materials (e.g., high-strength or ultra high performance concretes, possibly in combination with conventional and/or fiber reinforcement and damage absorption devices) should be studied, and future design guidelines should address such options.

Also, guidelines and recommendations should be provided on how to evaluate future capacity of previously loaded structures before and/or after renovation.

Recent studies showed that current design procedures may not be adequate for connections or plastic hinge regions for both structural concrete and steel, and raise questions about recommendations for both flexural and shear resistance models in slabs. Concepts for changing the essential quantities for dynamic resistance include mass and strength increases, modification of support conditions, span length changes , replacement of inadequate components, and loaded area reduction.

Additionally, retrofit effects on blast, ballistic, and forced-entry resistance should be addressed to include analysis techniques for predicting retrofit requirements, retrofit materials and how they should be used, forced-entry resistance retrofits, and the corresponding anticipated costs and benefits.

Although considerable attention was given to the behavior of subsystems that are typically found in hardened facilities subjected to nuclear effects (generators, air-, water-, and fuel-supply equipment, communication and computer equipment, etc.), there is no comparable source of information related to conventional weapons effects. Nevertheless, but one may use data from related studies for such purposes. The important findings indicate that most mechanical or electromechanical types of equipment are sufficiently rugged to survive the anticipated in-structure shock environments. Problems were encountered primarily with faulty wire installations or with inadequate attachment procedures for the structure. Although shock isolation is quite feasible, it was noticed that certain shock isolation devices may not provide the expected protection.

When approximate, simplified methods are used, one must assume a response mode and the corresponding response parameters. It is recommended to use such methods together with data from computer codes that are based on current design manuals. Current medium-structure interaction models are too simplistic, and they may not include nonlinear effects. To accommodate a practical range of numerical capabilities, simple, intermediate, and advanced computer codes are needed. Advanced numerical methods require significant resources, and they should be used in the final stages of detailed structural analyses for obtaining design guidelines, and/or in the detailed evaluation of the anticipated structural response. Furthermore, such advanced codes must be validated against precision test data before their application to a project to insure their reliability. It has been shown that developing effective code validation methodologies is very important, and that the best results are obtained when a structure is analyzed with a range of numerical approaches. The combined effects of material properties, loads, support conditions, and structural detailing are understood, at least empirically, and this state of knowledge is reflected in the current design codes.

The current quasi-static design approaches for structural damage assessment are reasonable for implementation. However, the application of traditional and simple pressure-impulse (P-I) diagrams should be re-evaluated, and the transition between different behavioral modes should be better defined. User-friendly and physics-based, single-degree-of-freedom (SDOF) codes that include various structural response capabilities should be developed and incorporated into the design process. Design activities should be supported by review of existing data, analysis, and testing, and design methods should be re-evaluated to include more precise criteria.

Unlike many current procedures, all designs should be based on acceptable design criteria that include the following: construction ability, performance, maintenance, and repair requirements for the facility under consideration. Guidelines on construction aspects and cost control should be provided. Robustness and response levels should be related to the facility's contents and its mission requirements (for civilian facilities, the mission requirement parameters would be changed to address considerations of safety). It is also desirable to introduce cost/benefit criteria for various design options. Designers should be guided with respect to design tradeoffs, but the design process should be well defined.

The following list of recommended long-term research activities has been developed:

- Protection methodology, threat and risk assessment, its mitigation and resource allocation.
- Threat and loading environment definition.
- Materials' behavior under single and combined loading environments.
- Both simple and advanced computational capabilities.
- Study the behavior and performance of building enclosures.
- Building and structural science behavior and performance.
- Facility and system behavior under combined WMD environments.
- Address multi facility conditions (e.g., installations, cities, etc.).
- Pre- and post-incident facility assessment.
- Environmental effects on all the above cases (e.g., very cold or very hot climates).
- Technology transfer, education, and training
- Use the knowledge gained from the recommended R&D efforts to establish multi hazard protection design approaches for facilities subjected to abnormal loading

conditions.

These R&D activities are needed to develop much more effective solutions to problems that can be currently addressed only with empirical and conservative approaches. The investment in the proposed approach will enable both very meaningful technological enhancements, and large cost savings in providing the required protection to society. Furthermore, these cost savings are estimated to be far larger than the cost of the recommended R&D.

6. CONCLUSIONS

This paper was focused primarily on addressing scientific and engineering issues to provide additional background on related capabilities in protective science and technology, and recommendation for long-term R&D in this critical area. The recommended activities can be conducted over the next three to five years, and they should be supplemented with follow up R&D activities for the foreseeable future. We must develop much more effective solutions to problems that can be currently addressed mainly with conservative and/or empirical approaches. Also, we must develop a competent scientific and technical human resource pool through effective education, training, and technology transfer. The anticipated contributions will have profound effects on critical national and international defense and security.