AMPTIAC

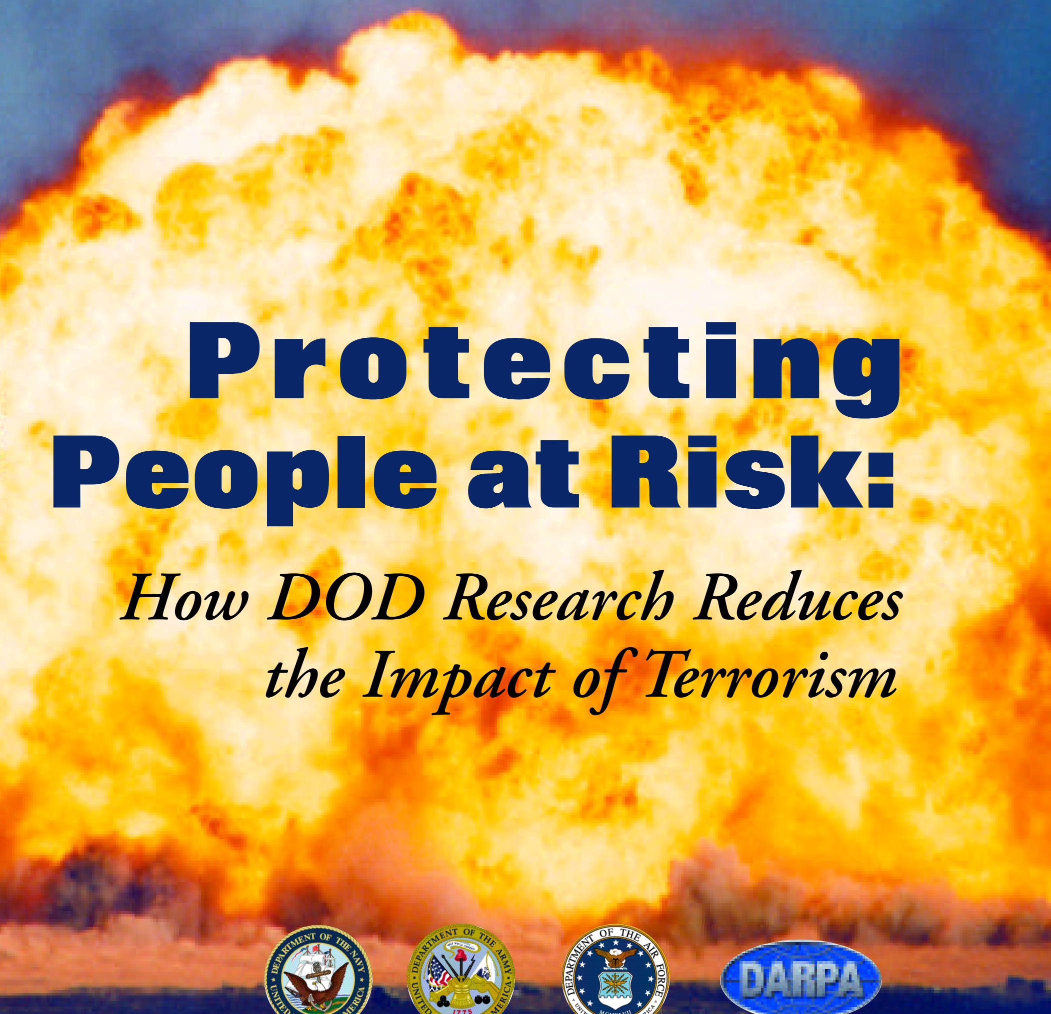
QUARTERLY

Volume 6, Number 4

Special Issue:

Protecting People at Risk:

How DOD Research Reduces the Impact of Terrorism



AMPTIAC is a DOD Information Analysis Center Administered by the Defense Information Systems Agency, Defense Technical Information Center and Operated by Alion Science and Technology

A few months ago, while watching one of the many television documentaries detailing the demise of the World Trade Center, I was struck by how the seemingly innocuous decisions of a structural engineer can have drastic ramifications. All types of engineers are often faced with difficult choices during their work. Factors such as cost, weight, strength, reliability, and ease of fabrication have to be weighed, balanced, and optimized in such a way as to meet production goals. It is these design parameters that establish baselines for our work, and guide us each and every day.

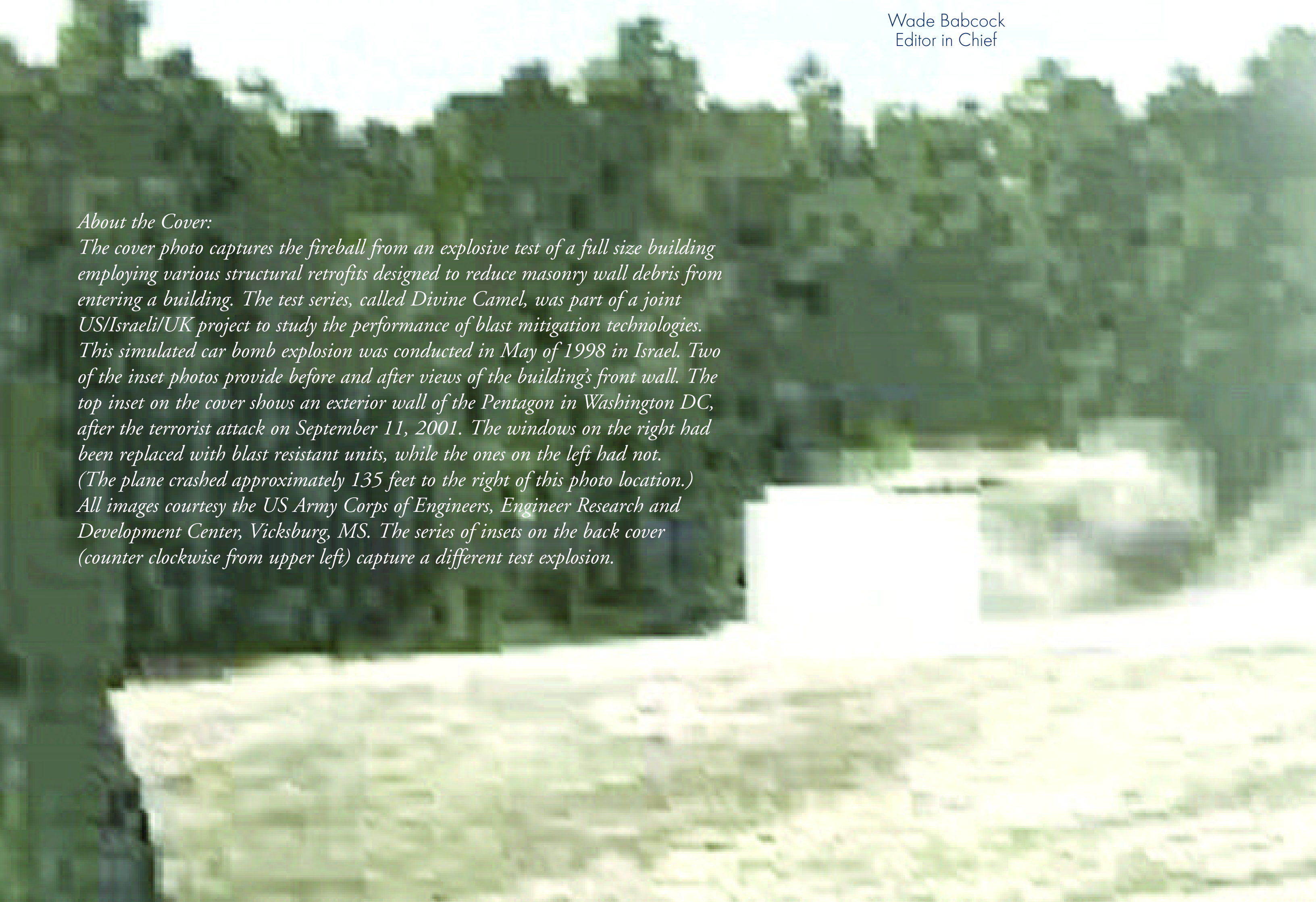
Editorial: Serious Ramifications for Otherwise Innocuous Decisions

In the case of the World Trade Center, the decision to use spray-on fire insulation addressed all the fire safety parameters designers and engineers had set forth. A study by the Federal Emergency Management Agency and the American Society of Civil Engineers released this year revealed that the spray-on insulation would later prove to be a flaw in the building's resilience. The insulation had spalled-off of structural members due to time, adhesion failure, maintenance, and most critically, due to the flying debris from the crashing aircraft. The building was able to handle two separate events: its structure was tough enough to survive the impact of an aircraft, and the spray-on insulation was designed to protect the structural steel from the heat of a fire. But when the two were combined on September 11th, the steel was left unprotected in the subsequent fire. The towers, which were designed to stand for at least four hours in the event of catastrophic fire, fell in less than 100 minutes. Thus a decision made more than 30 years ago, which was correct by every engineering standard and design practice of the time, was proven inadequate in this unimaginable incident.

All things in life teach us something and some of our greatest lessons come from tragedy. The majority of our decisions will not carry the weight of a single human life, much less those of thousands. But when designers of government, civilian, and military buildings put pen to paper today, they are taking human lives in their hands. Events of the last ten years have shown that all buildings, from the most prominent to the very mundane, are exposed to sophisticated threats.

Within this issue of the *AMPTIAC Quarterly*, we have brought together some of the Defense community's most respected researchers and practitioners of structural protection. They describe the resources and methods that save lives. I encourage everyone picking up this issue to consider the larger picture that it paints: the subtleties, the strengths, the structural and operational techniques that serve to protect us everyday. Perhaps also you will find application for some of these resources in your own work.

Wade Babcock
Editor in Chief



About the Cover:
The cover photo captures the fireball from an explosive test of a full size building employing various structural retrofits designed to reduce masonry wall debris from entering a building. The test series, called Divine Camel, was part of a joint US/Israeli/UK project to study the performance of blast mitigation technologies. This simulated car bomb explosion was conducted in May of 1998 in Israel. Two of the inset photos provide before and after views of the building's front wall. The top inset on the cover shows an exterior wall of the Pentagon in Washington DC, after the terrorist attack on September 11, 2001. The windows on the right had been replaced with blast resistant units, while the ones on the left had not. (The plane crashed approximately 135 feet to the right of this photo location.) All images courtesy the US Army Corps of Engineers, Engineer Research and Development Center, Vicksburg, MS. The series of insets on the back cover (counter clockwise from upper left) capture a different test explosion.

Issue focus:
How DOD Research Protects People and Buildings

CLARIFICATION: The cover story for our last issue described the Army's exciting Mobile Parts Hospital project. Within that article, a technology called Laser Engineered Net Shaping™ was presented which can fabricate replacement parts using a combination of computational design templates, a computer-controlled laser, and powder metallurgy. Laser Engineering Net Shaping™ and the LENS® acronym are registered trademarks and service marks of Sandia National Laboratories and Sandia Corporation.

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US Government Initiatives Reduce Terrorist Threat to Personnel and Structures

Wade Babcock and David Rose
AMPTIAC
Rome, NY

INTRODUCTION

One important consideration when enhancing the capabilities of the US and its allies in the War on Terrorism is the ability to rapidly develop and apply technology to meet the challenges posed by terrorists. The Technical Support Working Group (TSWG) is the US Government's focused response to this problem, and acts to coordinate the efforts of multiple departments and agencies to maximize our investment in combating terrorism. *(Please see the TSWG sidebar on page 8 for more details.)* Within the Department of Defense (DOD), the Defense Threat Reduction Agency (DTRA) takes the lead in reducing the threat of weapons of mass destruction; both in preventing their spread and use, as well as reducing the impact of their effects if they are used.

DTRA also provides operational and analytical support for nuclear stockpile stewardship duties and technical support for nuclear weapons in Defense Department custody. In addition it focuses DOD efforts to prepare for, and respond to chemical or biological attacks on US or friendly forces, including overseeing the development and implementation of special weapons technologies. These technologies provide US military commanders options for effective targeting against underground or hardened structures and enhanced capabilities to assess battle damage. The agency also implements on-site arms control inspection, escort and monitoring activities, and develops treaty verification monitoring technologies.

The main DOD thrust to develop protective technologies which protect people in buildings from terrorist bomb attacks is sponsored by the TSWG and managed DTRA. The program seeks to develop blast mitigation techniques for both retrofitting existing buildings and designing new ones. Many of these techniques are covered elsewhere in this Special Issue. While these methods and solutions have direct application to our military forces, they can also be applied to federal and commercial buildings, both domestic and abroad.

The various Government-sponsored blast mitigation projects have many goals, one of which is developing a much better understanding of vulnerability and survivability of buildings and their occupants. This involves a multi-pronged approach of characterizing blast effects, quantifying structural response, and classifying human injuries due to those factors. These are accomplished through various means, including evaluation of existing buildings, experimentation with test structures under controlled explosive events, and computational modeling. A key analytical tool to understand structural damage and injuries is to study terrorist events such as the Khobar Towers bombing in Saudi Arabia (See Figure 1) and the attack on the Murrah Federal building in Oklahoma City. Much of this work results in design guidance, which is incorporated into DOD documents for both new construction and retrofits to existing structures. Some of the most notable examples include the Pentagon in Virginia and the Ronald Reagan Building and International Trade Center in Washington, DC.

THE ORIGINS OF, AND POLICIES REGARDING, BLAST MITIGATION

The actual process of protecting people from blast effects is more a balancing act of money vs. protection, than it is of developing technology. "There are no real technology issues that can't be worked out," said Mr. Douglas Sunshine, the Program Manager at DTRA running many of the blast mitigation research efforts under DTRA and TSWG. "Most often, it's about money," he said, and balancing the need for protection with its cost, by using the various tools that structural engineers have available to them, like standoff and hardening.

In the mid-70's there was a string of Embassy bombings, encouraging Government planners to place more emphasis on structural protection. Then, the October 1983 bombing of the Marine Barracks in Beruit put a sharp point on all US efforts to protect its personnel both at home and abroad. Mr. David Coltharp, Technical Director for the Joint Antiterrorist/Force Protection Research program of the US Army Corps of Engineers' Engineer Research and Development Center (USACE/ERDC) in Vicksburg, MS said that this event truly marked the beginning of a whole new thrust within the Government to address structural protection. "The [USACE] Protective Design Center was stood-up at the Corps of Engineers' Omaha District and initial drafts of the security engineering manual were published. The State Department got involved, and stringent guidelines for new embassies were produced in the following ten years."

But protection of DOD facilities from terrorists was still not

Figure1. **Terrorists Killed 19 US Servicemen in the Khobar Towers Bombing.**

a pressing issue, until the Khobar Towers bombing in June of 1996. In this instance, 19 US servicemen were killed when terrorists detonated a tanker truck containing an estimated 15,000 pounds of plastic explosive at a US military complex in Saudi Arabia. (See Figures 1 & 2) The event highlighted the vulnerability of military targets to the terrorist threat. Dr. Robert Hall, Chief of the Geosciences and Structures Division of the Geotechnical and Structures Laboratory at ERDC said, "This was where the lack of antiterrorism standards (for military installations) was made clear." Prior to the Khobar Towers incident, military installations were thought to be fairly safe from terrorist actions, due to security perimeters, vehicle and personnel entry screening, and any number of other measures employed at specific locations. Coltharp explained that the responsibility of protecting troops was contained in the established chain of command for a particular location. "Commander[s] would protect [their] troops, along with [their] other tasks and responsibilities."

In the mid-nineties, guidelines and standards for DOD installations were established to counter the terrorist threat. Hall said the key at any site is to "balance security and strengthening." Providing stand-off from a potential threat is much less expensive and intrusive than thick concrete walls and bullet proof glass. But where stand-off is not available, the structure must be hardened to the assumed threat, he said. Coltharp added, "The antiterrorist construction standards address balancing these factors. Where stand-off is available, it is used. Where urban settings limit stand-off, hardening is employed. Base commanders now have other tools available to them, as well as guidance from the chain of command." The Joint Antiterrorism/Force Protection (JAT/FP) program Hall said, "provides a web-based site to train a commander on protection techniques. This gives commanders better tools, so that they can make the best decisions," he added.

There is, however, a strong need to balance available funding with eventual safety. Since the late 80's, antiterrorism has been identified in budgeting, and is a critical feature of new construction projects. Existing buildings are being prioritized for blast mitigation retrofits, or retrofits are being incorporated into major renovations. Sometimes the retrofits are as simple as choosing a blast resistant window during a scheduled window replacement in a building, but often these decisions are much more complex. Coltharp points out that for new construction, the added cost of most structural protection measures will often be less than 5% of the total cost, and the cost of protection can be much lower if careful site planning is employed. Additionally, Sunshine said that beyond meeting the safety criteria, engineers also have to balance hardening measures, cost, and in particular, aesthetics. "It turns out that [protection solutions] have to look good also," he said.

THE ROLE OF DTRA AND THE TSWG CONNECTION

DTRA places most of its emphasis on DOD issues like weapons of mass destruction, dismantling nuclear arsenals in the former Soviet States, and force protection. Within the area of force protection, DTRA sponsors work in all three services including ERDC, the Protective Design Center, the Naval Facilities Engineering Service Center at Port Hueneme, CA, and the Air Force Research Lab/Materials and Manufacturing Directorate at Tyndall AFB, FL. Many of these projects are featured elsewhere in this Special Issue of the *AMPTIAC Quarterly*. The two key areas that Sunshine directs research in are the methodologies to do structural assessments, and the eventual solutions to protect the structures. The results of these research efforts are then transitioned to Government agencies and industry. Often this work is conducted very closely with industry, as in the case of window systems.

Sunshine is also DTRA's representative to the TSWG, which

Figure 2. The Khobar Towers Truck Bomb Left a Crater More Than 15 Feet Deep.

has a mandate as a requirements-driven, multi-agency working group, and relies on experts in particular fields. This assures that in addition to the more fundamental research projects that it directs, there are plenty of avenues to solve members' problems. Sunshine says that often agencies come to him with specific questions about structural/force protection. In one case, a specific type of building common on many foreign US Government installations was under scrutiny for what type of hardening measures it would require. About $500,000 was spent looking at the issue and recommendations were made. The agency later said that the research investment resulted in a cost savings of $10-15 Million. "Results from the research program not only increase the protection of people in buildings, but save significant amounts of money," said Sunshine.

FUTURE DIRECTIONS FOR BLAST MITIGATION RESEARCH

So, what does the future hold? Hall and Coltharp agree that there are a number of critical issues facing the Government. First is placing facilities in campus-like settings, instead of downtown locations. Next is dealing with leased buildings that the government utilizes, and how that impacts local businesses, landlords, and other tenants who currently share space in a building with the government. These local impacts are often very difficult to fully characterize. In some cases it is simply a matter of commercial entities who share building space with the Government, and are therefore put at risk. In other cases, the effect is economic. For instance, leased floor space vacated by the Government can dramatically hurt landlords, as well as support businesses like restaurants, services and local vendors in the area.

Sunshine pointed out that the vast majority of blast mitigation research has been conducted on reinforced concrete and masonry buildings. There are many existing and planned buildings which utilize steel, therefore a lot of attention will be paid to steel frame structures in the near future, he said.

One of the most critical issues facing the military in general and the Government in particular is the patience of terrorists. Coltharp says that the enemy "is devious and patient. He attacks the 'soft spot,' and he doesn't really care where that spot is. If we secure the military base, he targets the Federal building. If we harden that, then he targets the Post Office, or the school." Coltharp adds that placing the emphasis for structural protection on many more types and classes of buildings that have rarely been considered as likely targets before will be one of the most critical issues facing us in the future, and one of the most expensive. Hall points out that while ERDC and similar DOD labs have well-defined roles in military force and infrastructure protection, their role in Homeland Security is still very much in flux. "We are still figuring that out," he said.

CONCLUSION

Protecting people from the threat of terrorism is one of the most challenging problems we currently face. While our response to the threat is still taking shape, agencies and groups like DTRA and TSWG are leading the fight. The research into blast mitigation, including structural hardening, structural retrofits, and site planning, obviously has importance to DOD, but is also critical in domestic preparedness measures. Much of this technology may be transitioned directly to many types of structures in all parts of the United States and around the world.

The Army, Navy, and Air Force are actively involved in developing the tools and technologies needed to harden buildings. They maintain close coordination between research activities that are developing novel approaches to employ materials in ways never envisioned when the materials were first developed. This Special Issue highlights how newer materials, such as polymers or composites, can be used in buildings to help protect them and their inhabitants from terrorist bombings.

The TSWG – *Closeup*

This sidebar presents a brief introduction to the Technical Support Working Group, or TSWG. Many government agencies participate in it and form the core of the US's development effort for counterterrorism technologies.

THE TECHNICAL SUPPORT WORKING GROUP (TSWG)

The April 1982, National Security Decision Directive (NSDD) 30 assigned responsibility for the development of overall US policy on terrorism to the Interdepartmental Working Group on Terrorism (IG/T) chaired by the Department of State (DOS). The TSWG was an original subgroup of the IG/T, which later became the Interagency Working Group on Counterterrorism. In its February 1986 report, a cabinet level Task Force on Counterterrorism led by then Vice-President George H.W. Bush cited the TSWG as assuring "the development of appropriate counterterrorism technological efforts."

Today, TSWG still performs that counterterrorism technology development function as a stand-alone interagency working group. TSWG's mission is to conduct the national interagency research and development (R&D) program for combating terrorism requirements. It also has commenced efforts to conduct and influence longer-term R&D initiatives and, reflecting the shift to a more offensive strategy, balance its technology and capability development efforts among the four pillars of combating terrorism: intelligence support, counterterrorism, antiterrorism, and consequence management.

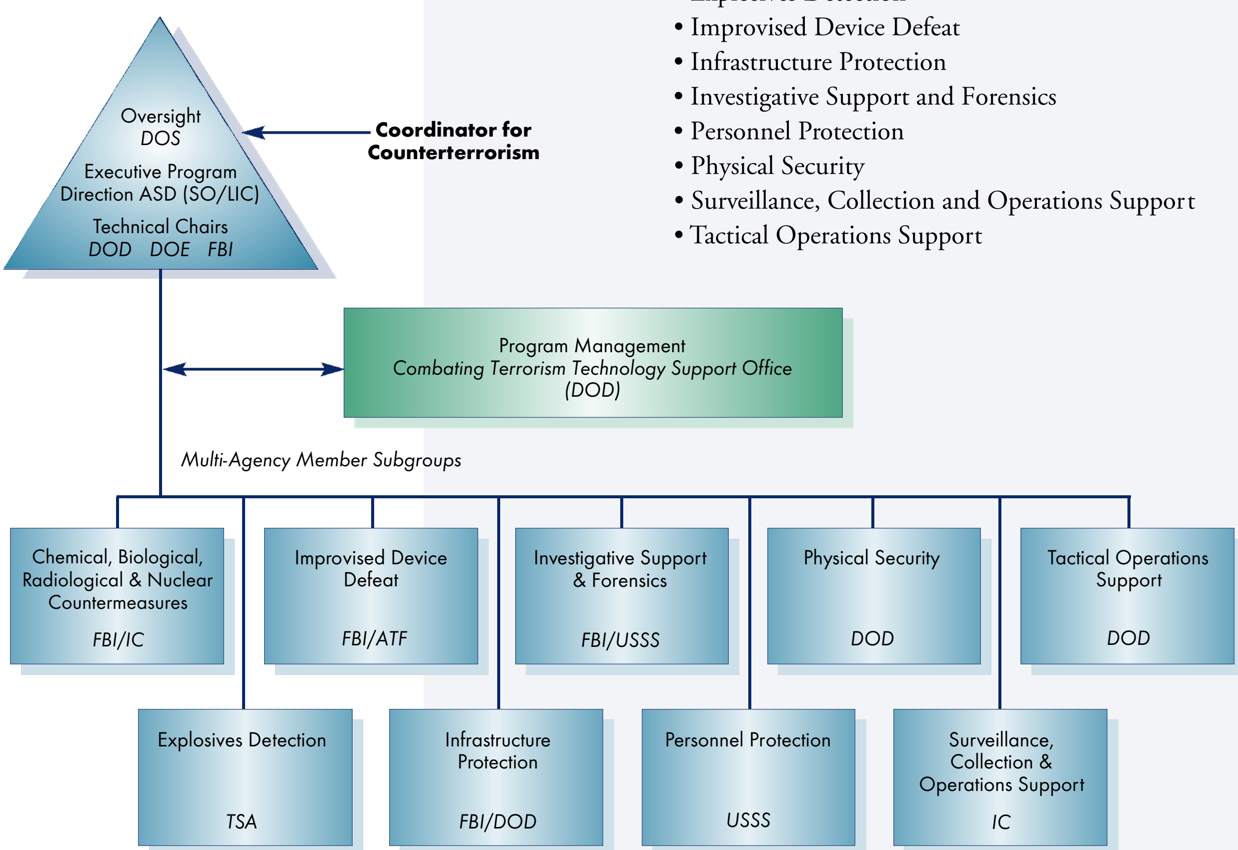
Structure

TSWG operates under the policy oversight of the Department of State's Coordinator for Counterterrorism, and the management and technical oversight of the DOD Assistant Secretary of Defense for Special Operations and Low-Intensity Conflict (ASD (SO/LIC)). Participation is open to all federal departments and agencies, and current membership includes representatives from over eighty organizations across the Federal Government. While the TSWG's core funds are derived principally from DOD's Combating Terrorism Technology Support (CTTS) Program, and the DOS, other departments and agencies contribute additional funding. They also provide personnel to act as project managers and technical advisors. TSWG conducts cooperative R&D with the United Kingdom, Canada, and Israel through separate bilateral agreements.

Member departments and agencies work together by participating in one or more TSWG subgroups. The nine subgroups, each focusing on a specific area of technology, are as follows:

- Chemical, Biological, Radiological and Nuclear Countermeasures
- Explosives Detection
- Improvised Device Defeat
- Infrastructure Protection
- Investigative Support and Forensics
- Personnel Protection
- Physical Security
- Surveillance, Collection and Operations Support
- Tactical Operations Support

TSWG Organization



RELEVANT PROGRAM AREAS

One can see that the mission of TSWG crosses many technical areas and scientific disciplines. The areas of most relevance to the structural protection community are presented below in more detail. More information on the complete activities of TSWG may be found at www.tswg.gov.

Infrastructure Protection

The Infrastructure Protection (IP) Subgroup's mission is to identify, prioritize, and execute research and development projects that satisfy interagency requirements for the protection and assurance of critical Government, public, and private infrastructure systems required to maintain the national and economic security of the United States. These critical systems include control systems for electric power, natural gas, petroleum products, and water; telephone, radio, and television communications systems; ground, rail, and air transportation facilities; and cyber communications networks.

Physical Security

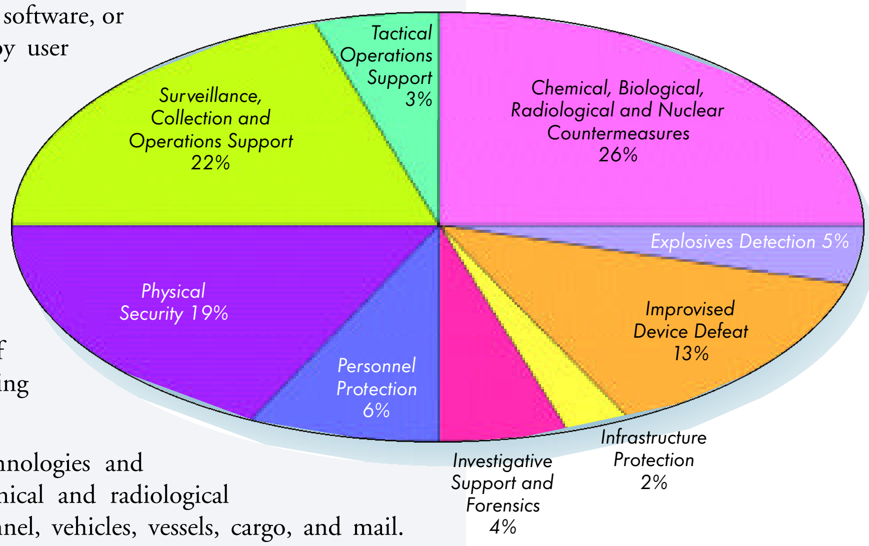
The Physical Security (PS) subgroup identifies the physical security requirements of federal agencies, both within the United States and abroad, and then develops the technology to protect their personnel and property from terrorist attack. The technology is developed by creating prototype hardware, software, or systems for technical and operational evaluation by user agencies.

Focus Areas The PS Subgroup focus areas reflect the prioritized requirements of the physical protection community. The following are some of the topics explored in FY 2002:

- Blast Mitigation - Develop building construction and retrofit techniques that better protect people and facilities from the two main causes of injuries resulting from terrorist bomb blasts - flying debris and structural collapse.
- Entry Point Screening - Develop multiple technologies and techniques to detect explosives, weapons, chemical and radiological material, and other contraband on or in personnel, vehicles, vessels, cargo, and mail. Solutions will increase the detection rate, throughput, and safety while reducing the number of security forces required to perform the screening process.
- Perimeter Protection - Develop advanced perimeter intrusion detection and surveillance systems that have a higher probability of detection, a lower false alarm rate, and the ability to operate continuously in demanding operational environments. These systems will provide security forces with improved early warning and response capabilities on land and at sea.

(Compiled from US Government-supplied information.)

TSWG FY 2002 Program Funding



Example TSWG Projects

COMPLETED

Structural Retrofit Methods

Retrofit design concepts and guidelines for strengthening existing reinforced concrete buildings against terrorist bomb attacks were developed. Retrofit techniques, such as spray-on polymers and composite wraps for structural columns have been evaluated and design guidance written. These techniques have been used to upgrade embassies and military facilities.

Quick Reaction Perimeter Intrusion Detection Sensor (QUPID)

QUPID is an ultra-wide impulse radar system with adjustable range gates that projects a "virtual fence" beyond the perimeter to detect intruders at distances up to 100 meters. TSWG successfully developed two prototype versions of the sensor in FY 2002: the first is compatible with the USAF Tactical Automated Security System and the second works with a commercial intrusion detection system. The Air Force transitioned QUPID into an acquisition program in July 2002 with fielding planned for FY 2003.

Military Mobile Vehicle and Cargo Inspection System (MMVACIS)

MMVACIS, a mobile gamma radiation imaging system, was developed for the inspection of vehicles and cargo. The system provides rapid deployment capability to established bases or with US expeditionary forces. It has been employed by the DOD since Fall 2001, and has been integrated into contraband interdiction and force protection operations.

ONGOING

Blast Effects Estimation Model (BEEM)

BEEM will be a single model capable of estimating the effects of blasts, fragmentation, building damage and personal injury. BEEM will incorporate the best features of two existing models, the Force Protection Tool (FPT) and the Anti-Terrorism Planner (AT-Planner) tool.

Glass Penetration Model

A human injury prediction model based on multi-hit glass penetration is being developed. The model inputs will be window characteristics, blast parameters, and the location of a person relative to the window. The model will output the severity of the injuries to that person. The final product will be a software model that will complement BEEM.

Lightweight Portable Boom and Underwater Sentry System

A lightweight boom, equipped with fiber optic and acoustic sensors to provide standoff detection of intruders for US Navy ships, is being developed. It is designed for easy deployment and redeployment by the ship's crew dockside or at anchor in transit ports. It will provide a temporary legal perimeter barrier as well as surface and subsurface intrusion detection capabilities against attacks by small boats and swimmers. The prototype system will continue developmental testing and evaluation during FY 2003, and will begin operational testing in FY 2004.

Advanced Vehicle Driver Identification System

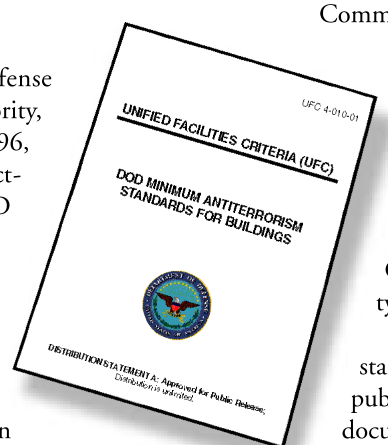
The Advanced Vehicle Driver Identification System (AVIDS) is being developed to expedite the screening process at vehicle entry points by providing force protection personnel with near real-time access to control databases. This modular system allows users to select only those components needed at their facility. AVIDS has been installed at a DOD facility, enabling verification of the occupants of a vehicle in less than three seconds over a secure wireless LAN that covers eighteen square miles and five vehicle entry points. Weigh-in-motion, RF tags, and license plate reader modules were expected to be integrated by the end of 2002, with biometrics modules integrated in 2003.

Protecting Personnel at Risk:

DOD Writes Anti-Terrorism Standards to Protect People in Buildings

Colonel Joel C. Bradshaw III, PE
Chief of Military Construction Programs
Office of Deputy Under Secretary of Defense (Installations and Environment)
The Pentagon, Washington, DC

Editor's Note: *The following article describes the development of and basis for the Department of Defense's antiterrorism and force protection policy. Many of the topics presented here are discussed in much finer detail within other articles in this special issue. We feel Colonel Bradshaw's summarization of the DOD policy builds a framework in which to better understand those research efforts, and thus helps to fill-in the "big picture" of how all the pieces eventually come together.*



UFC 4-010-01

UNIFIED FACILITIES CRITERIA (UFC)

DOD MINIMUM ANTITERRORISM STANDARDS FOR BUILDINGS

DISTRIBUTION STATEMENT A: Approved for Public Release; Distribution is unlimited.

Protecting people in Department of Defense (DOD) buildings has always been a high priority, but after the Khobar Towers terrorist act in 1996, the Department put more emphasis on protecting its people from terrorism. In 1999, DOD published its "Interim Antiterrorism (AT)/Force Protection (FP) Construction Standards." This was the result of a three-month intense effort by a DOD-wide team led by the Office of the Secretary of Defense (OSD) and the US Army Corps of Engineers (USACE) Protective Design Center in Omaha, Nebraska. As a result, buildings on military installations, beginning with Fiscal Year (FY) 2002 Military Construction (MilCon) funding, are now being constructed or renovated with features to protect people in the event of a terrorist attack.

After publication of the "Interim Standards," the DOD team, known as the Security Engineering Working Group, or SEWG, began to write the final standards. This was a collaborative effort of engineers and antiterrorism experts from the Services and Defense Agencies, as well as other government agencies, such as the General Services Administration and the State Department. The SEWG was co-chaired by Colonel Debra Lewis of the Joint Staff J-3 Deputy Directorate for AT/FP and Mr. Curt Betts of the USACE Protective Design Center. (See also Patrick Lindsey's article in this Special Issue.) In addition to USACE, the Navy's and Air Force's engineers were represented by the US Naval Facilities Engineering Command and the US Air Force Civil Engineer Support Agency, respectively. The Office of Deputy Under Secretary of Defense for Installations and Environment is responsible for the AT Building Standards and now co-chairs the SEWG along with USACE. The Assistant Secretary of Defense for Special Operations and Low-Intensity Conflict (SOLIC) has the overall responsibility for antiterrorism policy within DOD.

The SEWG began development of the new standards as soon as the Interim Standards were published. After eighteen months, the final draft document was published in August 2001 for coordination among numerous offices within DOD. More than 400 comments were incorporated into the final version of the standards which were completed in December 2001. The higher-level coordination within OSD took longer than expected because of a decision to publish the standards as a Unified Facilities Criteria (UFC). The new DOD system of UFCs was approved in May 2002, and the AT UFC went out for coordination in June. There was concern within OSD leadership over the rigid requirements for standoff distance and for the applicability of the standards to leased

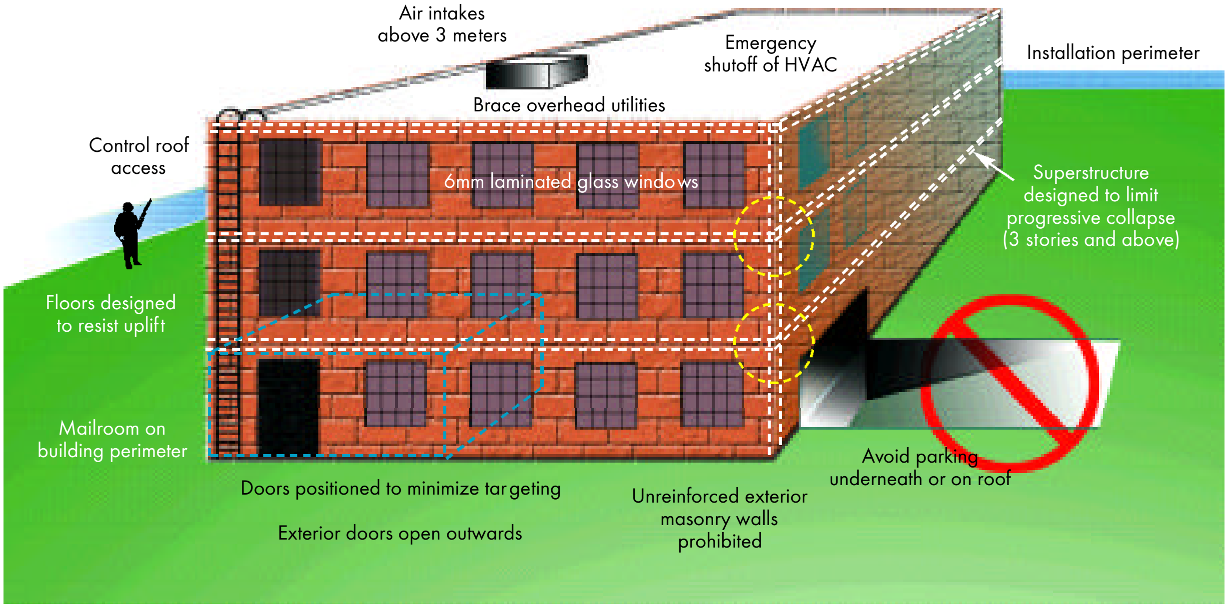


Figure 1. Building Standards.

Table 1. Guiding Principles for Minimum Anti-terrorism Standards.

- Maximize standoff distance
- Prevent building collapse
- Minimize hazardous flying debris
- Limit airborne contamination
- Provide mass notification

Table 2. Building Definitions.

- DOD Building
  - Any building or portion of a building owned, leased, privatized, or otherwise occupied, managed, or controlled by or for DOD
- Inhabited Building
  - Buildings or portions occupied by 11 or more DOD personnel
  - Population density greater than one person per 430 sq ft
- Primary Gathering Building
  - Inhabited buildings occupied by 50 or more DOD personnel
  - Family housing with 13 or more family units per building.
- Billeting
  - Building or portion where 11 or more unaccompanied DOD personnel are routinely housed

facilities. Eventually both issues were resolved; an "effective stand off" requirement was incorporated and it was agreed that DOD personnel in leased facilities should be given the same protection as those in DOD-owned buildings. The effective stand-off requirement enables the minimum stand-off distance to be reduced if the building can be hardened to give an equivalent level of protection. This can result in a much more expensive solution, but it does give an alternative in cases of restrictive land availability. This also encourages development of new technologies for building hardening.

On September 20, 2002, the "DOD Minimum Antiterrorism Standards for Buildings" was published as UFC 4-010-01. This UFC is part of the Whole Building Design Guide (WBDG), which is maintained by the National Institute of Building Sciences (NIBS), and is available to the general public. It can be found on the WBDG web site (www.wbdg.org) or the DOD site (www.acq.osd/ie/irm). Specific AT designs for DOD construction projects will not be releasable to the public.

The new UFC supercedes the Interim Standards, which were used for design of FY2002 and FY2003 MilCon projects. The new criteria however, are applicable to more than just MilCon. In addition to construction projects beginning in FY2004, they also apply to new leases in FY2006 and lease renewals by FY2010. The standards greatly improve the original guidance and ability to enhance protection. They expand to influence all funding sources and investments, and they make it easier to leverage new technology and engineering developments.

Although specific standards may change, the overarching strategy described in the new standards (Table 1) is designed to enhance protection of DOD personnel no matter what threats they may face in the future. The main goal is to increase survival rates in buildings targeted by terrorists, realizing that it would be cost prohibitive to achieve complete protection against all potential threats.

The final AT/FP standards (Figure 1) in the new UFC describe minimum criteria for protecting against terrorist

Table 3. Exemptions to the DOD AT/FP Standards.

- Family housing with 12 units or fewer per building
- Stand alone franchised food operations
- Stand alone shopettes, mini marts, and small commissaries
- Gas stations and car care centers
- Medical transitional structures and spaces
- Transitional structures and spaces occupied less than one year
- Recruiting stations in leased spaces

Table 4. Summary of Design Strategies from UFC 4-010-01.

Standard 1: Minimum Standoff Distance.
Applies to new and existing buildings, when triggered.

Standard 2. Building Separation.
New buildings must be separated to minimize collateral damage.

Standard 3. Unobstructed Space.
Ensure that obstructions within 10 meters (33 feet) of inhabited buildings do not allow for concealment of explosive devices 150 mm (6 inches) or greater in height.

Standard 4. Drive-Up/Drop-Off Areas.
Do not allow drive-through lanes or drive-up/drop-off to be located under any inhabited portion of a building.

Standard 5. Access Roads.
Ensure that access control measures are implemented.

Standard 6. Parking Beneath Buildings or on Rooftops.
No parking underneath or on rooftops.

Standard 7. Progressive Collapse Avoidance.
For all new and existing inhabited buildings of three stories or more, design the superstructure to sustain local damage with the structural system as a whole remaining stable and not being damaged to an extent disproportionate to the original local damage.

Standard 8. Structural Isolation.
Additions to existing buildings must be structurally independent from the adjacent existing building

Standard 9. Building Overhangs.
Avoid building overhangs with inhabited spaces above them where people could gain access to the area underneath the overhang.

Standard 10. Exterior Masonry Walls.
Unreinforced masonry walls are prohibited.

Standard 11. Windows and Glazed Doors.
Use a minimum of 6-mm (1/4-in) nominal laminated glass for all exterior windows and glazed doors. Frames and mullions must be aluminum or steel.

Standard 12. Building Entrance Layout.
The main entrance to a building must not face an installation perimeter or other uncontrolled vantage point.

Standard 13. Exterior Doors.
Ensure that exterior doors into inhabited areas open outward.

Standard 14. Mailrooms.
Locate rooms where mail is delivered or handled, to limit collateral damage.

Standard 15. Roof Access.
Control access to roofs to minimize the possibility of placing explosives or chemical, biological, or radiological agents where they would threaten occupants or infrastructure.

Standard 16. Overhead Mounted Architectural Features.
Ensure that overhead mounted features weighing 14 kilograms (31 pounds) or more are securely mounted.

Standard 17. Air Intakes.
Locate air intakes at least 3 meters (10 feet) above the ground.

Standard 18. Mailroom Ventilation.
Provide separate, dedicated air ventilation systems for mailrooms.

Standard 19. Emergency Air Distribution Shutoff.
Provide an emergency shutoff switch in the HVAC control system.

Standard 20. Utility Distribution and Installation.
Route critical or fragile utilities so they are not on exterior walls or on walls shared with mailrooms.

Standard 21. Equipment Bracing.
Mount overhead utilities and other fixtures weighing 14 kilograms (31 pounds) or more to minimize the likelihood that they will fall and injure building occupants.

Standard 22. Under-Building Access.
Ensure that access to crawl spaces, utility tunnels, and other means of under-building access is controlled.

Standard 23. Mass Notification.
All inhabited buildings must have a timely means to notify occupants of threats and instruct them what to do in response to those threats.

attacks when certain funding thresholds or other identified triggers are met. For example, the standards are applied to new construction or to significant renovation of buildings when the cost estimate exceeds 50% of the building replacement cost. The definitions in Table 2 illustrate other triggers that may invoke use of the standards. Recognizing the standards cannot be applied to every possible type of facility; there are several exemptions (Table 3), such as low-density family housing, franchised food operations, mini marts, gas stations, etc. The standards (Table 4) apply to most facilities, and will not need to be supplemented unless a specific terrorist threat is identified, or when an installation commander sees a need for additional protective measures.

The most cost-effective solution, if land is available, is allowing for a stand-off distance (Figure 2). Minimum standoff distances identified in Table 5 will ensure survivable structures for a wide range of conventionally constructed buildings and expeditionary or temporary structures. These buildings range from tents and wood framed buildings to reinforced concrete buildings. Standoff distances in the "Conventional Construction Standoff Distance" column in Table 5 are based on explosive safety considerations that have been developed as

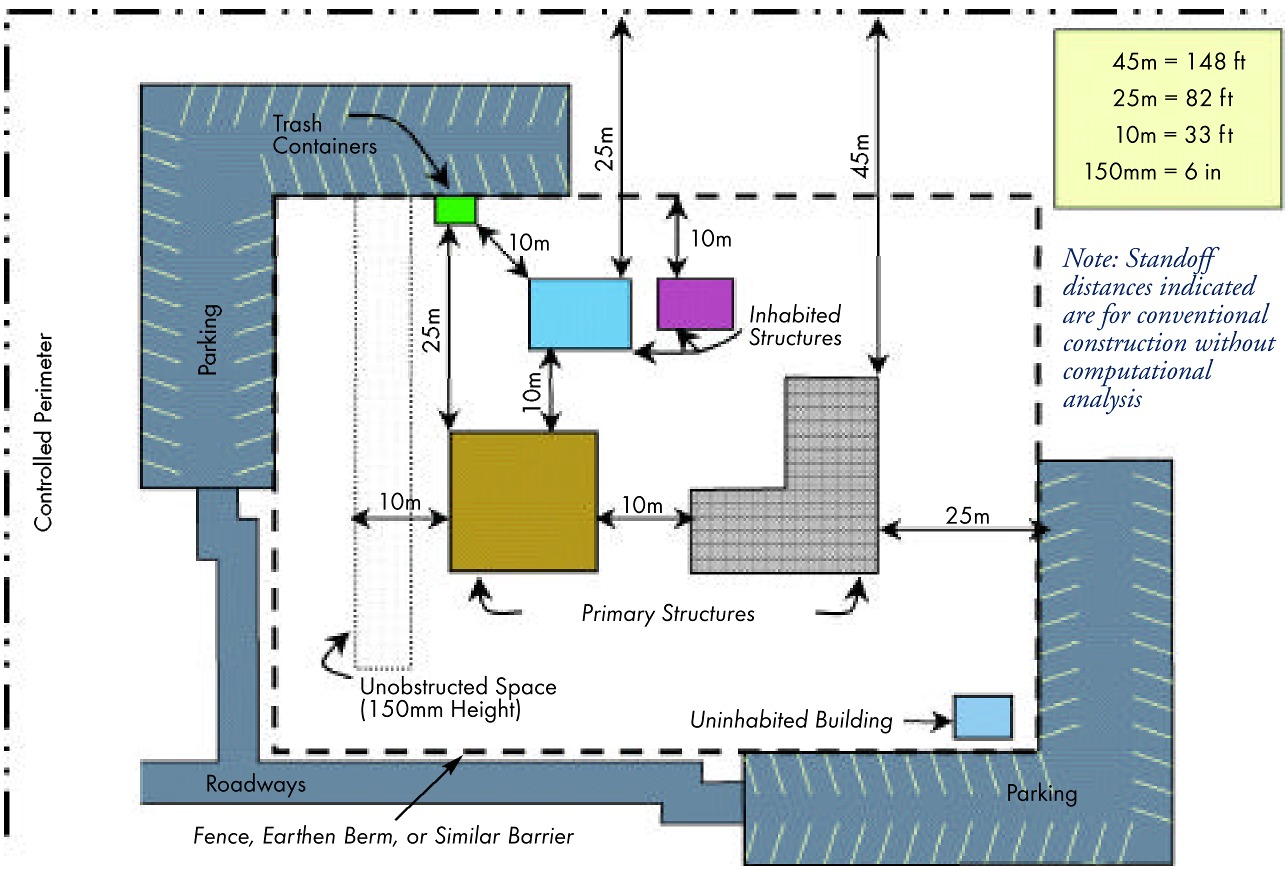


Figure 2. **Standoff Distances and Building Separations – Controlled Perimeter.**

a result of years of experience and testing. Because these distances may be conservative for some construction types, the standards allow for adjustment of standoff distances based on the results of a structural analysis considering the applicable explosive weights. For new buildings, even if such an analysis yields a shorter standoff distance than those shown in Table 5, the minimum specified standoff distance must be used to allow for future upgrades as a result of emerging threats. For existing buildings, lesser standoff distances may be allowed where the required level of protection can be achieved through building hardening or other mitigating construction or retrofit. The standoff distance may also be reduced if analysis proves the existing structure is sufficiently hardened.

Other agencies, such as GSA and the Department of State, have been developing antiterrorism standards for facilities. There are many similar criteria; however, there are several differences. All deal with multiple threats, but to differing degrees, and all include requirements for windows. The biggest point of contention is the issue of standoff distance. DOD has been insistent on standoff as the primary strategy, where others lean toward building hardening and less emphasis on standoff.

Incorporating AT/FP standards into new buildings, where required standoff distances are available, increases construction cost by three to five percent. Costs vary considerably where sufficient standoff is not available or when upgrading existing buildings. Cost increases are generally based on upgraded windows, structural detailing for the prevention of progressive collapse, and modifications of the building interior to minimize hazardous flying debris.

Although the DOD standards have been published, there are still several challenges. One of the biggest challenges is the cost to enhance or relocate from leased facilities. Lack of standoff distance is a big concern, especially on installations overseas where land is not available in many locations and in urban areas where leased facilities are downtown. Installations without standoff distances will rely on other construction techniques or mitigating measures. The issue of leased facilities will have to be resolved by October 2009 for lease renewals, but some of the alternatives may be expensive. Compliance with the standards will be managed by the Services and Defense Agency heads. The ultimate responsibility lies with the Installation Commanders, who must notify senior commanders of noncompliance.

Table 5. Minimum Standoff Distances and Separation for New and Existing Buildings[1].

Location	Building Category	Minimum Standoff Distances or Separation Requirements: Applicable Level of Protection	Standoff Distances For Conventional Construction meters (feet)	Effective Standoff Distances[2] meters (feet)
Controlled Perimeter or Roads & Parking without Controlled Perimeter	Billeting and Primary Gathering Buildings	Low	45 (148)	25 (82)
	Inhabited Buildings	Very Low	25 (82)	10 (33)
Roads & Parking within a Controlled Perimeter	Billeting and Primary Gathering Buildings	Low	25 (82)	10 (33)
	Inhabited Buildings	Very Low	10 (33)	10 (33)
Trash Containers	Billeting and Primary Gathering Buildings	Low	25 (82)	10 (33)
	Inhabited Buildings	Very Low	10 (33)	10 (33)
Building Separation (New Bldgs)	Billeting and Primary Gathering Buildings	Low	10 (33)	No minimum
	Inhabited Buildings	Very Low	No minimum	No minimum

[1] This table is derived from Table B-1, UFC 4-010-01, "DOD Minimum Antiterrorism Standards for Buildings," dated July 31, 2002

[2] Even with analysis, standoff distances less than those in this column are not allowed for new buildings (even when constructed in accordance with AT standards), but are allowed for existing buildings if constructed/retrofitted to provide the required level of protection at the reduced standoff distance.

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DOD Protective Design Manuals Have Wide Application

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INTRODUCTION

Many manuals are available within the DOD to aid engineers in the design of facilities subjected to blast loadings from bombs. Facility design in consideration of exterior blast loadings starts with locating a site that is adequate for the facility and level of protection required. The design basis threat (as defined by the installation master planning team) identifies the weapons, tools and tactics that could be used in an attack against the facility. The site or master planners then review the site plan and the design basis threat to determine if the amount of standoff distance that is available can provide a proper level of protection. The planners will then incorporate the use of controlled and non-controlled perimeters, locate appropriate exclusion or non-exclusion zones, define the standoff distances, and identify facility clear zones. They will also locate the facility's entry control points for vehicles and personnel. Should the site be inadequate for a structure built with standard construction techniques, then blast loadings will need to be accounted for to give the facility the same level of protection at the reduced standoff distance.

BACKGROUND HISTORY OF STANDARDS

Military Hardened Structures Progression

Since the invention of dynamite by Alfred Nobel in 1866, blast effects on structures have been observed. In 1870, Rankine and Hugoniot published their analytical solution to normal shocks in an ideal gas and these relationships have formed the foundation for studying gas dynamics and the interaction of shock waves with structures. It is well known that internal blasts are more damaging than exterior blast effects as the shock and gas pressure combine to act on the structure.

In the last 50 years, the engineering units within the Military developed many mathematical models to capture the structural interaction with blast waves. After World War II, these models started to show development when damage levels for masonry structures were correlated to crater size, crater location, and explosive weights used in bombing runs. Damage level was a measure of the amount of structure remaining based on the blast pressure and impulse the structure experienced from those bombs. From those early days of the 1950's other observations were noted that relate the many blast parameters to scaling laws, thus making it easy for engineers to develop models for predicting categories of damage based on: weight of explosive, range, and type of structure. The 1950's were also the beginning of the nuclear age, and many design ideas were developed during this era. A lot of the bunker mentality commonly associated with explosive effects came from this time period.

Anybody who has handled explosives knows the dangers associated with that endeavor, as many accidents have occurred as a result of their handling. A vast amount of knowledge was acquired from accident investigations of catastrophic events. To protect personnel, a Tri-Service group from the Army, Navy and Air Force was formed to develop a manual to give engineers a procedure that lets them design "Structures to Resist the Effects of Accidental Explosions" (commonly known as technical manual TM 5-1300). The primary purpose of the manual is to present methods for protective construction used in facilities for the development, testing, production, storage, maintenance, modification, inspection, demilitarization, and disposal of explosive materials. This manual was used as the standard for explosive effects for about thirty years. By using this manual, engineers could design structures to resist the effects of blast waves and fragments preventing the propagation of explosive effects from one structure to the next, or to prevent the mass detonation of explosives and provide protection to personnel and valuable equipment. Instrumental to this approach was a well-developed understanding of:

- the blast load parameters
- the response of structures to blast loads
- how to establish proper details for construction to develop the proper structural response
- establishing guidelines for siting explosives facilities.

Technical manual TM 5-855-1, "Fundamentals of Protective Design for Conventional Weapons" also came out of the post-World War II era. While this manual is dedicated to the design of structures to resist conventional weapons, during the 1970's great advances were made in the area of numerical modeling of nuclear weapon effects. These include the effects of dynamic response of aboveground, and belowground structures to air-blast, blast-induced ground shock, cratering, and the response of various materials to these effects. These modeling techniques were then applied to the conventional weapons arena and the manual has been updated several times since its original printing. This manual and TM 5-1300 deal with primarily concrete and steel structures, but not everybody works in those types of structures. Additional work has produced more data on how conventional construction responds to blast loads and that data has been incorporated into the new design guidance.

After the Marine barracks bombing in Beirut, Lebanon in 1983, the DOD looked for a group to develop procedures that could be implemented to prevent this type of incident from recurring. The Army established the Corps of Engineers Protective Design Center to take on this mission and its main purpose was to provide physical security and antiterrorism protection to military assets. The first document created by this group was called the Security Engineering Manual, which became the TM 5-853 series of manuals on security engineering. Much of the blast and fragment technology developed for TM 5-1300 and TM 5-855-1 had direct application to the area of security engineering. Within this series of manuals, aggressors, weapons, tools and explosives are defined to develop a design basis threat against specific assets. With this information protective measures are designed to counter these threats and protect the defined assets.

The physical security portion is that part of security concerned with physical measures designed to safeguard personnel; prevent or delay unauthorized access to equipment, installations, material, and documents; and to safeguard against espionage, damage, and theft. Prior to this period, many of the regulations were not interrelated or tied to design procedures, and at times it was difficult to determine what level of protection was being provided for an asset. This manual brought threats and protective measures together as a security engineering design procedure, balancing the design basis threat against the level of protection.

The antiterrorism aspects of facility design are the defensive measures used to reduce the vulnerability of individuals and property to terrorist attacks and often include a limited response and containment of the aggressor by local military forces, or a response force. Therefore, security engineering is the process of identifying practical, risk-managed short and long-term solutions to reduce and/or mitigate dynamic manmade hazards by integrating multiple factors, including construction, equipment, manpower, and procedures.

Application of DOD Manuals to Antiterrorism

The DOD manuals use the blast analysis and design tools created for the military and apply them to normal or civilian type structures. These are referred to in the security engineering process as conventional construction and include typical building systems including doors, windows, or manufacturers' components, which are not designed to resist tools, weapons, or explosives but are designed to resist common environmental conditions such as gravity, wind, and seismic loads. Two cases present themselves when blast loads are considered: external and internal blasts. While an external blast load is very devastating, it is easier to handle if a standoff distance is available. Standoff is the distance or open space placed between the external surface of the structure and the center of an explosive device. For a known or assumed explosive weight with a given standoff distance, the blast pressure, loading duration, and blast impulse can be calculated using TM 5-855-1, TM 5-1300, or TM 5-853-1 and applied to the facility components for design or evaluation.

Should an internal blast occur, blast shock and gas loadings reverse the normal loading direction of structural components: the compression side of a concrete slab will be put in tension, and vice versa. Normal structures are not designed for this loading condition and the structural system will be more susceptible to failure and collapse. When portions of a structure begin to fail the next step is to minimize the area of failure. If the area of failed members cannot be controlled then progressive collapse occurs. The damage seen in the Murrah Federal Building in Oklahoma City was the result of progressive collapse, as the area of collapse was disproportionate to that of the original area damaged. Another area of consideration when studying blast-loaded structures is the number of openings in the exterior envelope of the building. Doors and windows are typically weak points of the structure and can fail rather dramatically with blast loads. Therefore, many of the DOD standards (as defined by UFC 4-010-01) are being put into place to minimize casualties and damage for critical facilities, as well as to define a baseline level of protection that can be easily upgraded as the level of threat elevates.

Security Engineering Definitions

Controlled Perimeter The controlled perimeter is a physical boundary to control access of vehicles or personnel. Controlled perimeters are used on installation boundaries, or around critical facilities. This boundary must be capable of channeling all vehicles and personnel to a defined access control point (or points), where inspections can occur before entering the controlled area.

Standoff Distance Standoff distance is maintained between a structure or inhabited portion of a structure and the potential location of an explosive detonation. Standoff distance must be increased to reduce the blast effects on the structure. The required standoff distances will vary with building components used in the construction. Blast pressures near an exploding vehicle bomb are very high, but they decrease rapidly with increased standoff distance. Maximizing the standoff distance is the primary design strategy. Maximizing standoff distance also ensures that there is opportunity in the future to upgrade buildings to meet increased threats or to accommodate higher levels of protection.

Level of Protection The level of protection is the degree to which an asset is protected against injury or damage. This would include personnel and equipment. We could define three levels of protection: low, medium, and high. For a low level of protection, the structure would be near collapse, a medium level of protection would result in a damaged but repairable structure, and a high level of protection would cause superficial damage to the structure. Selecting the level of protection means trading-off an acceptable level of risk.

Exclusionary Zones Once the concepts of a controlled perimeter, standoff distance, and level of protection are understood, the application of an exclusionary zone is an easy concept. As shown in Figure 1, a controlled perimeter is established at a distance of d_e, where the structural system can accept a given blast load and provide a given level of protection. Vehicles that are authorized to enter these areas would be limited to those that provide for facility service, maintenance, delivery, disabled parking, etc. To gain access to this zone an entry control point would be used and depending on the mission, it may be manned or operated with an entry control device.

Nonexclusive Zones The next perimeter used in conjunction with an exclusive zone for a higher explosive threat condition is the nonexclusive zone, depicted in Figure 2. At the nonexclusive zone perimeter large trucks could be stopped, inspected, and turned around if necessary, prior to entering the exclusive zone. The intent is to minimize the number and size of vehicles that can park relatively close to the facility. Typically only automobiles would enter the exclusive zone. However, larger vehicles could enter after being searched. Therefore, entry to this area is through a continuously manned entry control point. The nonexclusive zone is useful when the primary type of vehicle entering the exclusive zone of the facility is an automobile.

Clear Zones A clear zone is used around facilities when a smaller hand delivered device can be placed close to the facility exterior. In order to aid in vision detection of such devices an obstacle free area can be provided around the facility. This allows for the direct observation of small packages that are within 30 feet of the exterior walls of the facility, as depicted in Figure 3. Grass and landscaping within this area should not be taller than 6 inches. In this case, there is at least 50 feet of standoff from the facility exterior to a seven-foot high fence or wall to reduce the likelihood of an explosive device being thrown toward the building. If it were to happen, the explosive would land in the clear zone where its detection would be made much simpler. This means that an entry-controlled opening will need to be provided through the fence or wall for access to the facility.

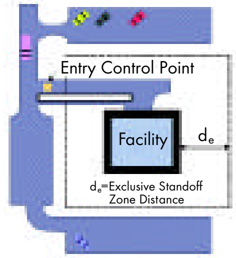

Figure1. Exclusive Standoff Zone with Entry Control Point That Does Not Need to be Manned.

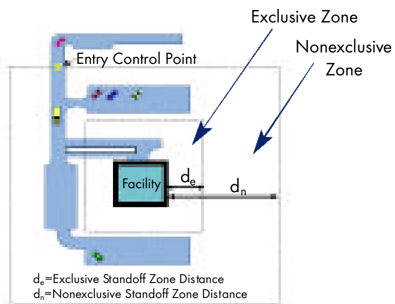

Figure 2. Nonexclusive Standoff Zone Requires a Manned Entry Control Point.

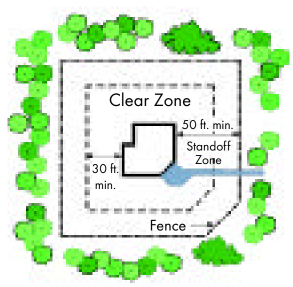

Figure 3. Clear Zone Used with a 50′ Standoff Zone.

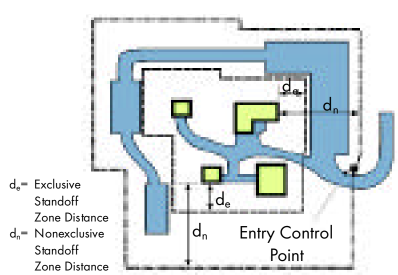

Figure 4. Facility Clustering of Buildings with Similar Threats Using the Same Exclusive and Nonexclusive Zones.

Facility Clustering A useful approach to protecting multiple buildings that are exposed to a similar threat is to use facility clustering as shown in Figure 4. The efficiencies of this scenario are apparent in that they are using common exclusive and nonexclusive standoff zones. This scheme also minimizes the number of entry control points to the area. This can be effective in a campus arrangement of buildings.

Lines of Sight Controlling lines of sight is important in a variety of threats, from visual observation, to ballistics. To protect the asset these lines of sight need to be blocked. There are many ways to accomplish this, such as the use of vegetation, structures, obscuration fencing, or window coverings. Another approach is to place assets to the interior of the building to remove them from unwanted lines of sight. For example, if the threat were from a ballistic weapon, then the window and door glazing would need to be designed to stop the ballistic threat, or hide the asset with blinds or shades.

Minimum Measures While not every threat can be anticipated, there are sets of minimum measures that can be applied to give a baseline level of protection. These measures can be applied to the facility regardless of the threat. Such measures could include: the elimination of hiding places that are near the facility, locating the facility within sight of other facilities on that installation, and providing 150-feet of standoff from the installation boundary. Other measures include eliminating straight-line approaches for vehicles driving toward the facility, minimizing vehicle access points, locating entry and exit doors on the opposite side of the facility than the installation perimeter fence, and eliminating under-building parking. Steps which should be utilized during the design phase are to locate the facility away from natural and man-made vantage points that provide advantageous lines of sight for an aggressor and illuminating the exterior of the building and parking areas. For a reinforced concrete-framed structure, use of more robust seismic details at the framing connections, and top and bottom rein-

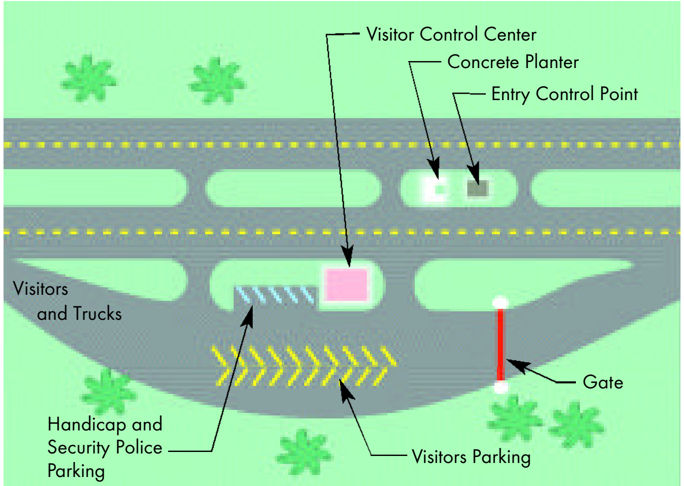

Figure 5. **Entry Control Point.**

Table 1. **Vehicle Processing Rates.**

Processing Pattern	Rate (Vehicles/Hour/Lane)
Verify driver and vehicle identification	200 to 400
Verify driver and vehicle for all trucks and perform visual observation of passenger and cargo area of random number of trucks	190 to 380
Perform all of the above and perform basic search of passenger and cargo areas of random number of trucks	150 to 280
Perform all of the above and perform comprehensive search of passenger and cargo areas of random number of trucks	90 to 170

forcement in the slabs will improve blast resistance. Another good idea is to locate protected assets to the interior of the building when practical, thus allowing the outside offices and corridors to act as standoff. When using this approach, the center of the building could be used as a courtyard to allow natural light to enter the interior located offices.

Entry Control Points

There are several systems used to make the entry control point function for the required level of protection and traffic flow rate. The system defined here is for the control of vehicles and personnel. At the installation perimeter fence this facility is constantly manned. However, during peak usage many such entry control points can be in use based on the processing rate at each gate.

Approach Road The approach road is the main road leading to the facility or area as shown in Figure 5. Controlling vehicle speed along this road is critical to the success of the entry control point since the momentum and kinetic energy of a vehicle is related to its entry velocity and the velocity squared respectively. For example, by reducing the approach velocity by one half, the kinetic energy would be reduced to a fourth, and a smaller barrier would be required. The common method used to reduce the speed of the approaching vehicle is through the use of massive concrete barriers arranged in a serpentine pattern. These barriers will control traffic flow, and the spacing between barriers will slow the vehicles' approaching speed. Typically, a single lane road would be used when entering an exclusive zone. Multiple lane roads are used when approaching a nonexclusive zone and traffic is segregated into lines for automobiles, and trucks.

Visitor and Truck Access Control Center Visitors wanting to enter the installation must report to the visitor control facility. Once there, they will have their ID checked, and if cleared they will be issued a permit for entry. This area is also separated from the facility or installation by a vehicle barrier to prevent access to the installation. The visitor control center will have a parking area and a truck inspection area. While parked in this area, vehicles can be searched, and if they do not pass this inspection, they can be rejected without entering the installation.

Entry Control Point The entry control point is that point whereby all access is allowed onto the installation. The requirements vary depending on whether the area being entered is used as an exclusive or nonexclusive zone. When entering the exclusive zone only a single lane of traffic and an active vehicle barrier is used because of the limited amount of traffic entering the zone. Even though the exclusive zone Entry Control Point need not be manned, it should have a means of communicating with the operator who processes clearance information within the facility. Once approved the vehicle can be cleared to enter the exclusive zone. When the threat level is low, electronic entry control equipment may be used for access control. The nonexclusive zone requires the use of a manned guardhouse, and an active vehicle barrier. The next concern would be the number of lanes required. This is determined by knowing the maximum throughput needed for the area or installation. Table 1 shows some typical throughput ranges per lane given various processing patterns. Last but not least, the entry control point needs to be illuminated in order to make the appropriate ID and vehicle inspections.

Gates and Barriers Two types of barriers are commonly used for the entry control point: passive and active barriers. Active barriers are operable gates that are designed to stop a moving vehicle. While the passive gates are not operable, they can also stop the kinetic energy of a moving vehicle. When designing a nonexclusive zone, large vehicles need to be directed to a search area that is provided with a rejection route outside of the nonexclusive zone. Barriers need to be provided on both incoming and outgoing traffic lanes to prevent the vehicle from trying to enter the facility by going the wrong direction.

Site Planning

Site planning integrates operational, logistic, and security requirements into an overall design package that includes buildings, exterior equipment, parking areas, road layouts, perimeter barriers and gates, and site landscaping. The most cost-effective overall solution for a project to mitigate explosive effects on the buildings is to keep explosives as far away as possible. The design team can optimize the project cost by balancing the available standoff distance and the appropriate level of building hardening. Normally that occurs when land is readily available and conventional construction can be used. The site layouts shown on Figures 6 and 7 identify the minimum standoff distances, that when achieved, will allow the buildings to be built with minimal additional construction costs. Where these standoff distances cannot be achieved because land is unavailable, DOD standards require that buildings be hardened to maintain the same level of protection as the minimum standoff distances. Costs and requirements for building hardening will be addressed in the new DOD Security Engineering Manual.

Vantage Points Vantage points are natural or man-made positions from which an aggressor can observe and target, people or other assets in and around a building. In many cases this is known as having the high ground, thus giving the aggressor the ability to shoot down on the unsuspecting personnel. The design team needs to identify the vantage points that are outside the control of personnel in the targeted building, and either eliminate them or shield the asset from a threat that is posed by that vantage point. There are several means available to the designer to eliminate this advantage, including the reorientation of the building to shield the personnel or asset, or to use one of many different screening techniques such as the use of reflective glazing, solid walls, privacy fencing, or vegetation with dense foliage.

Minimum Standoff Distances Minimum standoff distances as shown on Figures 6 and 7 are for a specific explosive weight and a given level of protection. When the project can use "Conventional Construction Without Analysis" the controlled perimeters standoff distances are shown on Figure 6. Should the project have an uncontrolled perimeter, conventional construction may be used with the minimum standoff distances shown in Figure 7. If those standoff distances are not available, the building must be analyzed by a qualified engineer and hardened to mitigate the effects of the explosives at the available standoff for the appropriate level of protection.

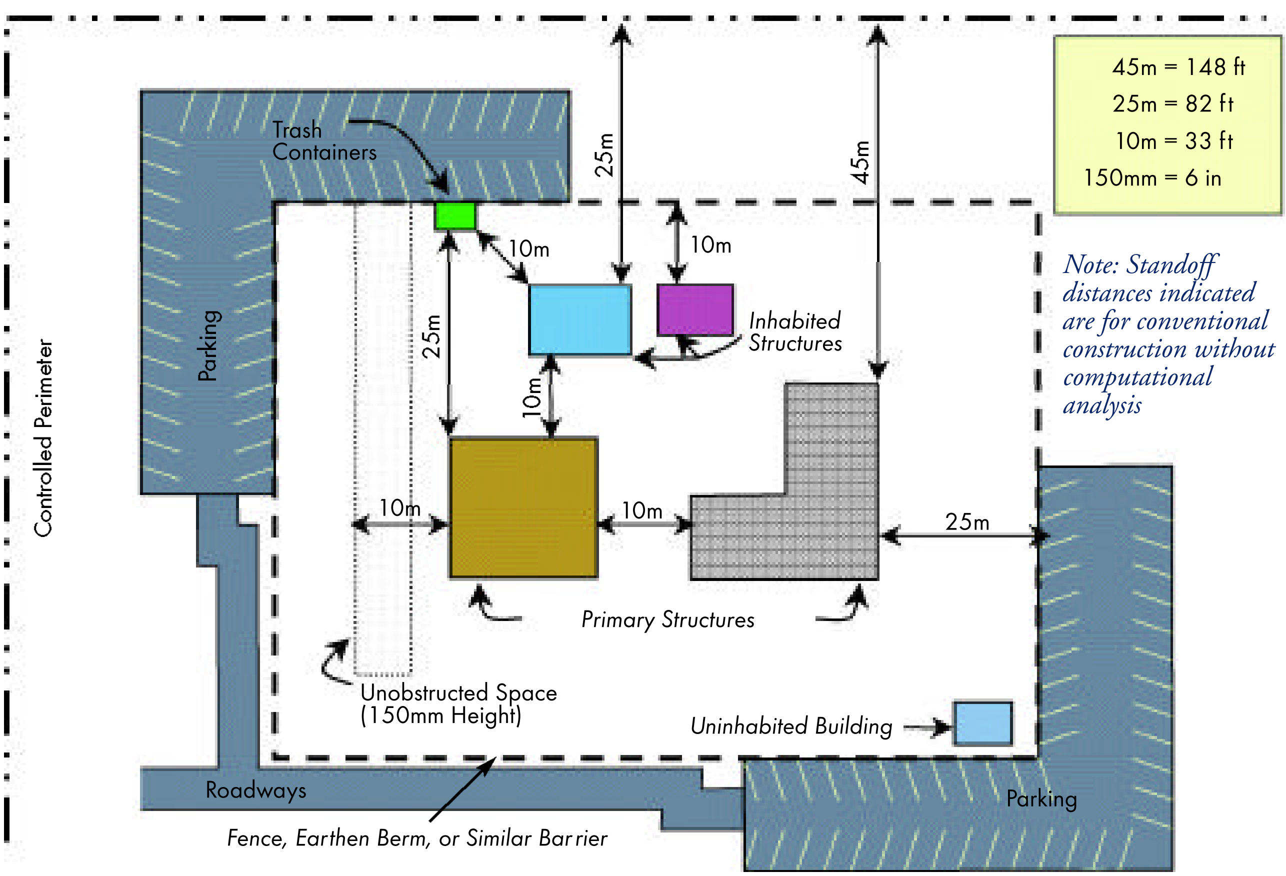

Figure 6. **Standoff Distances and Building Separations – Controlled Perimeter.**

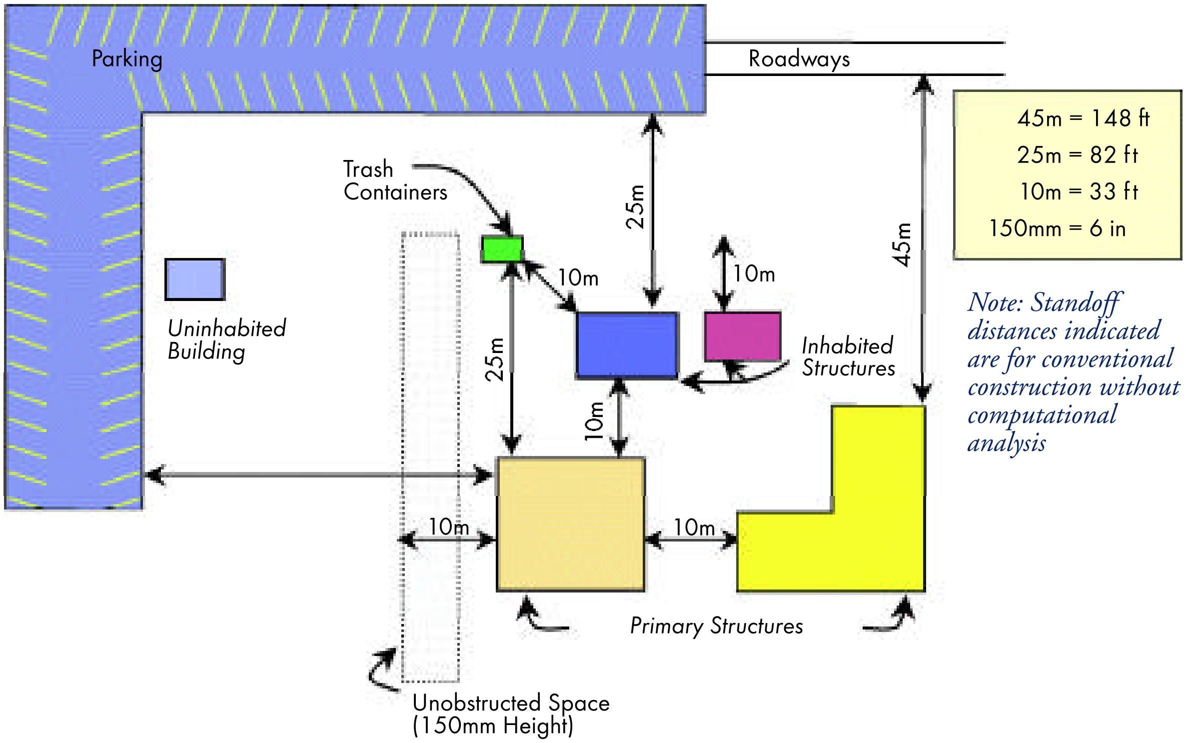

Figure 7. **Standoff Distances and Building Separations – No Controlled Perimeter.**

Unobstructed Space It is assumed that aggressors will not attempt to place bombs in areas around buildings where building occupants could visually detect an explosive device. Therefore, the site plan should use an unobstructed space of 30 feet around the facility. Vegetation within this area should not be greater than six inches in height. This does not completely preclude the placement of site furnishings or plantings around buildings. It only requires that any explosive devices placed in that space would be observable by building occupants.

Railroad Location Avoid sites for inhabited structures that are close to railroads. Where railroads are in the vicinity of existing buildings, standoff distances between the railroad and any inhabited structure should be provided based on the standoff distance and the explosive weight associated with the controlled perimeter. Where those standoff distances are not available, ensure that there are procedures in place to prohibit trains from stopping in the vicinity of inhabited structures.

Building Layout

Parking Beneath Buildings When vehicles are allowed to park under the building the blast load becomes an internal blast condition, and shock and gas loads need to be considered. These loads are very large and create a reverse loading condition for the structure, thus increasing the amount of damage to the facility. The first parking garage bombing at the World Trade Center removed two levels of support for columns of that structure. The columns then needed temporary support to stabilize them against buckling. Therefore, it is best to eliminate parking beneath buildings. In some instances, real estate is limited and this may make parking beneath the buildings unavoidable. When this happens, the following measures must be incorporated into the design: provide access control to ensure that personnel and vehicle access is limited, and ensure that the floors beneath inhabited areas will not be breached from an explosive detonation in the parking area.

Drive-up/Drop Off Locate the drive-up and drop-off zone away from large glazed areas of the building. This will minimize the potential for hazardous flying glass fragments in the event of an explosion. For example, the lane may be located at an outside corner of the building, or otherwise away from the main entrance. The drive-up/drop-off point should be coordinated with the building geometry to minimize the possibility that explosive blast forces could be increased due to being trapped or otherwise concentrated. For further discussion of this issue refer to the DOD Security Engineering Manual.

Superstructure All structural elements within a facility are subject to the progressive collapse provisions. For all structures that are over three stories in height, progressive collapse analysis is required. This provision requires that columns perform at twice the actual length to simulate missing lateral support when floor beams are lost. Also, beam strength needs to be increased to carry the remaining structure should a column be lost. Either of these conditions will force beams and columns into plastic yielding, and will lead to instability of the overall structure. Therefore, the beams and columns within the structure will require additional strengthening in order to prevent progressive collapse. Progressive collapse analysis is performed on load-bearing structures by removing a section of a wall, then analyzing the stability of the residual structure. During the progressive collapse analysis, plastic structural design limits are used in lieu of normal elastic building design limits. These limits include support rotations and ductility and are required for each member in the structure. Also, structural accelerations from falling debris and the catenary action of the members are considered. Structural connections need to be evaluated, as they will take on the characteristics of those used in seismic detailing.

Building Location Activities with large visitor populations provide opportunities for potential aggressors to get near buildings with minimal controls, and therefore limit opportunities for visual detection. Therefore, separation distance between DOD inhabited buildings and public spaces should be maximized. Also, buildings should be a minimum of 150 feet from the installation perimeter. This will provide sufficient space for the placement of barriers, vegetation screens, lighted perimeters, and standoffs against moderate sized explosive devices.

Asset Location To minimize the exposure of assets to direct blast effects and the potential impacts from hazardous glass fragments and other potential debris, locate critical assets and mission critical or high-risk personnel away from the building exterior. Such offices could be placed within interior spaces of the building and separated from the facility exterior by non-critical spaces such as storage rooms, hallways, utility rooms, and low use areas. If personnel are placed within an interior room an interior courtyard could be used to bring natural light into those office spaces.

Electrical and Mechanical Equipment Equipment located outside can be a security problem. Should a public use area be close to a critical facility, this equipment could be used to shield the location of an explosive device. Therefore, the preferred location for exterior electrical and mechanical equipment is outside the unobstructed space, or on the roof. All mechanical air intake louvers should be placed on the roof or at least 10-feet above the ground level. However, equipment such as: transformers, air-cooled condensers, and packaged chillers, could be placed within the unobstructed space as long the equipment does not provide the aggressor an opportunity to conceal explosive devices. If this equipment is placed within the unobstructed space, they should be placed in an equipment enclosure.

Equipment Enclosures If walls or other screening devices with more than two sides are placed around electrical or mechanical equipment within the unobstructed space, the equipment is to be enclosed on all four sides and the top. Openings in the screening material, and gaps between the ground and the bottom of the screens or walls making up an enclosure are not to be greater than six-inches. Openings within the enclosure are to be properly secured to prevent unauthorized access into the enclosed space.

SUMMARY

This article should provide the reader with a background into some of the procedures that are used in the security-engineering field. Many of those procedures deal with blast loadings from explosive events, since blast effects can be devastating to structures as well as personnel. Also, by considering the blast event, we can provide a more robust structure that can be used as an opportunity to defeat other types of threats against the facility and personnel.

The main goal of the DOD standards, as summarized in these pages, is personnel protection by incorporating smart protective measures into a facility during the engineering and design process. Many of the minimum measures are low-cost as we trade-off the value of hardening versus site considerations. When dealing with standard construction, the lowest cost alternative is to use more standoff distance. When standoff distance is not available, then the structure must be hardened to provide the same level of protection. Another key to the process is the understanding and appropriate use of controlled perimeters and zones. These zones not only provide standoff, but work as access control perimeters for entry into a controlled space around the facility.

The key to the security engineering process is to define a threat in terms of an aggressor, weapons, tools, and explosive, and then define the appropriate level of protection. Once the threat and level of protection are defined, the protective measures can be selected through the systematic security engineering process. Then the facility will have a known baseline level of protection that can be counted on should the threat level increase.

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Homeland Security vs. Homeland Defense...
Is there a difference?

Yes, there is absolutely a difference. While both entities serve the greater security interests of the nation, they are two distinct missions, separated by policy and constitutional limits of power. The White House defines them as follows:

Homeland Security is the prevention, preemption, deterrence of, and defense against aggression targeted at US territory, sovereignty, domestic population, and infrastructure, as well as the management of consequences of such aggression and other domestic emergencies. Homeland Security is the responsibility of the civil authorities at the local, state, and federal levels.

Homeland Defense is the protection of US territory, domestic population, and critical infrastructure against military attacks emanating from outside the United States. Homeland Defense is primarily the responsibility of the military (and the various intelligence agencies as well).

The distinction is important; defining the separation of civilian and military authority. This is a result of the Posse Comitatus Act, which specifically limits the use of the military in domestic law enforcement activities.

By virtue of their constitutional charge, the military's primary mission is Homeland Defense. In certain cases, the military may provide direct support to Homeland Security efforts, but in all such cases, the military units involved report to a civilian lead agency.

Polymer Composite Retrofits Strengthen Concrete Structures

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INTRODUCTION

This article describes Navy efforts to apply composite materials to pier decking and support columns for the purpose of repairing deteriorating installations and strengthening structures not designed for current load requirements. The successes of this program have laid the groundwork for a better understanding of how composite retrofits work in real-world, reinforced concrete structures serving in harsh environments. These retrofits have many similarities to some of the solutions proposed to retrofit buildings to make them more blast resistant. The approaches, if implemented, will increase load carrying capacity of floor sections, can enable sections designed only for gravity loading to withstand negative (upward) loads, and will reinforce support columns for higher strength and greater resistance to progressive collapse. Lessons learned in these Navy projects will help further advance the protection and hardening of land-based structures.

BACKGROUND

The Navy has many waterfront facilities that are already old and continuing to degrade as they remain in use. Many of these facilities are mission critical piers and wharfs that were built during or soon after World War II. The replacement rate for these structures has been slow, with the average age continuing to increase. The cost of current deficiencies is approaching $1B for piers and wharfs.

The two primary reasons for these structural deficiencies are deterioration and mission changes. In some installations saltwater has migrated through cracks or permeated the concrete to initiate corrosion of the steel reinforcing bars. As the reinforcing bars corrode, they expand and cause cracking of the concrete, thus leading to more saltwater intrusion. There is also speculation that global warming is leading to higher tide levels and raising the level of the splash zone to further aggravate the problem. In more recent structures, there is also evidence of chemically-induced deterioration of the concrete due to curing processes or aggregate composition. Changes in mission and operating practices also lead to deficiencies in structural capacity of piers.

In the past, the Navy designed and built piers with rail-mounted cranes which typically had large beams under the rails to take the loads. Today, the Navy prefers truck-mounted mobile cranes. These allow more flexibility in operations, since they can set-up anywhere on the deck. However, not all areas of the decks are able to sustain the outrigger loads from such cranes. These loads are increasing, because more ship maintenance and repair operations are being conducted pier-side rather than in shipyards.

Conventional methods to reduce deficiencies are costly and disruptive to operations. Construction of new piers requires budget approval and subsequent funding. Approvals may take many years, and actual construction can prevent operations at the site of the project and at adjacent berths. Conventional repair practices tend toward brute force methods. A typical approach is to simply increase the thickness of the deck. However, the increased mass could lead to seismic problems. Further, if the corrosion products are not carefully removed and the areas sealed, the corrosion will continue. This situation has led to the search for new materials or technologies that the Navy could use to strengthen and repair these structures.

TECHNOLOGY DEVELOPMENT

The Naval Facilities Engineering Service Center (NFESC), under sponsorship by the Office of Naval Research began a project in the early 1990's to explore the use of composite materials for repairing or strengthening waterfront structures. During that time the Navy teamed with the Army Corps of Engineers and what is now known as the Market Development Alliance (MDA) of the FRP (Fiber Reinforced Polymer) Composites Industry on a project for the Construction Productivity Advancement Research (CPAR) Program. The program involved testing of fender piles fabricated from FRP materials. The Navy uses fender piles* along the edges of piers to protect ships from impacts with the pier or wharf structure. Some of the piles were completely FRP, while others used an FRP casing around a concrete core [1][2]. This second type showed very good stiffness and strength properties under bending loads. The analogy to column wrapping for seismic upgrades was obvious.

NFESC fabricated a test site in Port Hueneme, CA to evaluate other FRP technologies in a controlled waterfront environment (Figure 1). The Army Corps of Engineers CPAR Program contributed funding and member companies of the Composites Institute of the Society of the Plastics Industry

Figure 1. **Advanced Waterfront Technology Test Site.**

Figure 2. **Placing Preformed Carbon Fiber Reinforced Polymer Rods Near the Top Surface.**

(forerunner of the MDA) contributed fabricated materials for the test site. Known as the Advanced Waterfront Technology Test Site (AWTTS), this structure has ten 10-foot test spans available for a variety of structural and materials specimens and two 20-foot spans holding an all-composite deck and a concrete deck with carbon fiber reinforced pre-stressing strands [3]. The South Dakota School of Mining and Technology contributed the pre-stressed concrete panel under a related CPAR project. The shorter spans simulate typical Navy piers at approximately one-half scale. Engineers, scientists and construction contractors have used the test site to evaluate the constructability and performance of concepts before taking them to an operational Navy application.

Numerical analyses, laboratory tests and tests at the AWTTS helped to validate the concepts for pier strengthening and repair. Small-scale beam tests showed that unidirectional carbon fibers bonded to the bottom (tensile stress) side of beams increased flexural strength and fibers bonded to the sides of the beams increased shear strength [4]. Adding both flexural and shear strengthening resulted in better load behavior with enhanced ductility and energy absorption.

Tests on small, under-reinforced, two-way concrete slabs showed that multiple layers of orthogonal carbon fiber sheets could increase both the flexural strength and punching shear resistance [5]. The increase in punching shear strength appeared to be consistent with the European code design guidelines. One-fifth scale laboratory tests and one-half scale tests at the AWTTS further demonstrated the increases in flexural strength, ductility and punching shear resistance with carbon fiber reinforcement bonded to the tension face [6]. The authors concluded that the increase in punching shear was attributable to the additional lateral constraint provided by the carbon fiber sheets.

Engineers also investigated the durability of the repair technique. A major concern was the durability of bonded carbon fiber strengthening on the topside of pier decks. On protruding or cantilevered sections of decks, or on continuous decks over pile bents*, the tension reinforcement must be on or near the top surface. Without proper protection, the carbon fiber would be damaged by vehicular traffic on the deck. The strengthening technique for the topside involved cutting a groove in the concrete surface, placing an epoxy adhesive in the groove, and embedding a preformed carbon fiber reinforced polymer rod in the groove (Figure 2). Laboratory tests demonstrated the strength and durability of strengthened members that depended on the bond between the epoxy, the rod and the concrete [7].

A similar series of tests also demonstrated the durability and strength of slabs with carbon fiber sheets bonded to concrete. Further tests evaluated the bond strength of adhesives to concrete under various moisture and temperature conditions [8]. These tests helped to establish the requirements for adhesive properties and surface preparation methods that would insure good load transfer between fiber sheets and the concrete substrate.

DEMONSTRATION PROJECTS

The technology development phase removed many of the hurdles to implementing this technology into Navy shore facility applications. The efforts validated previously postulated design methodologies, and identified critical areas in the construction or installation process. The results provided sufficient data to take the program to the field.

The demonstration projects that follow provided Navy field activities with the data necessary to specify the use of FRP materials for repair and upgrade of Navy piers. Although they were demonstration projects, they all corrected real structural deficiencies on operational Navy piers. In all cases, the activity shared costs with the technology demonstration project.

Typically the work was performed via design-build contracts which allowed the selection of contractors on the basis of best qualifications and best value. Except for the first project, Government specifications were more performance-based rather than proscriptive. The reinforcement was specified in force per unit length rather than calling for a specific number of carbon fiber layers and a given adhesive material. Bidders

Figure 3. **Pier 12 at San Diego.**

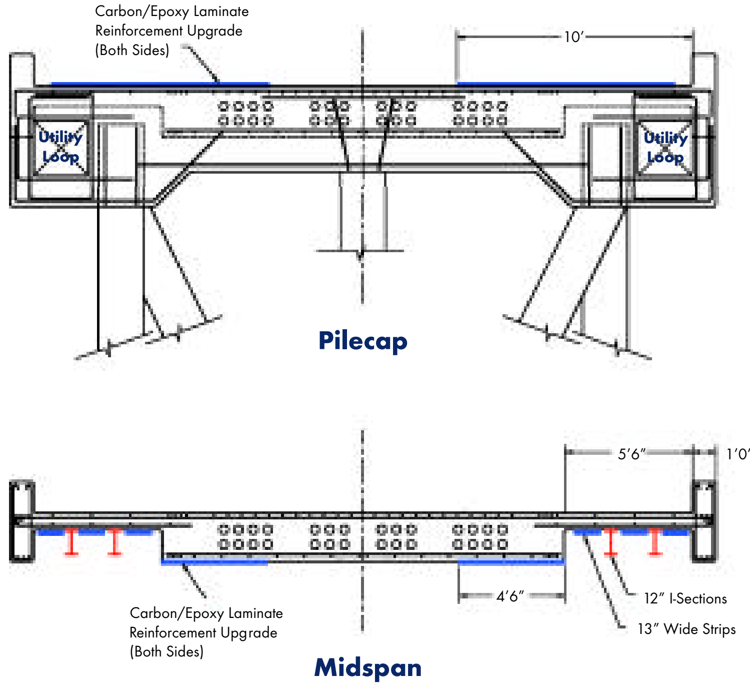

Figure 4. **Cross Sections of the Reinforced San Diego Pier 12 at the Pilecap* and at Midspan Between Pilecaps.**

had access to the test and development information developed by the Navy, but they were free to design their own retrofits. On successive projects, the bidders became more knowledgeable and more numerous. This led to more competition and lower unit cost for the technology. The engineering field divisions also became more knowledgeable in writing contracts for the work.

Norfolk Pier 11

The first of the three demonstration projects to apply external reinforcement to upgrade the strength of existing Navy piers was completed in December 1996. The project was executed on a deck span of Pier 11 at Naval Station Norfolk [9]. The project consisted of a load and condition assessment of the existing deck slab, the design of a graphite reinforced epoxy laminate composite overlay for the underside of the deck, preparation of the concrete surface, installation of the upgrade overlay, installation of monitoring sensors, and a load assessment of the upgraded deck slab. Contractors completed the entire project while the pier continued in service.

Pier 11 was designed for 70-ton truck-mounted cranes and limited use by 90-ton cranes. An engineering study identified deck slabs in the portable crane operating lanes in the 22-ft spans to have shortfalls that limited 70-ton crane service. The goal of the upgrade was to reinforce two crane operating lanes between bents 50 and 51 so that restrictions on 70-ton crane service would be removed.

Proof load tests verified the upgrade reinforcement to be integral with the deck. As a result, there was no need to place restrictions on operating 70 or 90 ton cranes on the upgraded span. The laminate overlay had little effect on the stiffness of the uncracked deck slab. However, in the damaged areas the retrofits increased the service load stiffness by as much as 5%, increased the strength by 10% while restricting crack growth, and added protection from salt water corrosion for the reinforcing steel. The upgrade is expected to have a service life of approximately 20 years. The project demonstrated that graphite/epoxy laminate overlays can be used to extend the useful life of existing piers at substantial savings compared to deck replacement.

NFESC is continuing to conduct intermittent tests and evaluations of the upgrade. Health and load monitoring sensors are in place and functioning under the deck for future tests.

San Diego Pier 12

This project strengthened Pier 12 at the Naval Station San Diego to meet demands of operational changes accompanied by higher vertical loads [10]. It is a cast-in-place, reinforced concrete structure 1,458 feet (444 meters) long and 30 feet (9.1 meters) wide. Pier 12 was one of several piers constructed in 1946 to berth the mothball fleet stationed in San Diego after World War II. It is currently used for berthing large but relatively shallow draft ships such as amphibious ships and landing craft (Figure 3). Deck operations were limited to 30-ton truck mounted cranes that could operate only in limited areas.

The project included concrete repair, surface preparation, and strength upgrades for 14 spans. The specific project tasks included:

1. Repaired deteriorated concrete of the deck and replaced corroded reinforcing steel.
2. Sealed existing cracks in the deck with polyurethane.
3. Embedded high strength carbon composite reinforcing rods in the top surface of the deck.
4. Bonded wet lay up, high strength carbon laminate to the bottom surface of the 24-inch thick deck section.
5. Bonded pultruded, high strength carbon composite strips to

the bottom surface of the 8-inch deck section.

6. Bonded pultruded, fiberglass composite I-beams to the bottom surface of the 8-inch deck section and anchored ends to pile caps, utility loops (as seen in Figure 4), and bollard platforms.*
7. Installed pre-formed fiberglass cylindrical shells around batter piles* and filled gaps with shrink-resistant grout.

Contractors installed these upgrades at each berthing of Pier 12 (Figure 4). The upgrade methodology allowed pier operations to continue without interruptions. With these upgrades the deck is suitable for 50-ton mobile truck crane operations with 100,000 pounds (450 kilonewtons) maximum outrigger loads. There would be no restrictions on the locations for the crane outriggers. The deck is also capable of supporting a uniform load up to 750 pounds per square foot (36 kilopascals). (For comparison, the floor in a typical commercial building is rated at a uniform loading of about 150 psf.) Proof tests after completion of the project demonstrated the upgraded areas could support these new loads at stress levels in the reinforcement that remained well within service limits.

Figure 5. Applying Carbon Fiber Sheets to Underside of the Deck.

Pearl Harbor Bravo 25

Bravo 25 at Naval Station Pearl Harbor is a cast-in-place, reinforced concrete deck and superstructure supported by precast concrete piles and is 550 feet (168 meters) long and 37 feet (11 meters) wide. The Bravo wharves are more than 50 years old. They were originally designed to support 50-ton (45 metric ton), rail mounted, portal cranes and train cars, as well as a distributed load of 900 pounds per square foot (43 kilopascals). In recent operations, truck-mounted, mobile cranes have replaced track-mounted cranes on the Bravo wharves. Mobile crane load limitations placed on Bravo wharves due to degradation were very restrictive. They limited crane outrigger loads to the track slabs and the rail girders. Other areas were restricted to truck and forklift wheel loads. Maximum uniform live load was limited to 490 pounds per square foot (23 kilopascals).

The objective of this project was to rehabilitate the concrete, protect existing reinforcement from corrosion, and increase the load capacity of the areas at each end of the Bravo 25 berthing [11]. This upgrade provided platforms with the ability to support mobile crane outrigger loads up to 125,000 pounds (560 kilonewtons) and a uniform load up to 750 pounds per square foot (35 kilopascals). To accomplish this, unsound concrete was removed and replaced, an impressed-current cathodic protection system was installed to protect the existing steel reinforcement, and carbon/epoxy composite reinforcement was added to the top and bottom surfaces of the deck and track slabs (Figure 5). The upgrade was completed with minimal interruptions to normal pier operations.

APPLICATION TO THE STRUCTURAL PROTECTION COMMUNITY

The applications of composite materials described in this article deal with strength upgrades for primarily static loads. The objective was to extend the life of structures with a minimal cost and disruption of activities on the piers. The Navy is doing follow-on work to consider the use of composite materials in the construction of new piers. But the work, which is still in progress, has indicated that the economics for employing composites in new construction are not as favorable as those for retrofits. The development effort to date indicates that a modular floating double deck pier constructed of high volume fly ash concrete with conventional post-tensioning strands and stainless steel secondary reinforcement has the most promise of providing a long life, low maintenance pier at a minimal increase in initial cost. In this case, dynamic or blast resistant design is not a major element.

Designers need to use caution when applying FRP technology to upgrades of slabs or panels for resistance to explosions. Carbon fiber may not be a good choice because of its cost and potential for a brittle failure. Also, the wet lay-up method presented here does not provide shear resistance around the periphery of the slab or panel. This may be a critical design parameter for some blast loading conditions. However, carbon fibers bonded to the bottoms and sides of reinforced concrete beams or girders could improve the overall strength of frame structures and help in the prevention of progressive collapse.

The process is analogous to providing external reinforcement for bending members. Even in an office building, this upgrade can be accomplished with minimal disruptions to operations.

The use of pre-formed FRP shells around existing columns may help to provide additional ductility under blast loads. This was the technique used on batter piles in San Diego. In many cases workers may need to gain access to a column by chipping away the adjacent walls. The two-piece round cylinder can be placed around any shape column and the workers fill the gap with non-shrink grout. This effectively increases the size of the column and provides confinement for additional strength and ductility. However, like the slab strengthening, it does not help transfer shear or moment to girders.

Another application of wet lay-up bonded carbon fibers might be in providing upgrades to floor slabs that were originally designed for gravity loads. Threat situations in which the blast loading could be coming from below the floor slab provide a unique situation, because the designer places the reinforcement to resist downward loads. Typically, there is little steel to resist negative (upward) loadings. To resist this type of loading, workers could bond carbon or other fiber sheets to the floor surface and place a floor covering over them to protect the fibers. This involves minimal disruption to the strengthened area.

All of these potential applications of FRP upgrades for blast resistant design have proven very effective for upgrading piers for new loadings. We have demonstrated and proven the technology in the relatively severe marine environment. Furthermore, by implementing the process through the people who design and specify upgrades to docks and piers, the methodology has transitioned to practical use. In addition to producing more test data for reducing risks of applying the same technology to blast design upgrades, we need to develop a similar strategy for the implementation process. This will insure the greatest number of qualified designers, suppliers and contractors and will help reduce the costs.

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ENDNOTE

* The following description of terms used in the construction of piers might be helpful to the reader. Piles are usually timber or reinforced concrete poles driven into the ground. Groups of piles (bents) are typically capped, and a flat deck is built across the pile bents. Batter piles are driven diagonally to help stabilize the structure from side loads. Fender piles line the edges of the pier to help protect both the pier and docked vessels from damage. Bollards (bulbous posts usually made of steel and concrete on Navy piers) and cleats (horizontal bars supported in the middle) are attached along the edge of the pier to tie off vessels at rest.

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Blast Retrofit Research and Development:

Protection for Walls and Windows

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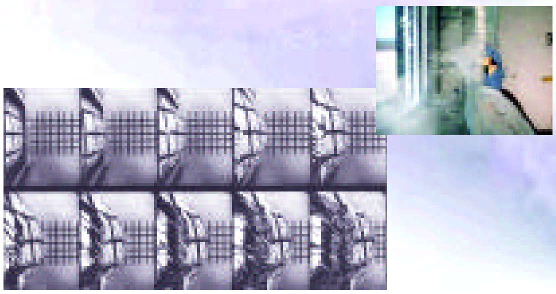

Figure 1. **High-speed Photos Depicting Glass Fragment Hazard.**

Figure 2. **High-speed Photo Showing Masonry Wall Debris Hazard.**

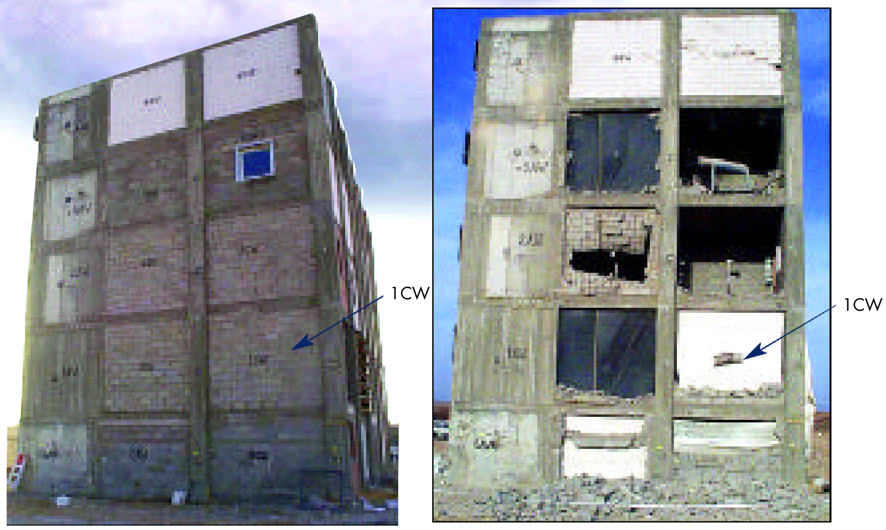

Figure 3. **Pre- and Post-test Photos of Test Structure.**

INTRODUCTION

Conventional building components are highly vulnerable to terrorist vehicle bomb attack. Common annealed glass windows break at very low blast pressures and the resulting flying glass fragments are a major cause of injuries in many bombing incidents (Figure 1). Masonry in-fill walls are also weak elements and another source of hazardous debris (Figure 2).

Through the combined research and development efforts of the Army Corps of Engineers, the Defense Threat Reduction Agency, the Technical Support Working Group, the Air Force Research Laboratory, and the Bureau of Diplomatic Security of the State Department, significant advances have been made since 1996 in improving methods for protection of conventional military and government facilities. Unique and innovative methods for retrofitting windows and walls have been developed that increase the blast capacity of these vulnerable components five- to ten-fold resulting in decreased standoff requirements and improved protection for personnel.

RETROFIT MEASURES

Fabric Coverings

Among the earliest of the innovative techniques for wall retrofit was the use of anchored high strength fabrics to catch wall debris. The fabrics used are typically woven polypropylene similar to those used for sandbags and often generally referred to as "geotextiles." This technique does not entail increasing the strength of the wall itself (as was the typical approach taken previously) but is based on catching the wall debris to prevent it from entering the building and posing a hazard to the occupants. This technique was developed and validated with full-scale tests in 1998, then transitioned to the Corps of Engineers' Protective Design Center for incorporation into design guidance. As later shown, anchored geotextile fabric was one of the components used to retrofit the exterior walls in the original Pentagon Renovation Project.

Figure 3 shows a full-scale five-story reinforced concrete frame structure with infill masonry walls constructed to

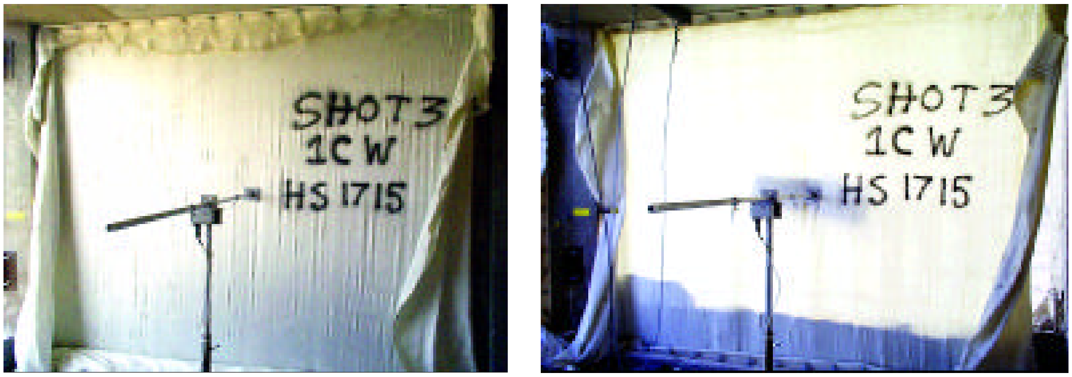

Figure 4. **Pre- and Post-test Photos of Anchored Geotextile.**

Figure 5. **An Infill Masonry Wall Retrofitted with Geotextile.**

Figure 6. **Pre- and Post-test Photos of Interior View of Laminated Glass Window in Steel Frame, Anchored Around Perimeter to Geotextile.**

Figure 7. **Pre- and Post-test Photos of Interior View of 3/4″ Polycarbonate Window, Secured Using Steel Straps, Anchored at Floor and Ceiling Using 3″ x 1/4″ Steel Straps.**

evaluate the effectiveness of various retrofitted infill wall types designed to protect building occupants from blast loading from a simulated vehicle bomb detonation near the building. Included in the evaluation were several geotextile, aramid, and E-glass fabrics.

Figure 4 shows pre- and post-test photos of the interior of the sample wall labeled 1CW in Figure 3. The wall consisted of an 8 in.-thick hollow concrete masonry unit (CMU) infill wall with no windows. This wall was retrofitted by anchoring a geotextile to the floor and ceiling on the inside of the wall. The geotextile performed as expected, preventing wall debris from entering the room.

Fabric Coverings with Windows

The geotextile retrofit proved to be a very practical and successful retrofit when applied to solid walls, so the concept was adapted to be applied to infill walls with window openings. Figure 5 shows an interior view of a 20' x 10' (nominal) infill masonry wall constructed using two wythes of clay bricks, and containing two “punch” windows. (Two wythes of brick refer to two vertical, parallel planes of stacked brick often separated by an air gap or some sort of fill.) The wall was retrofitted by applying a geotextile material, glued to the interior of the wall using a contact adhesive, and anchored at the floor and ceiling using concrete anchors. Gypsum board was glued to the geotextile-covered wall to achieve a finished interior wall surface.

Each of the windows was retrofitted differently. Window 1 (Figure 5 on left, viewed from inside) was retrofitted by constructing a steel frame that attached

Figure 8. Pre- and Post-test Photos of the Structural Muntin Frame System Installed as a Retrofit.

to the geofabric around the perimeter of the frame, and provided sufficient bite to hold a 1" thick laminated glass window when exposed to the blast pressures. The frame successfully held the glazing, and became detached from the geotextile very late in the blast response, preventing any debris or blast pressures from entering the room. The gypsum board became detached from the geotextile during the large deformation response of the wall, but with very low velocity, thus not presenting a hazard to occupants. The geotextile remained completely attached at the floor and ceiling, preventing any wall debris from entering the room. Figure 6 shows a pre-test and post-test photo of this window/wall retrofit.

The window 2 retrofit (on right as viewed from inside) consisted of a steel frame containing a 3/4" polycarbonate glazing, anchored to the floor and ceiling using 3" x 1/4" steel straps on each side of the frame. Figure 7 shows a pre- and post-test photo of this window retrofit. The window remained securely in the frame, and the straps remained securely attached to the floor and ceiling, but allowed the window system to deflect into the room approximately 42".

Muntin Window System

Another innovative window retrofit concept involves the installation of a blast-resistant glazing in a rigid steel frame that incorporates a structural steel muntin made from steel tubes. This system is designed to transfer the load from the glazing to the structural muntin and frame, which absorbs the blast energy and effectively reduces the span of the glazing and prevents the glazing from pulling out of the frame bite. This concept was successfully tested with a 5' x 7' window opening (Figure 8).

Sheet Steel Wall Retrofit System

Some wall retrofit systems have used sheet steel anchored to the floor and ceiling to prevent exterior walls from blowing into rooms. Sheet steel offers advantages of high strength to weight ratio, ductile performance, ease of fabrication, and familiarity to construction personnel.

Sheet steel was used as a wall retrofit during the experiment as shown in Figure 9. The exterior wall was two wythes of masonry with 4' x 6' (nominal) punch windows. The retrofit consisted of a custom made commercial product using 20 gauge steel sheets glued to 1/4" gypsum board. The gypsum board gave the wall a finished appearance. Six-inch legs were

Figure 9. Pre-test Photos of the Sheet Steel Wall Retrofit.

Figure 10. Post-test Photos of the of the Sheet Steel Wall Retrofit.

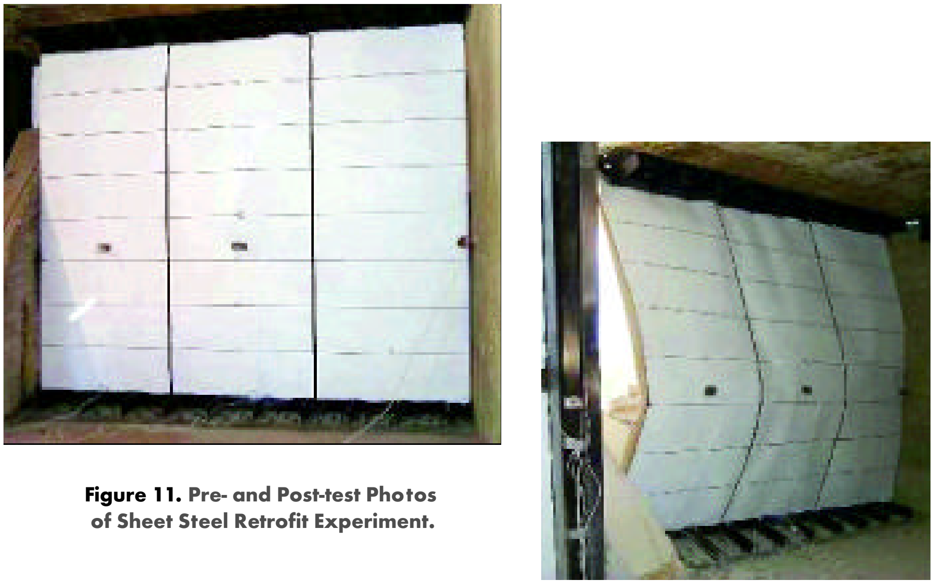

Figure 11. Pre- and Post-test Photos of Sheet Steel Retrofit Experiment.

bent on the top and bottom of the steel sheet. The sheet was then glued to the masonry wall, and anchored through the legs to the floor and ceiling. The windows consisted of a version of the muntin system described earlier. Results of the experiment (Figure 10) showed the retrofit performed as desired preventing debris from entering the room.

Another example of a steel sheet retrofit for a severe blast environment is shown in Figure 11. The exterior infill wall was one wythe of CMU. The retrofit was designed for a close-in detonation exposing the wall to very large blast pressures and consisted of 1/4" thick mild steel sheets spanning from floor to ceiling, and securely anchored to reinforced steel anchors that were attached to the ceiling and floor slab using concrete anchors. One of the keys to the success of this concept was detailed design of the concrete anchorage system.

Figure 12. Pre-test Photos of Steel Stud Retrofit Walls Before and After Installation of Interior Gypsum Board.

Steel Stud Wall

Another retrofit concept involves the use of conventional steel studs to construct an interior wall inside the existing wall. The studs are not attached in the conventional manner at the top and bottom. Instead, each stud is anchored to the concrete slabs at the top and bottom using concrete anchors. Retrofit blast resistant windows can be installed in a framed opening in the steel stud wall. Figure 12 shows photos of a retrofit steel stud wall prior to blast testing. Gypsum board was installed to the interior surface of the steel studs using adhesives and screws with bearing strips to prevent the gypsum board from pulling over the screw heads during blast loading.

Figure 13 shows the post-test photos of the steel stud wall, especially the windows. The windows remained intact, and the steel stud wall successfully prevented the exterior wall and debris from blowing into the room.

Figure 13. Post-test Photos of Steel Stud Retrofit Wall with Windows.

Spray-on Elasto-Polymer Coating

The fabric, sheet steel, and steel stud retrofits all require high strength bolted connections to the floor slabs to be effective. A less labor intensive method is the use of a spray-on elasto-polymer coating similar to that used in the industrial coating industry and in spray-on truck bedliners. The material is sprayed to the interior of the wall and overlapped onto the floor and ceiling slabs by a few inches to form a bond. Figure 14 shows an unretrofitted single wythe CMU wall (Wall 3A) and a single wythe CMU wall with 1/4" thick elasto-polymer applied to the interior of the wall (Wall 3B). Figure 15

Figure 14. **Pre- and Post-test Photos of Cubicle Three, the Right Half of Which Was Retrofitted with Spray-on Elasto-polymer.**

Figure 15. **Pre- and Post-test Photos of Cubicle Three, Wall 3B.**

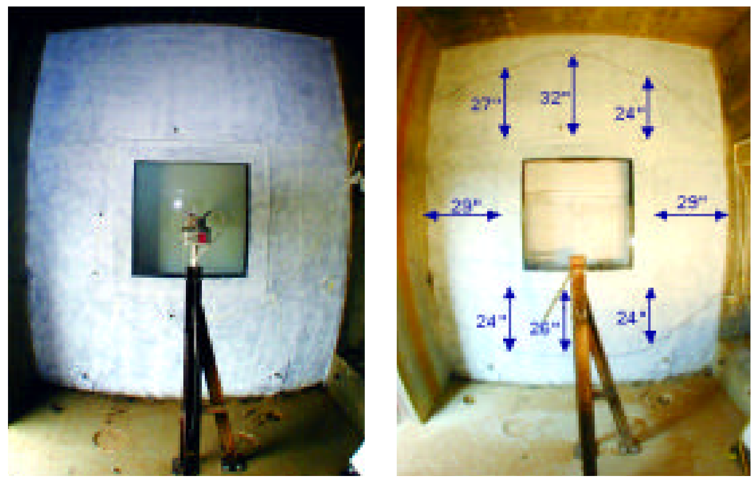

Figure 16. **Pre- and Post-test Photos of the Interior of a Reinforced Concrete Wall Containing a Window Retrofit Using Spray-on Elasto-polymer to Catch the Window During Blast Loading.**

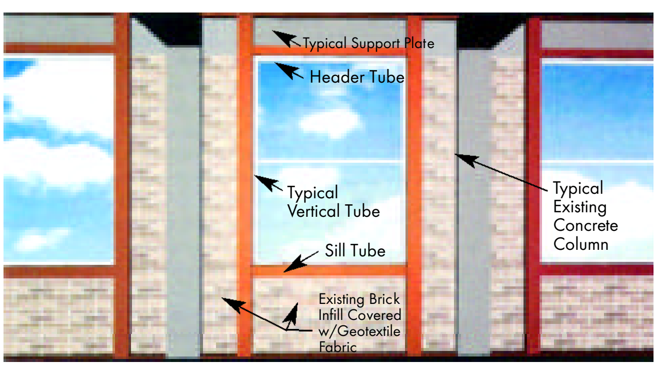

Figure 17. **Schematic of Pentagon Retrofit.**

shows photos of the inside of Wall 3B before and after the experiment. The control wall was breached. While the retrofitted wall was damaged significantly, no wall debris or blast entered the room, thus the hazard was eliminated.

Elasto-Polymer Wall Covering with Window

The success of the experiments using spray-on elastopolymer applied to the interior surface of solid infill masonry led to attempts to apply this retrofit technique to walls with windows.

Figure 16 shows a pre- and post-test photo of a reinforced concrete wall with a 40" x 40" window opening. This wall and window were retrofitted by developing a steel frame with a 3/4" polycarbonate sheet in a 3" bite. The steel frame also overlaps the concrete 3" around the perimeter. Elasto-polymer was applied to the entire wall and extended 6" over the steel frame, but was not applied to the window. The retrofit performed successfully. The elasto-polymer remained securely attached to the steel frame, but detached from the wall at least 24" in all directions around the window as indicated in Figure 16.

APPLICATION OF BLAST RETROFITS TO THE PENTAGON

At the time of the September 11 attack, the Pentagon was undergoing a renovation that included retrofit measures to increase the resistance of the structural envelope to terrorist attack, particularly for blast effects. These retrofits (Figure 17) included thermally tempered, laminated glass windows designed for blast resistance supported by horizontal steel tubes that framed into vertical tubes that ran from floor slab to floor slab. In addition, a geotextile membrane was used over the interior surface of the masonry wall to prevent the masonry from becoming a debris hazard during a blast event.

The effectiveness of these retrofits in mitigating blast damage

Figure 18. **Comparison of Small Bomb Standoffs for Original (red) and Retrofitted (yellow) Pentagon. (Satellite Photo of the Pentagon Courtesy and Copyright GlobeXplorer, LLC and Its Content Partners.)**

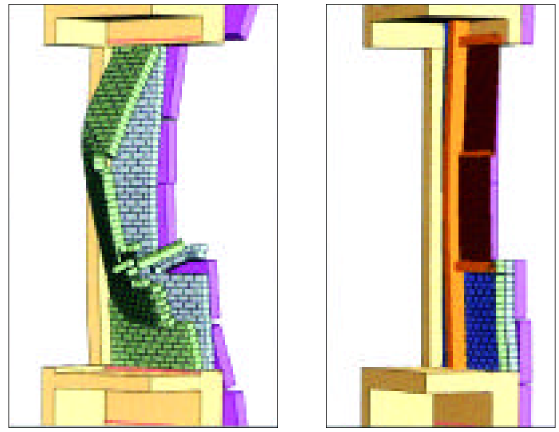

Figure 19. **Blast Response Simulation of Original and Retrofitted Pentagon Wall.**

and hazard to personnel is indicated in Figure 18 which compares the standoffs required for preventing high hazard conditions between the original exterior wall design and the retrofitted exterior wall design for two generic vehicle bomb sizes. High performance computing simulations (Figure 19) further indicate the effectiveness of the retrofits under a severe blast environment.

Fortunately, the section of the Pentagon that was hit on September 11 was the first and only section where the renovation had been completed. Although the retrofits were not designed for an airplane impact, their presence was credited with saving lives. In particular, many of the laminated windows remained intact, even when apparently engulfed in the fireball of burning fuel; thus preventing fire from entering offices on the upper floors (Figure 20). In addition, it was conjectured that the steel tubular supports for the windows added to the resilience of the building.

Figure 20. **Window Damage from September 11 Attack on the Pentagon. The Aircraft Impact Area Was Approximately 135 ft. to the Right.**

CONCLUSION

Conventional buildings come in a wide variety of structural types, component materials and construction details. No one retrofit technique is generally applicable to all conditions. As a result, engineers need a "catalog" of cost-effective techniques and design methodologies to apply and adapt to the particular situation. As discussed here concerning the attack on the Pentagon, application of some of these techniques has resulted in lives saved. Continued research on blast retrofits is needed to provide additional solutions to this problem with the ultimate goal of protecting building occupants from the hazards associated with the blast-induced failure of building components.

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MaterialEASE

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MATERIALS FOR BLAST AND PENETRATION RESISTANCE

The following MaterialEASE is an abridgement of an AMPTIAC report published in 2001. It describes materials and novel combinations of materials used for blast and penetration resistance and describes their application to structural protection. The field is far too broad to provide a comprehensive treatment within these pages, but this summary, in conjunction with the accompanying articles in this issue, present a thorough introduction to the materials and current DOD activities.

We suggest anyone interested in the most complete look at materials and structures for blast mitigation to consider obtaining the State of the Art Review (SOAR) this MaterialEASE is based on, "Blast and Penetration Resistant Materials" (AMPT-26), as well as a sister AMPTIAC SOAR focused on structures, "Applications of Structural Materials for Protection from Explosions" (AMPT-21).

INTRODUCTION TO BLAST AND PENETRATION RESISTANT MATERIALS (BPRM)

While only one part of the entire spectrum of structural protection technologies, materials is certainly one of its cornerstones. The focus of this article is on materials instrumental to providing protection against explosive blasts and projectile or fragment penetration of critical structures.

Armors, or penetration resistant materials, are the largest classification of BPRMs, but the term doesn't do justice to what materials and materials systems are available for today's protective shielding. Traditionally, when we think of armor, heavy military tanks on a battlefield roll into our imagination. Armor connotes a thick layer, typically steel, employed as a shield from projectiles fired from various weaponry. While such images accurately depict traditional armor systems, they are severely dated and do not reflect the advanced protective materials and systems available today. Protection against blast and penetrating fragments is accomplished with a plethora of materials and material combinations; sophisticated systems engineered to mitigate equally sophisticated projectiles and explosives.

The demand for well-engineered structures has dictated drastic improvements in ductility, fracture toughness, corrosion resistance and machinability of constituent materials. This in turn has driven materials engineers to conquer new problems. The threat of terrorist attack has heightened awareness of the need for better buildings. These improved structures will protect occupants from the shock pressure of a blast, and the biggest dangers to personnel in a building: fragmenting structural materials, breaking glass, and building collapse.

For buildings, weight plays some role, but cost is typically the driving force. Another key consideration in structural protection of buildings is that in most cases, blast and penetration protection schemes are installed as retrofits. Beyond the limitations of cost, the occupied volume of the installed materials and its impact on building form, fit and function is also critical and a major materials selection concern.

Barring building collapse, fragmenting wall structures and flying window glass would be the main cause of occupant casualties. Primary structural support in most buildings is provided by regularly spaced, reinforced concrete support columns, connecting rigid concrete and steel floor sections. The interior and exterior walls are typically not load bearing and are usually made of hollow concrete blocks, or metal or wood frames, covered by metal, wood, or gypsum board panels. All of these materials will deform, displace, and/or completely disintegrate when exposed to significant overpressures associated with bomb blasts, posing the greatest threat to loss of life.

There is ongoing research to replace or cover many of these materials with polymer, fabric, steel, or laminate sheeting that would maintain the aesthetic appearance of the building, while standing up to the shock pressure and not fragmenting or containing fragments. Combinations of these materials with foam cores may even help to mitigate the shock loading and further protect occupants from blast overpressures. For existing buildings, some researchers have proposed spray-on coatings that could achieve many of these goals without drastic remodeling.

In the Defense community, recent routine exposure of military personnel to operations in urban settings has raised the question of how to mitigate acts of terrorism in close proximity. The issue becomes one of retrofitting existing buildings quickly without serious degradation of mobility or performance. This is especially critical, as most domestic American civilian and government buildings currently offer little in the way of protection from explosions.

As we discuss the materials herein, you will begin to see how they may be incorporated into a facility for protection, based on the individual needs of each structure. Those protection needs are dictated by the desired level of protection the building must provide to its occupants or its ability to function. The three levels of enhanced protection described in Table 1 outline in broad strokes what the needs of a building might be. These levels give a general view of the danger occupants might face, but they also relate to what types of solutions would have to be employed to make them blast resistant. For instance, the Level 1 building will have to employ expensive structural hardening measures to make up for its lack of standoff. The Level 2 building is less likely to be targeted because of active security measures, but if it were hit damage would be extensive.

MATERIALS THAT MITIGATE SHOCK AND FRAGMENTATION EFFECTS

Delving into the nature, mechanisms, and applications of blast and penetration-resistant materials, it is important to develop the necessary context to examine this topic. This MaterialEASE addresses five main classes of materials that apply to the structural protection community. In general, the materials get more expensive as you proceed through the classes, just as the cost of protection increases with the level of safety. While most of the materials presented were developed and studied for strictly military purposes (for the defeat of battlefield shock pressure and projectiles like metal fragments and bullets) research has recently been focused on employing such materials for the mitigation of blast and shock effects in buildings and other structures.

Geo-Materials

Concrete and soil may not typically be thought of as BPRMs, but they are the two most widely used materials for protection from blast overpressures and fragments. Obviously they are also widely used in construction and site planning. Earthen berms are often used as a mitigating barrier around a facility's perimeter to reduce access, deflect blast pressure, and absorb bomb fragments. Concrete is the most widely used construction material for blast resistance, mostly due to its availability and status as a relatively inexpensive commodity. Concrete and soil provide mass and fragment absorption at a very low price when compared to any other material or material system.

Earthen barriers have been used in many applications for blast and penetration resistance since soil or sand is readily available and abundant in most locations. The typical use of soil in most structural protection applications is to create berms around the perimeter of a facility. Berms blend with the environment much more than a large wall or fence, and provide both fragment absorption and blast deflection, as well as helping to limit vehicle access. A number of commercial manufacturers produce lightweight fencing or wall structures which can be filled with soil to construct earth walls. These structures are designed for ease of installation, reinforcement of the soil, and decreasing the volume of soil required for the wall.

Concrete is used extensively as a construction material. It ranks second to steel as a stand-alone material in its ability to withstand blast overpressures, mostly due to its mass. The most important property of concrete when designing impact resistant structures is compressive strength. Spalling and fragmentation are however, problems that crop up as concrete is exposed to blast or fragmentation effects. Fragmentation may be reduced with fiber reinforcements, but can only be contained by adding surface layers of additional materials. Internal reinforcements can be added to increase strength or fracture toughness of the concrete. Typical reinforcements include steel bars or wires, fiberglass, carbon, and other polymer materials.

While concrete is one of the oldest and most common materials used in construction, that does not mean it is a stagnant technology. Please consult the article by Cargile et al in this issue for more information concerning advanced concretes.

Polymers and Glasses

Polymers are inexpensive materials that can be used to protect building occupants from potentially dangerous, fractured or splintered walls and shards of glass from shattered windows during an explosion. Simple cloths or fabrics (e.g. nylon) can be applied to walls inside the structure to capture or hinder debris from a fragmented wall. Recently, polymers

Table 1. Levels of Structural Protection.

Level 1

This building utilizes a small standoff perimeter and operational measures to keep unknown personnel away from the structure. The structure itself may have only minimal hardening features such as laminated exterior windows. The occupants would have a reasonable chance for survival, depending on their proximity to the blast, but there is a high probability that the facility could suffer severe damage and possibly collapse.

Level 2

This protected structure utilizes an adequate standoff, perimeter controls, some hardening features, and structural modifications to withstand shock and negative loads from an assumed level of bomb blast. This building and its site provide the occupants a significant level of protection and very good chance of survival. The building may not be able to continue its functioning without repair, but the damage will probably be superficial or limited.

Level 3

This level of protection is typically only seen on military installations. The facility provides all the exterior security measures discussed above, but also calls for a structure that is hardened to blast standards. This structure can take a direct blast of some specified size and not only protect its occupants, but continue to serve its intended function.

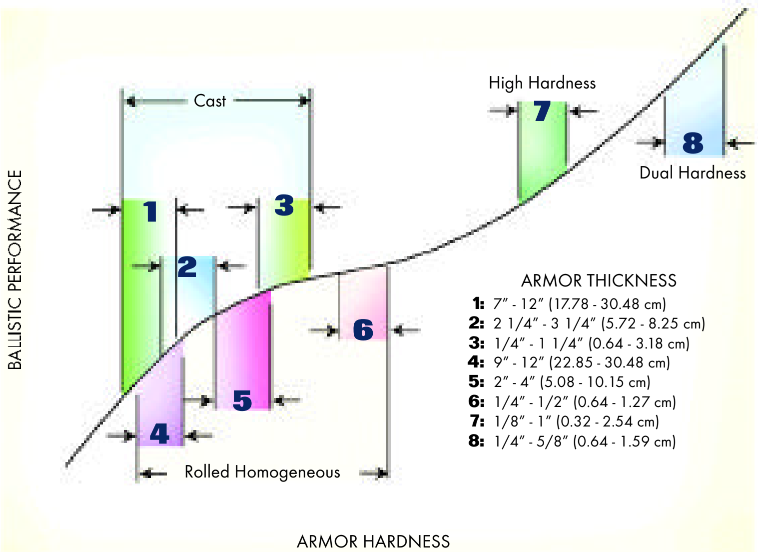

Figure 1. Hardness vs. Ballistic Performance for Various Steels[3].

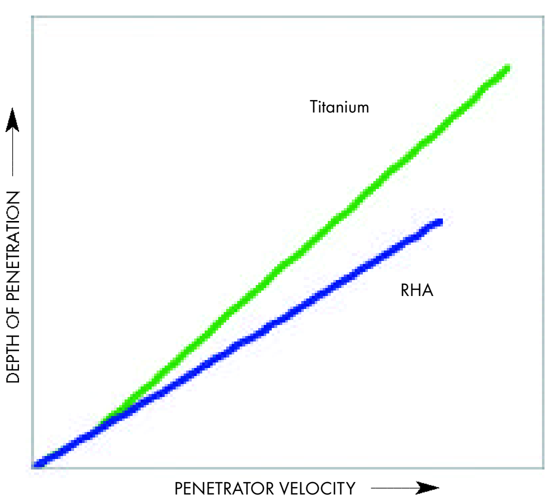

Figure 2. Resistance to Projectile Penetration for Ti-6Al-4V and RHA[5].

that can be sprayed onto a wide variety of surfaces have been shown to reduce fragmentation from blast pressures.[1] An elastomeric polymer has been tested on an eight foot by eight foot concrete wall, which was sprayed inside and out with the polymer and then subjected to 80+ psi blast pressures. The wall experienced severe fracturing but remained in place with no fragmentation. A follow-on activity identified additional polymers (e.g. polyurea) that may have better qualities to decrease wall deflections. The testing continued to show promising results with stand-off distances reduced over non-sprayed lightweight structures by as much as 50%. Furthermore, polymer foams can be inserted inside walls to act as an energy absorber, thus reducing the severity of a blast inside a structure. A further discussion of this technology is covered by Porter, et al in this issue.

Typical plate glass windows are extremely dangerous to occupants because they shatter when exposed to even a small overpressure, and the blast pressure can then carry the shards into the building at high velocity. Glass laminates or glass replacements, however, can be used to reduce or prevent this from happening. Thin films of polycarbonate laminated on glass, for example, will keep the shattered glass in one cohesive (though shattered) piece. An alternative is thermally tempered glass (TTG), which can protect against pressures up to about 40 psi.[2] TTG, also used in automobile windows, fractures into rock-salt size pieces which are not as dangerous to building occupants. In addition, thick polycarbonate can be used in place of glass, since it will not shatter upon impact or when exposed to a relatively high pressure. Advanced-technology transparent armor consisting of ceramic/polycarbonate laminates are also available, but are prohibitively expensive for the majority of structural protection applications.

Metals

Many metals make great BPRMs, and the most common include steels (ferrous alloys), aluminum alloys and titanium. The purpose of metals in structural protection is often two-fold: protection against fragments and secondly, maintaining structural integrity. Metals are highly useful in protecting structures against explosions because of their inherent strength and toughness and energy absorption capability. Additionally, metal poles, connectors, and plates can be used to reinforce masonry structures from negative loads and contain fragments, as well as adding structural support in the event of masonry failure. They are also useful in designs due to their relatively low cost and flexibility in modifying moduli and ductilities. The article by Coltharp in this issue provides an in-depth look at various reinforcement mechanisms, including metals.

Ductility provides an indication of a material's resistance to penetration of a projectile, such as a fragment, and its ability to absorb energy from a blast. A higher ductility allows greater deformation of the metal thus permitting the penetrating object to proceed farther through it. The converse is true for metals with low ductility where the object may damage the face of the metal, but would not penetrate far. In addition, the inherent strength and ductility of metals allows them to absorb blast energy while possibly maintaining structural integrity.

Some metals have high impact strengths, which are indicators of their toughness and resilience to fracture when hit by a projectile and also their ability to sustain multiple hits. Conversely, other metals are unable to survive these collisions, failing due to their low impact strengths.

Fracture toughness determines how resistant a metal is to crack propagation, which is an important factor when considering sustained loads. There is a strong correlation of hardness to ballistic performance in metals. High hardness metals perform well against ballistic projectiles, but are more susceptible to brittle fracture, and thus are poor structural materials. Lower hardness metals have good structural qualities, but are not as effective in resisting fragment penetration.

Steel exhibits many of the properties that are important for protecting against the effects of a blast, which is clearly important since steel is a common material in structures. The protection it offers against fragments is largely attributed to its hardness. As described above however, there is typically a trade-off between hardness and structural integrity. Many existing research programs have focused on improving the structural capability of the steel by providing a higher hardness to resist projectiles. Other steel research is focused on maximizing the hardness for the best protection against fragments in non-structural applications. Figure 1 shows the correlation between hardness and ballistic performance as well as the evolution of steel armors, 1 being the oldest, up to 1990.

The only armor grade steel that is currently in use for structural applications is rolled homogeneous armor (RHA). Weight has been a crucial factor in having all other integral armor steels replaced by alternative, better-designed materials. Rolled homogeneous armor has a density on the higher end of the metals spectrum and a hardness on the lower end.[4] When a ballistic projectile impacts RHA, it can be deformed relatively easily because of its ductility.

Although steel in general is highly resistant to penetration, it is quite dense; therefore, lighter metals must be considered in applications where weight is a factor. Titanium alloys have some advantageous properties (including good high temperature performance and a significantly lower density than steel) but have not been extensively used because of their high cost and difficulties in machining and welding.

Since its development in the 1950's, the Ti-6Al-4V alloy has become the only titanium alloy in use for armor applications (as defined in MIL-A-46077). Compared to RHA, Ti-6Al-4V has similar hardness and strength properties, but has outstanding mass efficiency resulting in a weight savings of about 25%.[3] Moreover, Ti-6Al-4V has a high impact resistance and fracture toughness, and is capable of sustaining multiple hits. It can however, be susceptible to stress corrosion cracking (SCC). This particular alloy provides exceptional protection against ballistic fragments, while no other titanium alloys have performed better against ballistic projectiles. Ti-6Al-4V performs almost as well as RHA in ballistic protection, and the two are very comparable. Figure 2 is a comparison of the ballistic protection performance between RHA and Ti-6Al-4V.

There are several aluminum alloys that are used in blast mitigation and penetration resistance applications. Aluminum alloys have a significantly lower density than steel, although they are only slightly less dense than titanium alloys. Although aluminum alloys typically have low hardness (making them less resistant than steel to ballistic projectiles), some have good resistance to projectile puncture and fragments. Beyond weight advantages, some aluminum alloys are less susceptible to SCC and have good machining and welding capabilities.

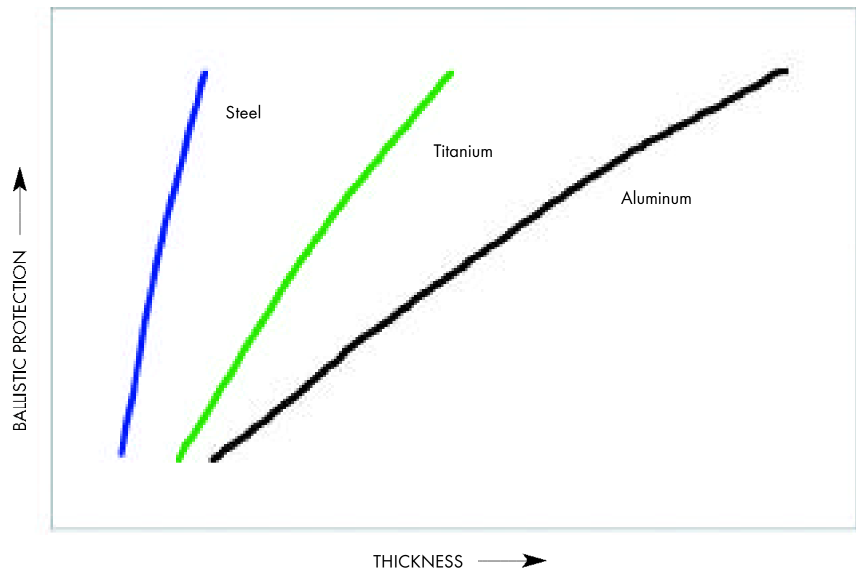

Figure 3. Ballistic Performance Comparison of Steel, Titanium and Aluminum.

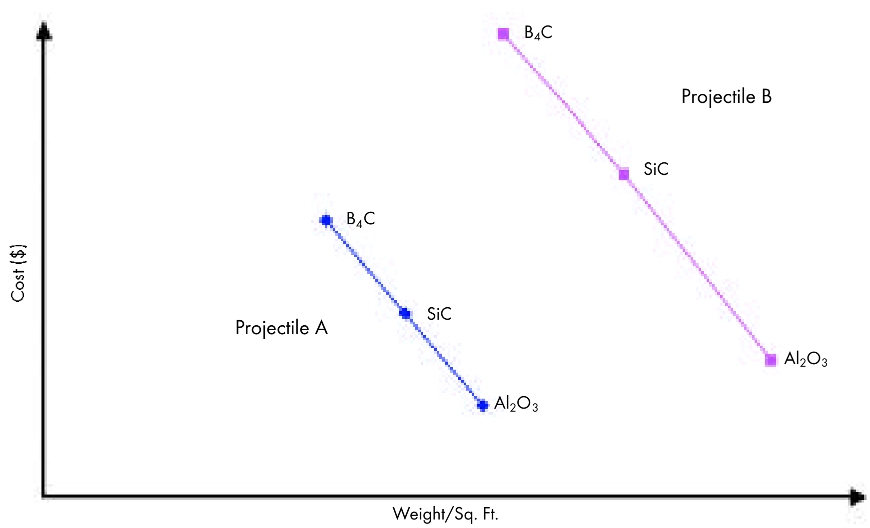

Figure 4. Cost-Weight Correlation of Ceramic Armor[6].

EXPLOSION EFFECTS

The selection of blast resistant materials for the protection of structures requires an understanding of explosion effects and the way shock interacts with structures. This sidebar discusses shock characteristics and the effects they have on structures.

The Explosion

An explosion is the rapid release of stored energy. This energy is released in part as thermal radiation; the rest manifesting as shock waves that are combinations of air blast and ground shock.

The air blast is the main damage mechanism. Air blast has a primary effect, which is the ambient over-pressure or incident pressure, and a secondary effect, which is the dynamic pressure or drag load. The first effect is caused by the air blast (due to shock waves) that propagates at supersonic velocity, and compresses air molecules in its path. As the shock wave encounters a wall, it is reflected thus amplifying the over-pressure, often by some significant factor greater than two. The air blast enters the building through wall-openings and failed windows, affecting floor slabs, partitions, and contents within the building. The shock waves undergo diffraction as they interact with various surfaces, thus increasing or decreasing in pressure. Eventually, the air blast subjects the entire building to over-pressure. The pressure decays exponentially in time and with radial distance from the epicenter and eventually becomes negative (negative loading phase), creating suction forces.

Dynamic pressure or drag loading manifests as a high velocity wind that propels debris generated by the blast. Another secondary effect is the ground shock that produces motions similar to high-intensity, short duration earthquakes. Figure 1 illustrates the various blast loads on a building.

The following effects are characterized from a blast wave:

• Magnitude of the overpressure or the peak pressure during the overpressure phase of the blast wave.

• Impulse or duration of the overpressure. Impulse is the area under the overpressure-time curve. Duration measures how long the overpressure phase of the blast wave lasts.

• Shape and rise-time of the overpressure pulse. A shock (or near-zero rise-time) is usually the worst case. Well-engineered high-explosives will typically have a very high shock value with close-to-zero rise-time, which then decays rather rapidly. Figure 2 illustrates the parameters of a typical blast wave.

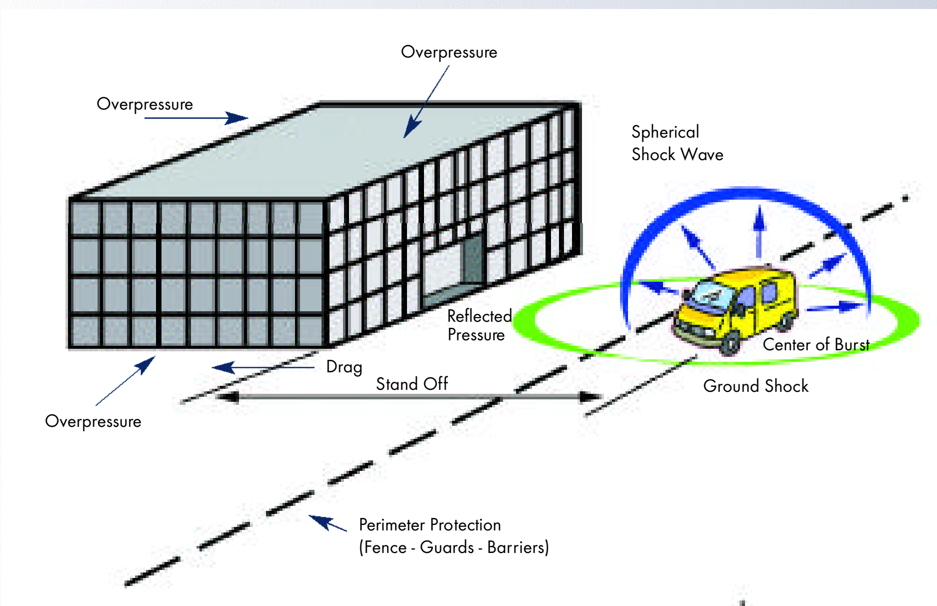

Figure 1. Blast Loads on a Building.

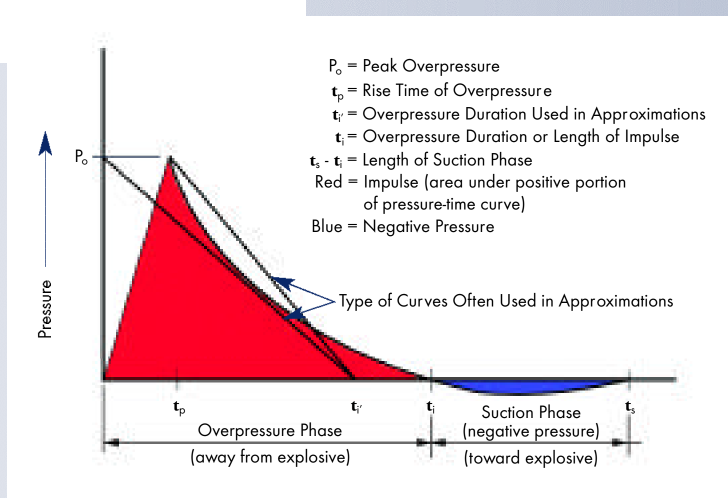

Figure 2. Blast Wave Parameters.

Comparison of Steel, Titanium and Aluminum

Steel has the greatest resistance to penetration of all of the metals considered, but at the expense of added weight to the application. Ti-6Al-4V provides very good ballistic protection at a much lower density than steel, and aluminum alloys are comparable to steel in penetration resistance, but require a much greater thickness. Figure 3 shows a comparison of the ballistic performance for typical alloy compositions of steel, titanium and aluminum.

Polymer Matrix Composites

Polymer matrix composites (PMCs) are used for personal protection for the defeat of small arms projectiles and as backplates, usually with ceramics, against larger projectiles and blast fragments. PMCs combine the beneficial properties of both polymer resins (ability to absorb and mitigate kinetic energy) and high performance fibers (high to ultrahigh elastic modulus). High performance composites possess higher specific strengths (ultimate tensile strength divided by density) than their metal counterparts. That is, they are capable of providing equivalent ballistic protection at reduced areal weights. Polymer matrix composites utilized for armor applications include fiberglass, aramid fiber, and polyethylene fiber composites.

S-2 Glass® fibers, developed by Owens-Corning Fiberglass Corporation, have been widely used due to their lower cost. Kevlar® is a man-made aramid fiber which was first introduced by the DuPont Corporation in the early 1970's. It is best known for its use in personal body armor (bullet-proof vests). Kevlar has exceptional impact resistance and small caliber ballistic resistance capabilities. Spectra® is a highly oriented polyethylene fiber originally developed by Allied Signal Corporation.[3] Spectra is a tough, low density fiber with excellent impact resistance and ultrahigh tensile strength. Spectra has been shown to outperform equivalent composite armors made with Kevlar fiber because of its high strength to weight ratio (Spectra has a density only 2/3 that of Kevlar).

Matrix resins used in conjunction with these fiber materials are usually thermosets. Thermosets are easier to process, have higher operating temperatures, are more chemically resistant, and are significantly less expensive than thermoplastics, but are more susceptible to cracking and are toxic in their uncured state. Epoxy resins are generally used for the best energy absorption properties while phenolic resins are used for fire, smoke and toxicity resistance. Layered composite backplates utilizing epoxy and phenolic materials are used in some cases to combine the beneficial properties of both resins. Such composite laminates are generally stitched together for multihit applications as delamination problems may occur especially after low velocity impacts.

Many laminates and laminate systems can be expensive to apply in structural protection. However, with judicious selection and design, these materials may be applied in a very cost effective manner in select, critical areas where performance criteria demand them. The article by Odello in this issue describes various composite structural modifications in detail. Also, consult the article by Coltharp for a look at how laminates perform in explosive events.

Ceramics

Ceramic armor materials are used for the containment of blast fragments and bullet penetrators. They were developed strictly for projectile resistance with a high hardness and compressive strength causing most

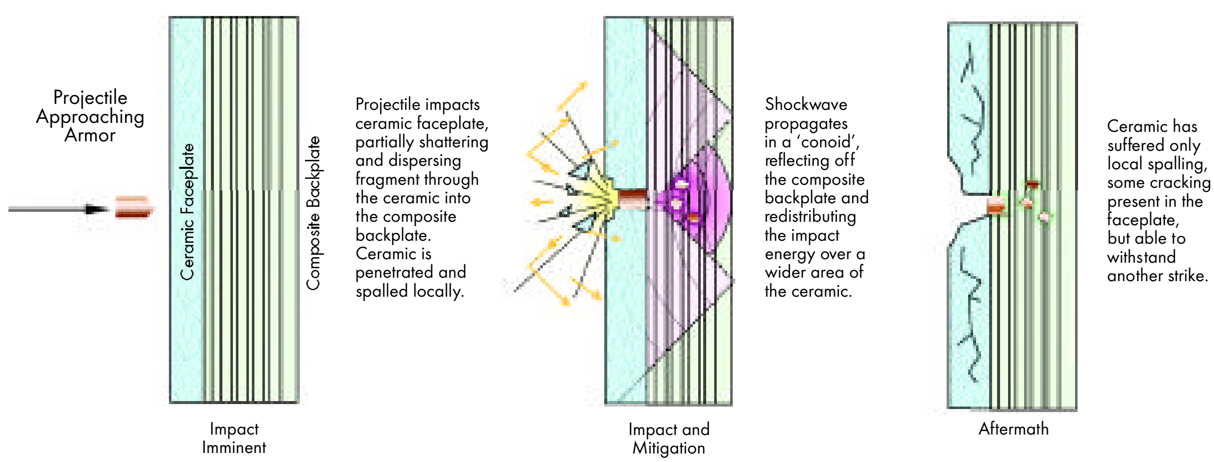

Figure 5. How Ceramic/Composite Armors Work.

penetrators to break up upon impact. The need for lighter protection materials for use in military aircraft brought about the use of ceramic armor materials. Ceramics offer an advantage over steel in weight reduction, and over all metals in impact energy absorption. The densities of ceramics are typically 2.5 – 4 grams per cubic centimeter (g/cc), while steels are roughly 7.8 g/cc.

There are considerable differences between the way ceramics and metals function when used for penetration resistance. Metals absorb the penetrator's kinetic energy through plastic deformation, while ceramics absorb the energy through fracture of the ceramic. Any protection scheme utilizing ceramics must also employ backing plates of metal, polymer, or composite. Backing plates are required to provide the structural support to the ceramic during the impact event.

To improve upon the multihit capability of ceramics, ceramic tiles are used to limit the fracture area. A thin covering over the ceramic tiles also helps to keep fractured pieces in place providing some additional protection while also preventing flying ceramic shards. Encapsulated ceramic armors have been found to further increase protection as the fractured ceramic cannot easily move out of the projectile's path. The penetrator must essentially pulverize the ceramic into powder which then moves around the path of the projectile.

The most common ceramic materials used for armor applications are alumina (Al_2O_3), boron carbide (B_4C), silicon carbide (SiC), and titanium diboride (TiB_2). Alumina (85% pure) is the most widely used due to its lower cost, while B_4C offers the best combination of performance and low weight. Figure 4 shows the cost to areal weight correlation required for three of the ceramics to defeat two different projectiles (Projectile B is larger than Projectile A). Titanium diboride is used to a lesser extent because of its higher density as well as price.

Ceramics are used in conjunction with a backplate material, a metal or polymer matrix composite (PMC), which catch penetrator and ceramic fragments after impact and absorb impact shock waves, as depicted in Figure 5.

EVOLUTION OF BPRM SCIENCE

In buildings where the threat of bomb blast or projectiles are greatest and standoff is not available, variations of those materials with larger energy absorbing capabilities will enable designers to lower overall shock overpressures transmitted through building walls, thus reducing fragments. In lesser-threatened buildings where standoff is available and blast overpressure is the main concern, combinations of concrete walls, steels, polymers, and less sophisticated laminates can lessen shock and fragment propagation at more reasonable costs. Engineers will continue to improve material properties, while at the same time improving their ability to control properties precisely. Processing enhancements will lead to lower costs in the long term, which could lead to greater adoption of sophisticated materials to mitigate threats.

Current work in BPRM seeks to further optimize the properties of combinations of materials. Laminate structures will take center-stage as the protection systems of the future. They employ diverse materials arranged to make the most of breaking up incoming fragments, allowing them to diverge, absorbing the energy of the fragments and eventually dissipating that energy.

SUMMARY/CONCLUSIONS

Defending personnel and structures from the effects of explosions is one of the most important aspects of military technology, and it is becoming all the more important in the civilian world due to the increased threat of random terrorist violence. Materials engineers will have to provide many of the solutions to these problems, with full consideration given to issues such as weight, formability, cost and the ability of the BPRM solution to not intrude on the human environment within the structure.

The appropriate selection of materials for specific applications is one of the most important roles that materials engineers and design professionals perform. The field of materials engineering is an applied science, and a highly qualitative one at that. More so than many of the other design and engineering disciplines, the materials field is application-driven. That is, engineers must develop an appreciation for the context of the problem before offering a potential solution.

Integrating materials knowledge into the design process at the inception of a project will foster superior solutions to complex blast and penetration issues. Materials support available from DOD agencies can provide some of the fundamental principles of this emerging science – bridging the knowledge gap – thus giving engineers the appropriate context to conduct their work. In that light, the potential material choices for blast and penetration protection in any given scenario are numerous. Like any other material selection process, generating appropriate BPRM solutions requires balanced management of all design requirements, both BPRM and other more traditional requirements.

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New! Textile Preforms for Composite Material Technology

Newly released, this publication is the first and only one of its kind – A panoramic and thorough examination of fiber/textile preform technology and its critical role in the development and manufacture of high-performance composite materials. This product was prepared in collaboration with Drexel University and authored by Dr. Frank Ko, the Director of Drexel's Fibrous Materials Research Center. Dr. Ko is one the world's foremost authorities on fibrous preforms and textile technology.

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Applications of Structural Materials for Protection from Explosions

This State-of-the-Art Review provides an examination of existing technologies for protecting structures from explosions. The report does not discuss materials and properties on an absolute scale; rather, it addresses the functionality of structural materials in the protection against blast. Each chapter incorporates information according to its relevance to blast mitigation. For example, the section on military structures describes concrete in arches, and concrete in roof beams for hardened shelters. The discussion on concrete is not limited to materials only; rather, it addresses the issue of structural components that incorporate concrete, and describes the materials that work in concert with the concrete to produce a blast-resistant structure. The report also illustrates various materials used for concrete reinforcement.

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A first of its kind publication, this State-of-the-Art Review provides a comprehensive overview of the unique requirements, problems, and opportunities faced by engineers designing and manufacturing spacecraft and launch vehicles. The book is authored by Dr. Carl Zweben, a major leader in the materials and space communities over the past several decades. While all material aspects of spacecraft and launch vehicles are addressed in this work, a special emphasis is placed on the unique qualities of materials used in space and highlights differences between them and their counterparts used in air/land/sea applications.

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Computational Materials Science (CMS) – A Critical Review and Technology Assessment

AMPTIAC surveyed DOD, government, and academic efforts currently studying materials science by computational methods and from this research compiled this report. It provides an in-depth examination of CMS and describes many of the programs, techniques, and methodologies being used and developed. The report was sponsored by Dr. Lewis Sloter, Staff Specialist, Materials and Structures, in the Office of the Deputy Undersecretary of Defense for Science and Technology. BONUS MATERIAL: Dr. Sloter also hosted a workshop (organized by AMPTIAC) in April 2001 for the nation's leaders in CMS to discuss their current programs and predict the future of CMS. The workshop proceedings comprise all original submitted materials for the workshop - presentations, papers, minutes, and roundtable discussion highlights and are included with purchase of the above report.

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Blast and Penetration Resistant Materials

This State-of-the-Art Review compiles the recent and legacy DOD unclassified data on blast and penetration resistant materials (BPRM) and how they are used in structures and armor. Special attention was paid to novel combinations of materials and new, unique uses for traditional materials. This report was sponsored by Dr. Lewis Sloter, Staff Specialist, Materials and Structures, in the Office of the Deputy Undersecretary of Defense for Science & Technology. BONUS MATERIAL: Dr. Sloter also hosted a workshop in April, 2001 (organized by AMPTIAC) for selected experts in the field of BPRM and its application. The workshop focused on novel approaches to structural protection from both blast effects and penetration phenomena. Some areas covered are: building protection from bomb blast and fragments, vehicle protection, storage of munitions and containment of accidental detonations, and executive protection. The proceedings of this workshop are included with purchase of the above.

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New! $YBa_2Cu_3O_x$ Superconductors – A Critical Review and Technology Assessment

An up-to-date report highlighting recent research on the processing of $YBa_2Cu_3O_{(7-\delta)}$ (YBCO) superconducting materials to produce high critical current densities. The processing of powders through the fabrication of bulk materials and the deposition of films is covered, along with advantages and disadvantages of the various manufacturing methods. Problems in finding suitable substrate materials along with the associated property characterizations are presented. Some applications for YBCO superconductors under research, and ones that have been realized, complete the report.

Order Code: AMPT-27 Price: $50 US, $75 Non-US

Polymer Coatings Increase Blast Resistance of Existing and Temporary Structures

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INTRODUCTION AND BACKGROUND

One of the greatest threats during a bombing attack comes from fragmentation – pieces of walls, windows, equipment, and vehicle debris flying at high speeds can result in extensive injury and death. (See Figure 1) A key tactic to defeating this threat is to ensure that the exterior wall of a building can survive the bomb blast without contributing to the fragmentation problem. While this is typically accomplished in existing buildings by adding strength and mass to the wall (usually with concrete and steel), this is often difficult to implement, time-consuming, heavy, and expensive. The Materials and Manufacturing Directorate of the Air Force Research Laboratory (AFRL/ML) at Tyndall Air Force Base Florida is pioneering simpler, lighter, and more expedient polymer retrofit solutions to introduce ductility and resilience into walls. The premise of the retrofit technique is to apply an elastomeric coating that bonds to the wall forming a tough elastic membrane. Although fracture of the wall may occur, the polymer membrane will not rupture and can effectively contain the debris.

Figure 1. **Debris Hazard.**

Expedient Retrofit Techniques

The Force Protection Branch of AFRL at Tyndall Air Force Base has been developing expedient retrofit methods for unreinforced infill concrete masonry unit (CMU) walls in existing buildings, and for lightweight temporary structures. (CMUs are commonly referred to as "concrete blocks," the hollow-core, pre-cast blocks used for construction.) In many parts of the world, the most common exterior construction technique for buildings is to use steel or concrete frames (vertical columns and horizontal beams) to carry the gravity loads, and fill the open areas with stacked CMUs to form walls. (Hence the term "CMU infill" walls.) Unreinforced construction is composed of CMUs with no embedded steel. When overloaded by airblast, unreinforced CMU walls typically fracture into pieces that are propelled at high velocity into the interior of the structure, possibly causing severe injury or death. As a result of the threat posed, this wall type has been prohibited for new military construction in the recently released *DOD Minimum Antiterrorism Standards for Buildings*. Many buildings utilizing this type of construction, however, are still occupied and in use, resulting in the need for effective retrofit solutions.

Fiber-Epoxy Composite Initial research efforts to develop expedient retrofits produced a field-made composite of high-strength fabric (aramid or glass) in an epoxy matrix that is bonded to the entire interior face of the CMU wall as shown in Figure 2. The composite is extended beyond the edges of the CMU wall and overlapping the concrete frame, which helps it to resist the applied blast pressure. To enhance shear strength at the connections,

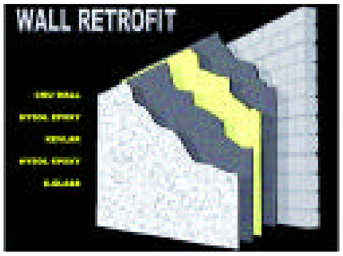

Figure 2. **Composite Retrofit.**

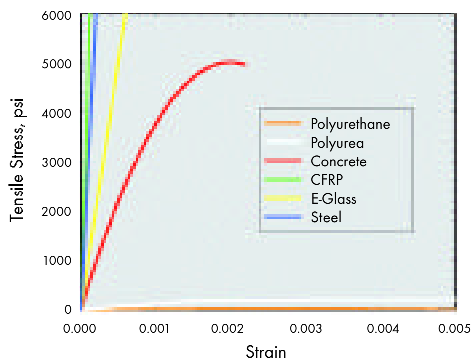

Figure 3. **Typical Stress-Strain Curves.**

Figure 4. **Application of Elastomeric Retrofit.**

Table 1. **Polymer Characteristics.**

Property	Value	Test Standard
Secant Modulus[1]	24,000 psi	ASTM D638
Elongation at Rupture	90%	ASTM D638
Maximum Tensile Strength	2000 psi	ASTM D638
Flammability	Flame resistant; 2-hr fire rating	ASTM E119 ASTM E84
Toxicity	Nontoxic after curing	Review MSDS

[1] The slope of a straight line drawn from the stress-strain diagram's origin to a point on the curve at 60% of maximum tensile strength.

additional layers of composite can be used to reinforce the connection points. In the event of an explosion, the composite enhances the bending strength of the wall and prevents broken pieces of the wall from entering the protected space and causing injury to the occupants. While this method of increasing wall ductility and strength is an option, the application method is time consuming and difficult.

In order to improve upon the composite retrofit, a search for an easier and faster retrofit technique was undertaken. Coupled with trying to reduce the difficulty and time required for installation, was a desire to introduce significant resiliency into the structure - even at the expense of strength and stiffness. This shift in philosophy was founded on the premise of containing the fragmentation and eliminating the debris hazard to occupants, rather than preserving the structural integrity of the wall itself. Figure 3 shows some engineering stress-strain curves for typical building materials and retrofit materials and demonstrates the shift from stiffer, stronger materials like steel and glass fibers to those with more ductility like polymers. Although the x-axis is truncated at 0.5% strain, many polymers can undergo up to 100% elongation without rupturing. As a result, elastomers were investigated as potential retrofit materials because they are easy to apply, cure very quickly, and could introduce significant ductility and resilience into the wall system.

Polymers In the fall of 1999, AFRL began evaluating spray-on polymer coatings as an expedient retrofit technique for non-load bearing CMU walls. The material that was used is an elastomer that is ductile, tough, and has modest strength. The material is sprayed directly onto the interior surface of the wall and cures almost instantly, as shown in Figure 4. The thickness of application is relatively easy to control, and the polymer bonds to a wide variety of surfaces. This retrofit technique takes advantage of the toughness and resiliency of modern elastomers to effectively deform and dissipate the blast energy, while containing shattered wall fragments. Although the retrofitted walls may shatter in a blast event, the elastomer does not rupture and effectively contains the debris.

ELASTOMERIC MATERIALS

The resilience and large strain capacity of elastomers can be exploited to absorb blast energy and contain building debris. Elastomers are composed of long polymer chains, usually cross-linked or connected by chemical bonds. Cross-linking makes elastomers reversibly stretchable within a significant range of deformations. In the unstretched state, the polymer chains are oriented in random directions. When stretched, the polymer chains become elongated and ordered along the

Figure 5. Retrofitted Lightweight Temporary Structure.

deformation direction. When no longer stretched, the cross-links guide the elastomer back to its original shape as the chains once again randomize.

The elastomer used in this study was a two-component sprayed-on polyurea. Polyurea elastomers do not require a catalyst to accelerate the chemical reaction when the two components are mixed. The polyurea material must be applied at high pressure and temperature, with 1:1 mixing of the hardener and resin occurring just beyond the spray gun to minimize clogging. Temperature does not affect curing of polyurea. With proper training and equipment, the polymer material can be safely applied to wall surfaces.

Material Properties

Polyureas are characterized by high elongation, high tear strength, and superior modulus of elasticity. Typical physical and mechanical properties of the polyurea used in this study are indicated in Table 1.

Emissions and Fire Performance The polyurea material was evaluated to determine the type and amount of volatile organic emissions off-gassing from polymer-coated aluminum plates at room temperature (70°F) and at 95°F to simulate a warm condition. The rate of emission for each compound identified decreased as a function of time and most of the emissions were undetectable one week after application. With adequate ventilation provided, the levels of emitted compounds will be below National Institute for Occupational Safety and Health (NIOSH) time weighted averages (TWA) for continuous 10-hour exposures one day after application.

Two performance tests were conducted to evaluate the hazard resulting from a fire in a retrofitted structure. The first test was performed on a CMU wall in accordance with ASTM E119-00, "Standard Test Methods for Fire Tests of Building Construction and Materials." The second test was performed on a polymer specimen in accordance with ASTM E84-00, "Standard Test Method for Surface Burning Characteristics of Building Materials" (NFPA 255, ANSI/UL 723 and UBC 8-1). The wall assembly coated with the polymer met the temperature and structural requirements of ASTM E119-00 for a period of 120 minutes, and did not have a significant negative impact on the assembly's fire rating. The polymer specimen was determined to be a Class III material according to the 1997 Uniform Fire Code with relatively large smoke generation potential. In practical applications, the smoke hazard can be mitigated by alternate material formulations or by using an additional intumescent (swells and chars when exposed to flame) coating on the retrofit.

Engineering Properties The polyurea was much stiffer than many other candidate materials. This initial stiffness helps to reduce wall deflections in response to a lateral load such as airblast. The high elongation at rupture provides the toughness and ductility to contain the debris and fragmentation, even if large deformations occur. Based on the engineering properties determined from uniaxial tensile tests, dynamic models of the wall system can be used to predict response to airblast loads. While simple single-degree-of-freedom models have been developed, higher fidelity models are required to fully understand the effect that varying the retrofit material properties will have on dynamic performance of the wall system. Current practice, therefore, relies on laboratory and full-scale explosive experiments to validate retrofit performance.

LIGHTWEIGHT TEMPORARY STRUCTURES

Because of the promise shown by the elastomeric retrofit concept and the common use of lightweight temporary structures, AFRL developed methods for increasing the survivability of these facilities, which are characterized by timber stud walls, exterior aluminum siding and interior veneer-plywood paneling. Since these walls are load bearing and provide support for the roofing system, the elastomeric retrofit technique was combined with additional lightweight framing to prevent collapse of the structure once the load bearing capacity of the walls is diminished. A series of full-scale tests was conducted at Tyndall Air Force Base Florida and, as part of an international cooperative research and development program, in Israel to validate the performance of the retrofit method. Figure 5 shows a typical test result, where the unretrofitted half of the trailer was destroyed and the retrofitted half is intact. This test article was coated on the interior and exterior to evaluate where the retrofit material was most effective. While the exterior coating may provide some load distribution benefits, the interior coating is critical because it forms the tensile membrane that contains the wall fragments.

Based on this series of tests and analytical results from single-degree-of-freedom models, retrofit design criteria were established that can reduce standoff distances required for protection by up to 50 percent. The recommended retrofit consists of a 1/2-in thick coating on interior wall surfaces, or both interior and exterior coatings each 1/8-in thick.

CONCRETE MASONRY UNIT (CMU) WALLS

A series of explosive performance tests of full-scale unreinforced CMU walls were conducted at Tyndall Air Force Base and in Israel. The wall aspect ratios and boundary conditions were varied, as were the blast loadings. Some walls were retrofitted on the interior only, while others were retrofitted on the interior and exterior. Three unretrofitted control walls were also included in the test series. In each test, peak displacement was measured using an active displacement gauge or a passive indicator (scratch gauge).


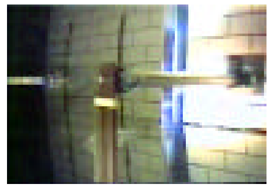

Figure 6. **Unretrofitted and Retrofitted CMU Walls.**

Typical pre-test and post-test photographs are shown in Figure 6. In general, post-test observations indicated that the exterior faces of the CMU were shattered at least half way through the CMU, with the interior faces of the CMU remaining adhered to the polymer liner. However, in all but a one case, the polymer liner remained intact and effectively contained the fragmentation from the fractured CMU. In several cases, particularly in the tests in Israel, peak dynamic deflections were near two feet, which are likely unacceptable in a real world situation. These deflections can be controlled by material formulations with greater initial stiffness or by increasing the thickness of the membrane.

The data from the blast performance tests and analytical results from single-degree-of-freedom models were used to develop design criteria for buildings consisting of a concrete or steel frame with non-load bearing CMU infill walls. The criteria were developed assuming an 8-inch nominal CMU thickness and a wall height of 12 feet and connected on only two opposing edges (one-way action). These criteria will be conservative for walls connected on all four edges (two-way action), shorter walls, and for walls with thicker CMU. As described earlier for temporary structures, the recommended CMU wall retrofit consists of a 1/2-in thick coating on interior wall surfaces, or both interior and exterior coatings each 1/8-in thick.

SUMMARY AND CONCLUSIONS

Unreinforced CMU in-fill construction and lightweight temporary structures are particularly vulnerable to overloading from bomb-induced airblast. Many such buildings are currently in use with inadequate standoff from roadways, parking lots, or protected perimeters. The spray-on polymer retrofit technique offers one solution that decreases the vulnerability of occupants of these common building types. This innovative retrofit technique takes advantage of the toughness and resiliency of modern polymer materials to deform and effectively dissipate the blast energy while containing the shattered wall fragments.

Blast load capacities for unreinforced non-load bearing CMU walls retrofitted with polyurea are presented in terms of charge weight versus standoff distance in Figure 7. In the chart, charge weight is the equivalent weight of TNT and the standoff distance is the distance from the center of the charge to the outside face of the wall. The curves represent the threshold of failure, defined as collapsed walls with objects thrown into the interior space, such that serious injury and/or death would be

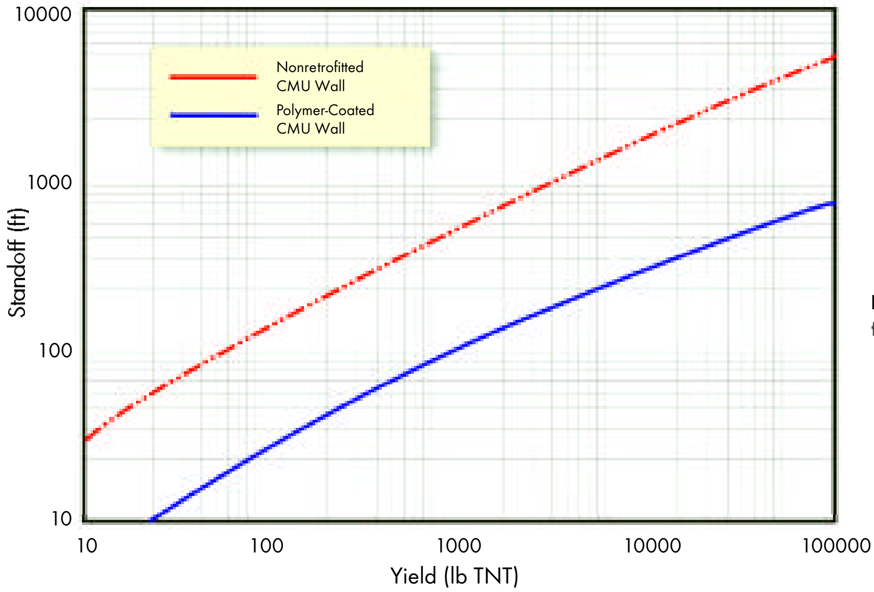

Figure 7. **Charge Weight versus Standoff for Unreinforced CMU Walls.**

Figure 8. **Retrofitted CMU Wall with Window Retrofit.**

expected. These curves show that the polymer retrofit technique for CMU walls can reduce standoff distances required to limit serious injury and death by as much as 80 percent. Similar charts for lightweight temporary structures show that the technique can reduce standoff distances by as much as 50 percent.

Ongoing efforts are focused on extending the philosophy of introducing resilience to other building components such as door and window frames, with the goal of providing a retrofitted building system with balanced resistance to airblast loads. Figure 8 shows the results of a test in which a blast resistant window was connected to the wall system with the polymer retrofit. By connecting the window frame to the retrofit rather than only to the structural wall components, the tolerance for deformation is greatly enhanced. Conventional retrofits that increase mass and strength result in limited deflection of the wall, which makes adequate connections for windows and doors even more problematic. By exploiting the resilience afforded by the polymer retrofit technique, the entire wall system can be held together, providing an expedient retrofit that greatly reduces the probability of casualties in the event of a terrorist bomb attack.

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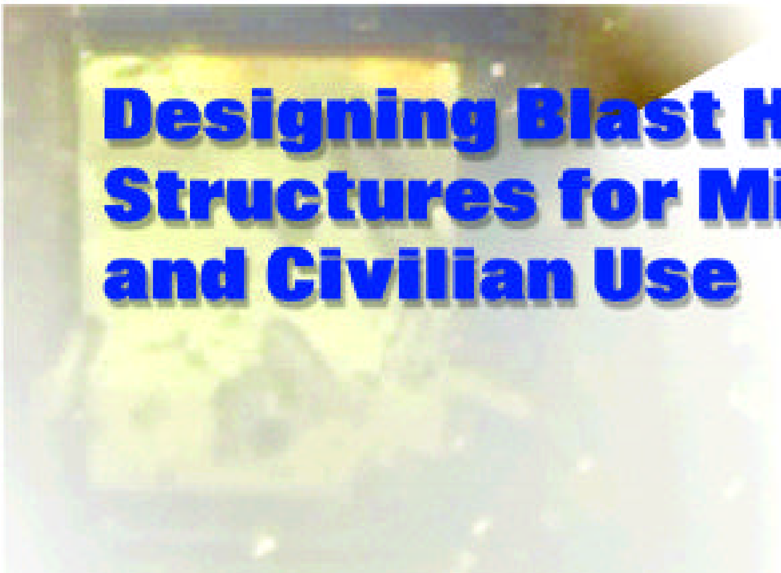

Designing Blast Hardened Structures for Military and Civilian Use

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INTRODUCTION

Protective structures over the years have relied on distance and mass for protection. For thousands of years, people have used caves and massive stone or wood structures to protect assets. Exterior walls had few openings because doors and windows are difficult to harden and defend. Defenders have used guards, fences, walls, ditches, hills, moats and other barriers to keep potential threats at a safe distance. Like ancient protective structures, most hardened structures today use massive construction of wood, rock, soil, or reinforced concrete with few windows or doors. Contemporary threats are kept at a safe standoff by operational and physical means similar to those used over the millennia. This article provides a broad, overall perspective on the problem of designing a hardened structure. A hardened facility design example is presented to demonstrate the procedure.

DEFINITIONS

The terms "hardened structure" and "protective structure" mean different things in different contexts, and lately with the increase in the terrorist threat, the common definitions have changed again. Antiterrorism Protection, Physical Security, and Hardened Structures are terms being used by many. The following definitions will hold for the bounds of this article:

Physical Security

Physical Security consists of measures taken to address criminal and vandal threats. Physical Security uses defensive measures that provide layers of detection and delay around an asset. The defensive layer must provide enough delay time to allow a response force to halt the attack. For the DOD, Physical Security is addressed primarily by policy that defines operational procedures, electronic security systems, and structural security measures to provide the required delay time. The assumption is that some minimal level of protection is required and risk is evaluated on an organization-wide basis with the assumption that there is always a criminal threat.

Antiterrorism Protection

Antiterrorism Protection addresses the design of both the building and the site to minimize the blast loads and weapon effects from terrorist threats to assets - usually people. This may mean the building is destroyed, but damage to assets is minimized. The actual threat to a specific asset is seldom known and it is unlikely that a specific asset will ever have a terrorist attack. The price people are willing to pay for protection from an unlikely threat of unknown magnitude has historically been very little in this country, but it is changing. As part of Antiterrorism Protection, blast hardening is sometimes done, but does not commonly meet the level of protection in the following definition of a hardened structure.

Hardened Structure

A *Hardened Structure* is usually designed to perform its primary mission after a wartime attack making hardening one of its primary requirements and a significant part of its cost. The facility is protected against a wide range of threats including forced entry, Chemical/Biological/Radiological (CBR), airblast, ground shock, penetration, fragmentation, and damage to the structure and equipment due to explosive loading. Designs must consider how camouflage, concealment and deception, active defense, and manned response can reduce or limit the effectiveness of the threat. The design assumptions are that during a war, the facility will be attacked and that it must survive and function after the attack. Almost all hardened structures inherently satisfy the requirements for both Physical Security and Antiterrorism Protection.

Likelihood of Protection

The conceptual differences between the three types of protective measures defined above are the likelihood of the protection actually being needed, the consequences of it not working, and the willingness of the user to pay for the protection. The government is willing to pay a limited price for physical security for all facilities and a high price for hardened structures for specific assets. In the past we funded antiterrorism protection at a low level because the likelihood was low, but in light of recent events, our population is reevaluating this stance.

DESIGNING FOR WARTIME THREATS

Designing facilities hardened for wartime threats is sometimes politically easier than designing normal facilities for the terrorist threat; because the users of the wartime hardened facilities understand the importance of hardening and are willing to give up things like large doors and windows, fancy interior finishes, and easy access. Some of the key aspects in design include:

Conventional Weapons

A wartime conventional weapon threat can range from airblast only to direct hits from precision-guided bombs and penetrators. Fully hardened facilities are designed to withstand a direct hit and detonation of a penetrating weapon. Semi-hardened facilities are designed to withstand small area weapons and near miss detonations of larger bombs. Other protected facilities are only designed to withstand airblast and fragments from bombs detonating at a distance.

Balanced Survivability

Whatever the threat, the designer tries to incorporate balanced survivability into the building. Balanced survivability is a condition wherein no significant facility failure mode has been overlooked or its importance underestimated, thus the facility has no "Achilles Heel." Balanced survivability exists for a facility when all critical subsystems and resources required for accomplishing the facility's mission are equally survivable at a specified threat level.

A balanced survivability assessment (BSA) determines the capability of a facility to survive against a specified threat spectrum and still perform its mission. The BSA is a systems approach to survivability, yielding recommendations that facility designers can use to make prudent investment decisions in light of what they consider to be the most critical systems and most worrisome threats. A BSA can be performed on a facility design or an operational facility, and it is ideal if a team trained in BSA techniques examines design drawings early to identify potential survivability flaws.

Balanced survivability ensures that no threat is neglected, and that all threats are addressed consistently. Additional design considerations are reliability, maintainability and logistics. Incorporating post-attack expedient measures for a facility's systems that could help it recover quickly after an attack (or prevent further damage) should be considered. Such measures may include incorporating utility cutoffs, additional fire protection, adequate utility backup connections, and structural repair kits.

Site Planning

Key elements in planning the site include:

Dispersion Placing resources in irregular patterns, and using physical separation, orientation, staggering, and system component distribution will increase survivability. Dispersion greatly increases an attacker's targeting difficulties, and reduces the chance of simultaneous or collateral damage from any single strike.

Orientation Hardened facilities should be oriented so their most vulnerable sides face away from nearby critical structures. Aircraft shelter entrances should not face each other or nearby critical facilities. This decreases the potential for damage to vulnerable sides of the structure if a nearby structure is hit. A critical review of the site, its surroundings, and the building's orientation and location on the site should be performed. If this siting analysis shows an explosive threat is more probable from one direction, the facility should be oriented and/or the entrances located to minimize blast and fragment loads on the blast door.

Separation From a survivability standpoint, there is an optimum distance between hardened facilities, such that no two facilities can be attacked by a single weapon or be acquired by an airborne target acquisition system on a single pass. Siting facilities too far apart however, may degrade their operational performance.

Building Layout

Redundancy The survivability and overall operability of the protected system can be improved by incorporating redundant facilities, components, paths, and circuits into the system. In this manner, damage to one part of the system will not necessarily shut down the entire system, but instead shift the operation to a redundant part.

Footprint and Floor Plan The footprint of a hardened structure should be a rectangle, square, or other regular geometric shape that attenuates the effect of an explosive blast. Designers should avoid reentrant corners that tend to amplify blast pressure and enhance a structure's radar image. (Areas such as recessed entryways contain reentrant corners.) Activities of a less critical nature should be located on the exterior of the building. Hallways should be located along the exterior wall. Compartmentalized functional areas (isolation zones) should be considered to prevent fire or internal bomb blasts from propagating from one area or zone to another. Compartmentalization can be accomplished both by careful functional zoning and by proper design of walls, internal blast doors, and other separations.

Exterior Openings Exterior openings include personnel and equipment access, fresh air ventilation, cooling, and combustion equipment intake and exhaust portals. Designers should anticipate the possibility of blast pressure, heat, dust, fragments, and toxic gases entering the facility through exterior openings, and take appropriate preventive measures. Entrance openings should be kept as small and few in number as possible to minimize shielding problems, but still satisfy operational and emergency ingress and egress requirements.

Proportioning components The structural design process has two major, interdependent phases: (1) selecting a trial structural configuration (arrangement, shape, and material), and (2) proportioning components to prevent failure under prescribed influences. The proportioning phase is calculational in nature, and therefore requires a numerical response threshold (performance criterion) for each failure mode (failure modes are established during design). Typical failure modes are those associated with airblast, fragmentation, spall, weapon penetration or perforation, shock motion, cratering, fire, suffocation, and CBR agents. For the various failure modes, the performance criteria quantify the survivability requirements of the protected system elements and functional spaces in terms of personnel tolerances, equipment tolerances, endurance periods, and post failure capabilities.

TERRORIST THREATS

Once a defined threat is specified, standard design procedures for hardened structures are applied. Even if no threat is defined, the DOD has determined that a minimum level of protection is warranted for all inhabited buildings, and Unified Facilities Criteria (UFC) 4-010-01 *"DOD Minimum Antiterrorism Standards for Buildings"* is applied. This standard establishes criteria for DOD-inhabited buildings to minimize the potential for mass casualties and progressive collapse from a terrorist attack. The overarching antiterrorism philosophy is that an appropriate level of protection can be provided for all DOD personnel at a reasonable cost, and reduces the risk of mass casualties. Full implementation of the standards provides a level of protection against all threats and significantly reduces injuries and fatalities for the threats upon which these standards are based. The costs for these protective measures are not significant for most projects. The primary methods used to achieve this outcome are to maximize the standoff distance, to construct superstructures resistant to progressive collapse, and to reduce flying debris hazards from glazing.

Maximize Standoff Distance

Maximizing the standoff distance keeps the threat as far away from critical buildings as possible. It is the easiest and least costly method for achieving the appropriate level of protection to a facility. When standoff distance is not available, the structure needs to be hardened to give the same level of protection that it would have with a greater standoff. While sufficient space around a structure is not always available to provide the minimum standoff distances required for conventional construction, maximizing the available standoff distance will always result in the most cost-effective structural solution. Maximizing standoff distance also ensures that there is opportunity in the future to upgrade buildings to meet increased threats or to accommodate higher levels of protection. If minimum standoff distances are achieved, conventional construction should minimize the risk of mass casualties from a terrorist attack, with only a marginal impact on the total project cost.

Progressive Collapse Avoidance

Progressive collapse is a chain reaction of failures following damage to a relatively small portion of a structure. The resulting damage from a progressive collapse failure is out of proportion to the damage of the initial failed area. Consequences of progressive collapse are unnecessary loss of life and the entrapment of survivors in the collapsed structure.

The UFC has provisions that minimize the ability of the structure to go into a progressive collapse mode of failure. Designing those provisions into the buildings before construction begins, or during a major renovation project is the most cost effective solution. All inhabited structures of three stories or more, are to have a progressive analysis performed. This analysis assures that the structure will remain stable when key members are removed and is accomplished by providing structural continuity, redundancy, or energy dissipating capacity (ductility) in the remaining members of the structure. There are two approaches to perform a progressive collapse analysis - the direct and the indirect methods.

Direct Design Approach Direct design explicitly considers structural resistance through the alternate path method or through the specific local resistance method. When a local failure occurs, such as the removal of a structural member, the alternate path method seeks to find a load path that will absorb the loads created. The specific local resistance method applies loads to the structure that must be accounted for in the design.

Indirect Design Approach Indirect design implicitly considers a structure's resistance to progressive collapse by defining a minimum level of strength, continuity, and ductility for structural members. Typical guidance recommends using highly redundant structural systems such as moment resisting frames, continuity across joints so the member can develop the full structural capacity of the connected members, and design members that accommodate large displacements without complete loss of strength. Other design details that minimize the possibility that collapse of one part of the building will affect the stability of the remainder of the building should be incorporated. Examples include designing floor systems with top and bottom steel to accommodate load reversal, and designing building additions to be structurally independent from the protected portions of the existing building.

Minimize Hazardous Flying Debris

A high number of injuries result from flying glass fragments and debris from walls, ceilings, and fixtures (non-structural features). Flying debris is minimized through the proper design and selection of appropriate building materials. The glazing used in most windows will break at very low blast pressures, creating hazardous, dagger-like shards. The simplest protection from flying debris is to minimize the number and sizes of windows used in the building design. Additional protection can be garnered by using enhanced window units. Blast-resistant window and door units must be purchased as complete, tested assemblies that include the glazing unit, door or window frame, and frame connections to the structure. When installed, these elements become an integrated structural system. The UFC requires that all glazing units use a 1/4-inch laminated glass in all new construction and major renovations.

OBSERVATIONS OF CONVENTIONAL STRUCTURES

Review of typical structures often reveals that structural members have different capacities during the positive and negative phases of the blast load. Also, these members can have significant blast load capacity, but the connections may not. Special provisions of the concrete and steel design codes need to be followed to make a structure perform well, even when a reasonable amount of standoff is provided.

Conventional design of buildings results in balanced design for normal loads and usually a very unbalanced survivability for blast loads. Most buildings are initially designed for easy access and natural lighting, which results in numerous lightweight doors, and larger windows. Hardening doors and windows for blast and fragment loadings is difficult and very expensive, typically 2 to 10 times that of normal construction. This results in a significant increase in building cost. Typical roof construction is kept lightweight especially in high seismic areas and the lack of mass in these elements makes it difficult to design them for blast loads.

GENERAL REFERENCES

Department of Defense, *Interim Antiterrorism / Force Protection Construction Standards*, December 16, 1999 (hereby cancelled)

Department of Defense, UFC 4-010-01, *DOD Minimum Antiterrorism Standards for Buildings*, July 2002

Department of Defense, Instruction 2000.16, *DOD Antiterrorism Standards*, June 14, 2001

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Department of the Army, and the Air Force, TM 5-853-3, AFMAN 32-1071 Vol. 3 *Security Engineering Final Design*, May 1994

Department of the Army, TM 5-853-4, *Security Engineering Electronic Security Systems*, May 1994

Department of the Army, the Navy, and the Air Force: TM 5-1300, P-397, and AFR 88-22, *Structures to Resist the Effects of Accidental Explosions*, November 1990

Department of the Navy, MIL-HDBK-1013/1A, *Design Guidelines for Physical Security of Facilities*, October 1987

Department of Defense, UFC 3-340-01 (TM 5-855-1), *Design and Analysis of Hardened Structures to Conventional Weapons Effects (DAHS-CWE)*, June 2002

ENDNOTE

* "Bare charge" refers to an unconfined explosive mass where the energetic material is not contained in a rigid vessel. When an energetic material is confined in a rigid container (for instance a thick, tightly-wound paper or metal casing) its explosive effect is enhanced.

Design Example– Exterior Blast Upgrade

The following design example will help to illustrate the use of hardening techniques to strengthen civilian type structures. The example involves modifying the in-process design of a building to provide resistance against an exterior terrorist bombing attack. Blast loads from the example's standoff threats will cause damage, but the desired level of protection may be achieved with implementation of relatively minor modifications.

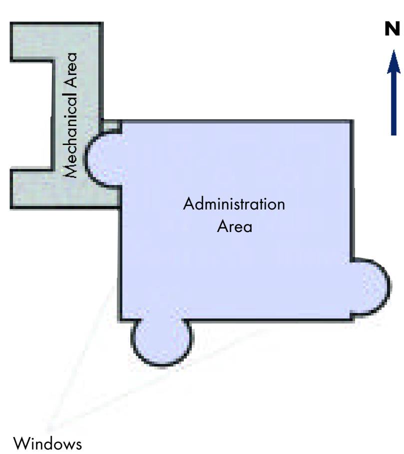


Figure 1. **Schematic Floor Plan of Example Building.**

Project Description

Review of an ongoing structural design (new construction), and incorporation of blast resistant components. The scope of the review was to examine structural components and cladding, and then upgrade them for various blast loading events.

Facility Description

The structure being analyzed was designed for standard seismic, gravity, wind, and live loads, but not blast effects. The facility consists of an administrative and operations area, and a shipping-and-receiving area that houses the mechanical and electrical rooms. (See Figure 1) The administration area is a two-story steel braced-frame structure with a composite steel and concrete roof deck, and a square floor plan that is 135-feet by 135-feet. The mechanical area is a one-story attached structure measuring about 59-feet by 122-feet. It is constructed as a mixed system of braced steel frames, and load-bearing cast-in-place concrete walls. The roof is a steel joist with metal decking. The back and sides are cast-in-place concrete walls, while the front (west) wall is made of precast concrete panels. Windows are located on the west and south walls of the administration area.

Blast Events

Two bomb weights were considered in this review. Bare explosives were used in the analysis, and fragments were not considered. The first threat was 50 pounds of TNT located 100ft from the nearest point on the building exterior. The second was 1000 pounds of TNT, located 200-ft from the building perimeter. The mechanical area was closer than the administration area, and needed to be analyzed for the 1000 pound detonation.

Design Standards Used

Many structural design standards and Army manuals are used in preparing this structural analysis and design. They are the American Concrete Institute (ACI) 318 - *Building Code Requirements for Structural Concrete*, the American Institute of Steel Construction (AISC) - *Manual of Steel Construction (LRFD-Load and Resistance Factor Design)*, and Army Technical Manuals: TM 5-853-3, TM 5-855-1 and TM 5-1300 for designing building systems to resist explosives effects. This design primarily uses TM 5-855-1 (the Design and Analysis of Hardened Structures to Conventional Weapons Effects {DAHS CWE} Manual), and its associated computer codes to determine the blast loads and structural responses. Response limits were taken from TM 5-1300, which has a greater margin of safety, and is more consistent with the protection of civilian personnel during peacetime.

Airblast Prediction

Airblast calculations were made using the BLASTX computer code, which accurately computes both the positive and negative phases of the shock wave. The negative phase of the blast wave is often neglected in structural analyses, but is of particular importance when reviewing unhardened, or normal structures. The shockwaves used in the design analysis are shown in Figure 2. This is a plot of the incident (unreflected) shockwaves obtained for both 50-lb TNT at 100 ft, and 1000-lb TNT at 200 ft. It is presented to illustrate the relative size of the two threats, and it is apparent the 1000-pound explosion creates a higher pressure and impulse, even at twice the distance. These pressures are what the roof structure would experience, while the walls receive reflected pressures that are about twice these magnitudes.

Dynamic Analysis

Structural elements subjected to blast loads were analyzed individually using the SPAN computer code. SPAN applies the BLASTX output, and performs a Single degree-of freedom Plastic ANalysis of wall panels, and beams. It then performs a numerical integration of the dynamic response to that blast load. The SPAN analysis for one precast wall panel showed that the panel was fully plastic for both the inward and outward (rebound) response. This relatively large rebound was due to the fact that negative pressure (suction) coincides with the structural elements' rebound response. Rebound loads were significant in this design review, and need to be treated as rigorously as the blast load response during the positive phase loading.

Structural Response Criteria

Two limits were addressed in this design review for blast loadings: (1) the structure needed to be repairable and the operation of the facility not severely impacted, and (2) operating personnel should be protected. Therefore, dynamic response limits of structural elements in flexure are defined to prevent excessive element damage but are within the limits allowed by TM 5-1300 for personnel safety.

Structural Analysis of 50-pound Threat

Damage to the structure was assessed at the worst case bomb location for each individual structural element. The analysis results showed that the roof, and the precast wall system of the main area would not be damaged. However, the mechanical area would receive damage to the roof joists and beams during the upward rebound because the bottom flanges of the joists were not adequately braced. This would occur because the roof deck did not have a concrete topping. As seen in Figure 3, the entire roof of the mechanical area was damaged as were a few of the precast panels. In all roof areas however, roof decking, steel columns, and roof beam connections were adequate for this loading condition.

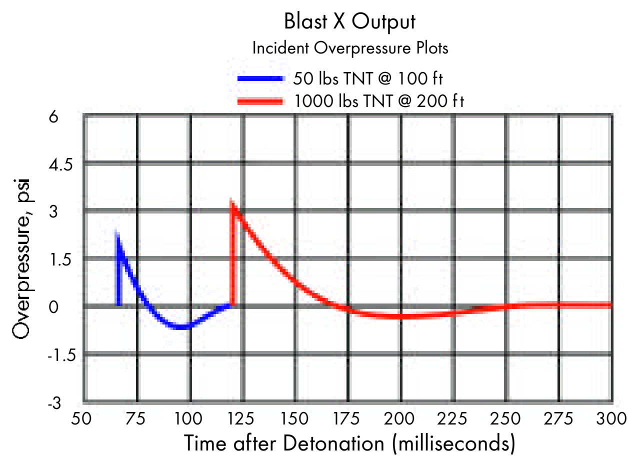


Figure 2. **Blast Pressure for 50 lbs TNT at 100 ft and 1000 lbs TNT at 200 ft.**

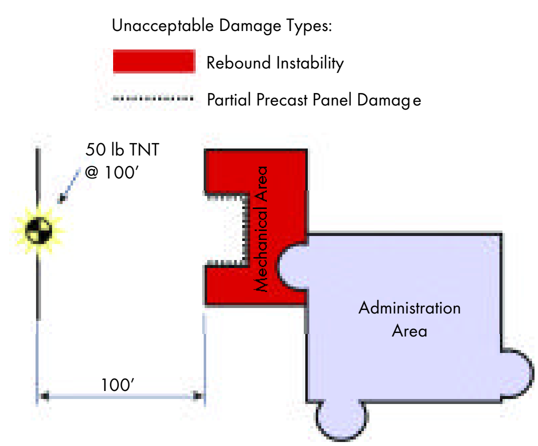


Figure 3. **Structural Damage from 50-lb Threat.**

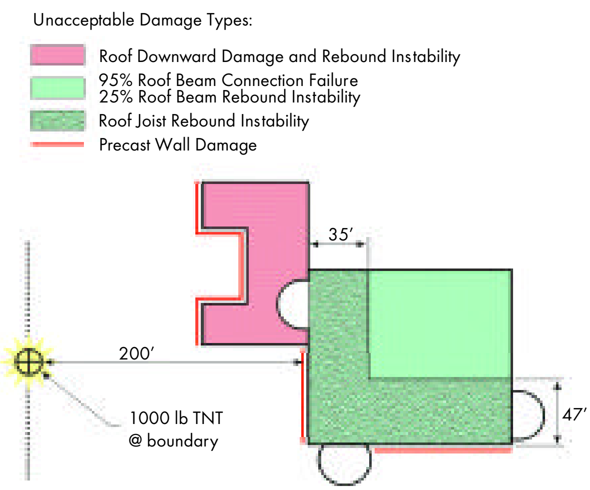


Figure 4. Structural Damage from 1000-lb Threat.

Structural Analysis of 1000-lb Threat

When this facility was analyzed for the 1000-pound event, the damage was much more significant. It can be seen in Figure 4 that the area of damage covers the entire facility, as unacceptable damage occurs to about 60% of the admin area roof, 100% of the mechanical area roof, and 100% of the precast wall panels in both areas. In each event all roof joists, except the long span joists in the main area, experience a lateral instability failure during roof rebound, as do many of the roof beams. There were considerable beam connection failures in the admin area roof. Also, in all areas the roof decking and the steel columns were found to be adequate.

Structural Upgrades for the 50-lb Threat

The following structural upgrades were required to harden this facility.

(1) Main Area - No changes required.

(2) Mechanical Area

- Modify all open web roof joists to increase the uplift capacity for rebound resistance, and increase joist shear strength to exceed flexural strength by at least 10%.
- Provide lateral bracing to bottom flange of all wide flange roof beams at midspan.
- Provide vertical supports for precast panels on each side of door and louver openings on the west side walls.

Structural Upgrades for the 1000-lb Threat

The following structural upgrade was required to harden this facility.

(1) Main Area

- Modify all open web roof joists to have full uplift capacity (equal to downward load capacity), and increase shear strength to exceed flexural strength by at least 10%.
- Provide lateral bracing to the bottom flange of all main roof beams at midspan, and at midspan and third points for the remaining roof beams.
- All beam connections need to carry at least 60% of the beam web shear capacity.
- All column base plate anchorages need to develop the ultimate strength of the anchor bolts in tension.
- Increase reinforcement in the 5" thick precast walls panels, and increase the size of the embedded plates for the increased vertical and horizontal loads.
- Increase reinforcement in the 5" thick south and west precast panels by 25%, and increase the steel support capacity by 20%.

(2) Mechanical Area

- Add a 4.5" thick composite steel and concrete roof deck.
- Use revised joists and beams to support new roof deck.
- Modify all open web roof joists to have full uplift capacity (equal to downward load capacity), and increase shear strength to exceed flexural strength by at least 10%.
- Provide lateral bracing to the bottom flange of the roof beam at midspan, and bottom-flange bracing at midspan and third points on the other roof beams.
- All beam connections need to carry at least 60% of the beam web shear capacity.
- Replace west side exterior precast wall panels with a 10" thick cast-in-place reinforced concrete wall.

Window Recommendations

The analysis of the building's window systems for both threats requires a design layup of an Insulated Glass (IG) unit using two l/4" laminated heat strengthened glass panels separated by a 1/2" air space. This layup will fracture, but remain in the frame for the worst-case event (1000 lb at 200 ft). The minimum glazing bite was 1/2" for all panels and applied a static frame design load (applied to the glazing surface) of between 3.12 lb/in and 8.85 lb/in of frame length depending on the window size. The specifications were modified to require the contractor to design the frames, mullions, and connections to resist the load without reaching the yield strength of the materials.

Hardening Costs

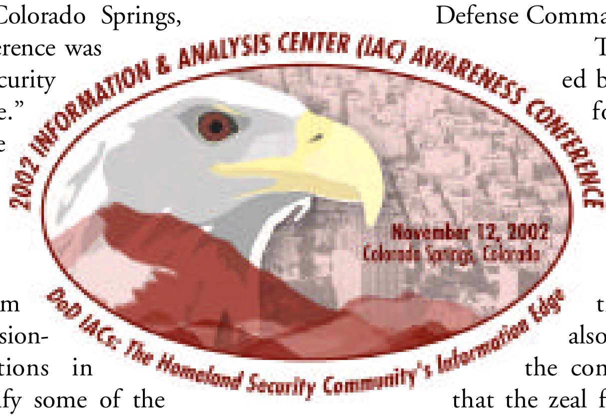
The cost of this building was around $9 million, not including the cost of installed equipment. The structural upgrades necessary to blast-harden the building added $150,000 to the price of the project, or just 1.7%.

Bruce A. Walton is a registered structural engineer with the US Army Corps of Engineers' Protective Design Center in Omaha, Nebraska. He is a member of the US Army Corps of Engineers' Urban Search and Rescue Team as a structural specialist. Mr. Walton is a retired Air Force Lieutenant Colonel, who has worked for the Protective Design Center since 1989. He has many years of experience in research and design with both the Air Force and Army. His background consists mainly of research in the areas of weapon effects, rapid repair of wartime facility damage, and the design of facilities to resist the effects of nuclear weapons, conventional weapons, and accidental explosions. He has developed computer programs in the areas of weapon effects prediction and computational dynamics. He was also a major author of UFC 3-340-01, Design & Analysis of Hardened Structures to Conventional Weapons Effects. Mr. Walton was also the primary DOD structural investigator for the World Trade Center, Oklahoma Federal Building, and Khobar Towers – Saudi Arabia bombings.

The IAC Program Rises to Meet the Challenges of Homeland Security and Homeland Defense

While the theme of this issue of the *AMPTIAC Quarterly* is protecting people and buildings, our staff informally refers to it as "The Homeland Security Issue", as the two topics are inexorably linked. AMPTIAC and its twelve sister organizations within the Defense Information Analysis Center (IAC) Program are already actively joined in the campaign to support and improve Homeland Security (HLS) and Homeland Defense (HLD) (see sidebar page 24).

The IAC Program's sponsoring organization, the Defense Technical Information Center (DTIC), recently hosted the 2002 IAC Awareness Conference held November 12, 2002 at the Cheyenne Mountain Resort in Colorado Springs, Colorado. The theme of the conference was "DOD IACs: The Homeland Security Community's Information Edge." The conference was open to the Department of Defense (DOD), Federal Government Agencies, State and Local Governments, and associated industry representatives.



The conference served as a forum for this diverse collection of professionals to explore strategic directions in Homeland Security and to identify some of the scientific and technical needs of the community. The conference objectives were:

1. To introduce the IACs' subject matter expertise to NORTHCOM and the HLS community
2. Promote awareness of IAC resources and information within the HLD/HLS community
3. Reinforce relationships between NORTHCOM, the other unified commands, the HLD/HLS community, and the IACs
4. Identify ways in which the IAC Program and IAC resources can support NORTHCOM and the HLD/HLS community.

The agenda featured a slate of speakers that was a virtual "who's who" of senior principals from the DOD and HLD/HLS communities. The outstanding speakers shared their own insights on the information needs and support requirements of their respective organizations.

The introductory speaker was Dr. Ronald M. Sega, the Director of Defense Research and Engineering (DDR&E). Dr. Sega set the tone for the morning session by discussing the overarching issues of information analysis and dissemination, and identifying areas of criticality in the support of HLD/HLS initiatives. In his position as the head of DDR&E, he is the chief technical advisor to the Secretary of Defense.

Two keynote addresses were delivered, the first of which was presented by US Army Lieutenant General Edward G. Anderson III. General Anderson is the Deputy Commander of the United States Northern Command (NORTHCOM), which was recently stood up at Peterson Air Force Base in Colorado Springs, Colorado. During his presentation, he outlined the mission of NORTHCOM, and specifically discussed the unified command's role in Homeland Defense. General Anderson also serves as the Vice Commander of the North American Aerospace Defense Command (NORAD).

The second keynote address was presented by the Honorable James S. Gilmore III, former Governor of Virginia (1998-2002). The Governor spoke about the continuing threat of terrorism within the United States and the nation's ability to respond to such threats, both in terms of after an attack and in anticipation of such attacks. Governor Gilmore also provided the most sobering thought of the conference: he cautioned the participants that the zeal for domestic security, if allowed to run unchecked, posed a serious risk to our constitutional liberties, which in long run would constitute a greater threat than any act of terrorism. Since 1999, Governor Gilmore has served as Chairman of the Congressional Advisory Panel to Assess Domestic Response Capabilities for Terrorism Involving Weapons of Mass Destruction. Also known as "The Gilmore Commission", the panel's findings were influential in developing the Office of Homeland Security.

There were also presentations from the Joint Task Force for Civil Support Initiatives, the Defense Threat Reduction Agency (DTRA), the DOD Chem/Bio Defense Initiative, the Federal Emergency Management Administration (FEMA), and the State of Colorado's Office of Emergency Preparedness.

The thirteen DTIC-sponsored IACs (as well as several other technical organizations) exhibited their information analysis capabilities at the conference. Mr. Ron Hale, the manager of the DTIC IAC Program, gave a presentation on how the IACs can respond to HLD/HLS needs, both presently and in the future. In addition, two of the IACs, CBIAC (chem/bio), and SURVIAC (survivability), gave overviews of their current HLD/HLS support efforts for both military and civilian authorities.

In need of vital technical information or analyses? Chances are that one of the IACs can help you!
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AMPTIAC	Advanced Materials & Processes	MSIAC	Modeling & Simulation
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CPIA	Chemical Propulsion	NTIAC	Non-Destructive Testing
DACS	Software	RAC	Reliability
HSIAC	Human Systems	SURVIAC	Survivability
IATAC	Information Assurance	WSTIAC	Weapons Systems
IRIA	Sensors & Detection		

Very-High-Strength Concretes for Use in Blast- and Penetration-Resistant Structures

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INTRODUCTION

Most fixed protective structures employ concrete in some way. The US Army Engineer Research and Development Center (ERDC) is conducting research to provide force protection in everything from foxholes to fixed facilities and against threats ranging from small arms to advanced conventional, and even terrorist weapons. Concrete is a highly economical material, it can be cast into many shapes, and can be formulated for varying degrees of strength and durability. It is primarily used for its compressive strength, as concrete is much stronger in compression than it is in tension. With the proper use of tensile reinforcement, concrete can be used in many tensile-loaded applications, such as flexural members, eccentrically loaded compression members, and direct tension members.

Because of the wide use and availability of concrete, it is useful to elaborate on its fundamentals. Additionally, a better understanding of the complex creation of concrete variants will assist engineers and architects in choosing the best materials that address aesthetic, engineering, and protective considerations.

ADVANTAGES OF HIGHER STRENGTH CONCRETE AND ITS APPLICATION TO STRUCTURAL PROTECTION

The variability of concrete's strength and mass make it a useful material in structural protection. The mass of a concrete member can be varied by altering its component materials and geometry. For applications where ample mass is needed, a large section of normal-density concrete or a smaller section of high-density concrete can be used. For applications where mass or size is detrimental, yet strength is necessary, concrete structures can be designed with thin sections of higher-strength concrete.

Engineers are constantly looking for new materials to provide answers to complex problems. As construction and material costs escalate, demand has increased for stronger materials that occupy less space. Research has been examining high-performance concrete materials for use in protective structures [1-4]. Developments in very-high-strength concrete (VHSC) [5-8], a material made using conventional constituents combined in critical proportions, have further expanded these capabilities.

Limitations of Conventional Concrete

Unreinforced concrete is inherently brittle, having very little capacity for inelastic deformation before failure. It is also very weak in tension. Under compressive loading, it exhibits linear elastic behavior until initiation of first cracking of its matrix. As loading continues above this point, concrete exhibits increased non-linear plastic deformation for a short time before ultimately failing in a brittle manner.

The unconfined (concrete with no exterior covering such as a steel sleeve) compressive strength of conventional concrete is generally less than 41 MPa. Concretes with design strength in compression greater than 41 MPa are called "high-strength". High-strength concrete having design compressive strength of 100 to 125 MPa is available in many areas. The tensile strength of most concrete generally does not exceed 10% of the compressive strength (i.e. approximately 4 to 10 MPa). VHSC does not follow this proportional relationship however, as its tensile strength is often no higher than 10 MPa. For use as a protective material, both tensile and compressive strength are important properties. From a ballistic point of view, they are important in resisting the cratering and break-up of the structure caused by projectile penetration and, in many cases, detonation of a weapon.

VHSC Principles

VHSC is made from the same general constituents as conventional concrete (cementitious material, water, aggregate, and additional compounds for removing air and water from the mix {admixtures}). Yet, the careful selection of constituents and their proportions, as well as proper mixing, results in significantly improved tensile and compressive strength, toughness

Table 1. Principles of Very-High-Strength Concrete.

- Improved homogeneity through particle size and material selection.
- Increased density by optimization of particle size and mixing technology.
- Improved strength by maximizing reactive materials and minimizing water content.
- Increased microstructure by application of pressure before setting and post-set heat treatment.
- Increased tensile strength, toughness, and ductility by incorporation of steel fibers or steel micro-fibers.

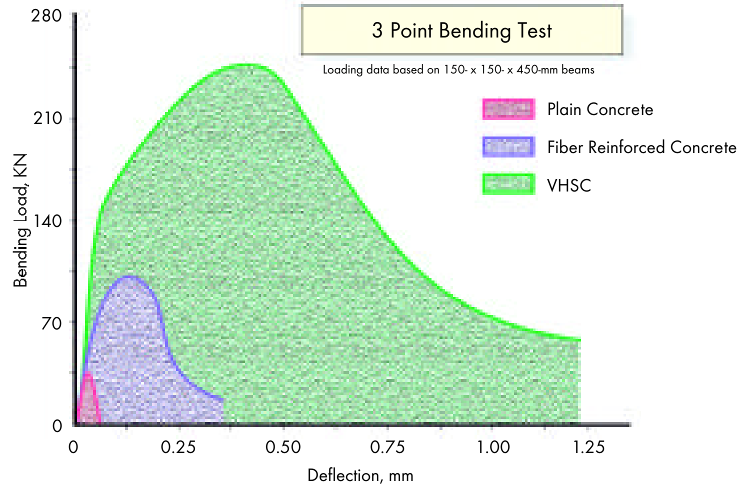


Figure 1. Flexural-toughness Comparison for VHSC Concrete vs. Plain and Fiber-reinforced Concrete.

and durability, as well as reduced water permeability. The physical and mechanical properties can be further improved by the application of heat and pressure during the casting and curing stages of hydration. The principles used in producing VHSC are listed in Table 1. Some significant differences from conventional and high-strength concrete are:

- size and composition of constituents
- ratio (by weight) of water-to-cementitious material (w/cm)
- the use of steel fibers (sometimes micro-fibers) to improve ductility and toughness
- the amount of mixing energy employed
- curing procedures used

Conventional concrete is a very heterogeneous material with components from fine cement to coarse aggregates, each exhibiting different strengths and modulii of elasticity. Under a system of forces, all these component materials deform at different rates. The differential movement of these components produces strains between the component materials that begin the process of tensile fracture when the strains exceed the tensile strain capacity of the concrete. Concrete such as VHSC is composed of particles of similar modulii and size, which helps increase the homogeneity of the composite material thereby reducing the differential tensile strain in the concrete and increasing the ultimate load-carrying capacity of the material.

High density* is the second principle employed to increase strength and decrease permeability. In choosing the volumes of component materials, particle-packing techniques can be used to maximize the amount of solids per unit volume of concrete. As with conventional concrete, the material having the largest particle size in VHSC is the aggregate. In VHSC that aggregate is sand whose particle size is limited to a maximum of 4.75 mm. The material having the next largest particle size is the cement, which is on the order of 10 to 100 µm. The smallest particles are silica fume, which are on the order of 0.1 µm in diameter. The component volumes of all these particles are chosen to achieve the greatest particle packing, and hence the greatest density of the paste. The higher the density, the greater the strength of the paste and the lower the permeability because there are fewer and smaller voids.

Strength of VHSC is further improved by increasing the volume of pozzolanic components (fine siliceous or aluminous powders) that can react to form hydration products. In VHSC, materials with a high silica content are necessary for optimum performance. Cements that are high in silica content (such as low-carbon silica fume [6]) produce higher strengths. These materials provide chemically active silica that helps to produce larger volumes of calcium-silicate-hydrate (CSH), bonding the other component materials together. High amounts of CSH increase the strength of the binder and improve the bond between the cement and the aggregate.

To optimize performance, the w/cm ratio in VHSC must be carefully controlled. Excess water in the mixture is detrimental to the strength of concrete. The quantity of water required to hydrate all of a given amount of Portland cement is about that present at a w/cm ratio of 0.4. Water that is not chemically or physically combined in the hydration or pozzolanic reaction, weakens the paste and thus the compressive and tensile strength of the concrete. The volume of water used in VHSC is kept low to insure that there is no excess. This volume is less than that needed to hydrate all the cement so as to insure that all water is consumed in the hydration/pozzolanic reaction process. However, this small quantity of water usually does not provide sufficient workability to the mixture. High-range-water-reducing admixtures (HRWRA) are used to make the otherwise very stiff concrete flowable.

All these mixture principles combine to produce concrete with an ultimate compressive strength up to approximately 175 MPa, when mixed and cured at ambient temperatures. Strengths greater than 200 MPa can be achieved when the concrete is cured at 90°C for a few days. The processes of adding pressure sufficient to expel any excess liquids and air from the fresh mixture during the casting operations, and providing a curing environment of up to 400°C, can produce concrete with a compressive strength greater than 800 MPa.

Table 2. **Concrete Mixture Proportions (kg/m³).**

Material	CSPC	HSPC	HSFR	VHSC*
Type I Portland Cement	328	546	459	24
Silica Fume	0	71	59	13**
Class F Fly Ash	0	119	59	0
Coarse Aggregate	1034	817	520	0
Sand	806	0	451	0
Limestone Fine Aggregate	0	657	469	40
Water	187	166	171	17
Water Reducing Admixture	1.7†	0	0	0
High Range Water Reducing Admixture	0	12	6	3
Air Detraining Admixture	0. 3	1	0.6	0
w/cm	0.57	0.22	0.3	0.18
Fibers	0	0	158	3

* Mixture proportions for VHSC are given in % by volume.
** In VHSC, 8% is silica fume and 5% is silica flour (crushed quartz)
† Water reducing admixture given in l/m³

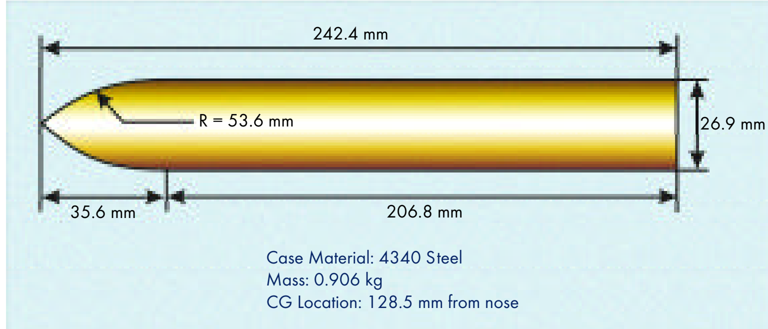


Figure 2. **Drawing of Armor-Piercing Projectile.**

Table 3. **Hardened Material Properties.**

	CSPC	HSPC	HSFR	VHSC
28-day Compressive Strength, (MPa)	35	104	85	157
Compressive Modulus of Elasticity, (GPa)	34.5	45.2	45.2	46
56-day Tensile Strength, (MPa)	3.5	4.8	4.5	9.0
Tensile Modulus of Elasticity, (GPa)	44	39.5	39.6	–

Tensile Properties

The tensile strengths of VHSCs can be higher than those of conventional concretes. As mentioned previously, tensile strength of VHSC may nominally be only 10 MPa, while its compressive strength is on the order of 180 MPa. The addition of steel fibers increases the first-crack load, increases the ultimate load-bearing capacity, and dramatically increases the flexural toughness.

Very-high-strength concretes exhibit near-linear stress-strain characteristics up to failure when fabricated without the addition of fibers. Their fracture energy, defined as the area beneath the load-deflection curve, is somewhat less than 140 J/m². The addition of fibers to the matrix improves the behavior of the concrete in the post-first-crack region of the load-to-failure cycle. In VHSC, various percentages and types of steel fibers have been used but the best overall results (incorporating cost considerations) have been obtained with hooked-ended, steel fibers 30 mm in length and 0.5 mm in diameter.

The large number of small fibers which cross the path of potential cracks, coupled with the good bond between fiber and matrix, provide high resistance to fiber pullout during tensile-cracking, and greatly increase the toughness of the material. Figure 1 shows the load-deflection curve of a typical VHSC beam. By comparison, a load-deflection curve for a conventional concrete and a conventional fiber-reinforced concrete are added. Comparison of the areas under the curves gives a relative relationship for the increase in toughness afforded by the very-high-strength concrete. The greatest effect is in the area of the curve beyond the first-crack load, where the sample's load-deflection behavior transitions from linear to non-linear. Up until this load, the tensile-carrying-capacity of the concrete has been responsible for the shape of the curve. In the unreinforced concrete, the magnitude of the first-crack load is about one-tenth that of the VHSC and the load and deflection of the post-first-crack portion of the curve is very small. Likewise, even with conventional fiber-reinforced concrete the first-crack strength is lower than VHSC and the post-first-crack portion of the curve is also smaller.

Toughness is a measure of the amount of energy that must be expended to open cracks in the matrix under tensile loading. An example of toughness would be the resistance to a projectile passing through a material. This toughness is important in the performance of protective structures. The amount of energy required to penetrate the VHSC concrete will be greater than that required to penetrate conventional concrete. This means that some projectiles will be less effective at penetrating the structure, and perhaps will even be stopped by the VHSC. If the projectile completely passes through the VHSC, the exit velocity will be lower than that through the same mass of conventional concrete. Also, the amount of material fragmented from the back of a protective-structure member as the projectile passes through (also called spall) will be reduced by the steel fibers in the VHSC matrix.

Penetration Experiments

Normal impact experiments studying depth-of-penetration versus striking velocity were conducted with VHSC concrete targets. The experiments evaluated the resistance of VHSC to penetration by a robust projectile (one that should not deform significantly). The VHSC mixture proportions, as well as those for conventional-strength portland cement (CSPC) concrete, high-strength portland cement (HSPC) concrete, and high-strength, steel-fiber reinforced (HSFR) concrete, are given in Table 2. (The mixture proportions in Table 2 provide the required masses of constituents in order to produce roughly one cubic meter of finished concrete.)

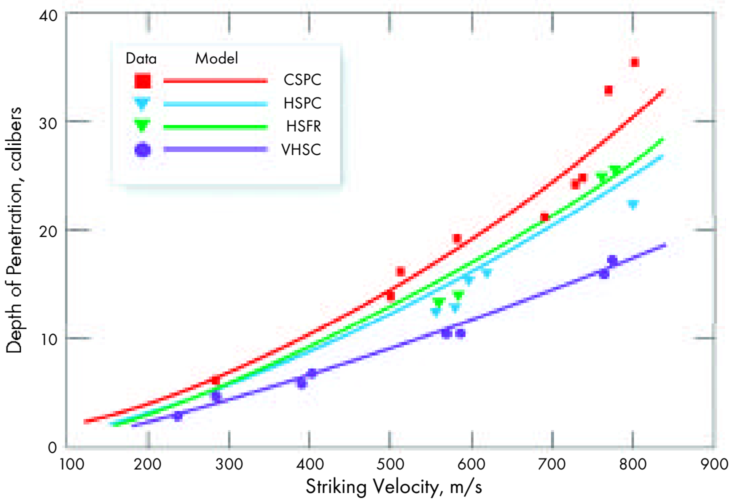


Figure 3. Comparison of Penetration Experiment Results and Spherical-cavity Expansion Model Calculations for CSPC, HSPC, HSFR, and VHSC Concretes.

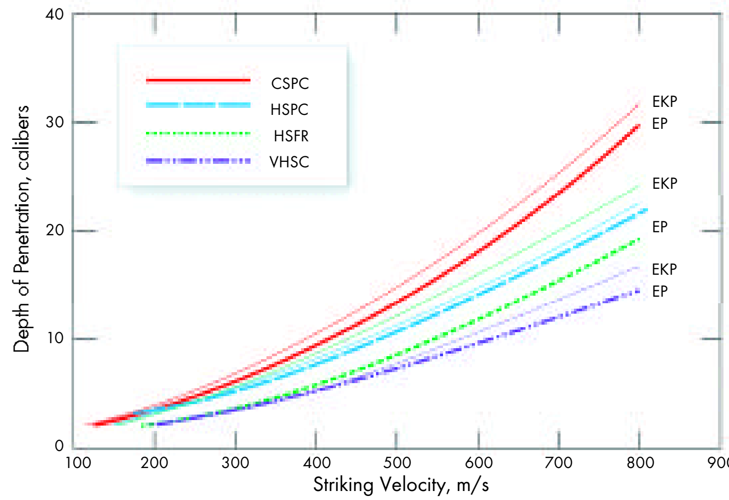


Figure 4. Comparison of Calculations Using the Elastic-Cracked-Plastic (EKP) and Elastic-Plastic (EP) Versions of the Spherical-cavity Expansion Model.

The concrete for the targets was placed into corrugated, galvanized-steel culverts measuring approximately 762 mm in diameter by 914 mm in length. The culverts were wrapped in insulation to maintain heat during curing. Curing of the targets consisted of ponding water on the top of the targets for 7 days and then continuing the curing in ambient conditions until the time of the penetration experiments. The penetration experiments and at least two unconfined-compression tests on samples of the concrete were conducted on approximately the same day. The age of the concrete at the time of the penetration experiments ranged from 30 to 60 days.

The 0.906-kg projectiles were machined from 4340-steel rods and heat treated to a hardness of 43-45 on the Rockwell C scale. Each projectile had an ogive nose, a shank diameter of 26.9 mm and an overall length of 242.4 mm as shown in Figure 2. At the time of the penetration experiments, the targets were placed on their sides, still in the metal-culvert forms, and centered on the longitudinal axis of the gun. The projectiles were launched into the targets using the ERDC (formally WES) 83-mm, smooth-bore powder gun [9] at striking velocities (V_s) ranging from 229 m/s to 754 m/s.

Depth of penetration (P) in calibers (penetration depth/projectile diameter) for the experiments into VHSC are compared to results from penetration experiments into a CSPC concrete [10], HSPC concrete [10], and HSFR concrete [11], as shown in Figure 3. The experiments into the CSPC, HSPC, and HSFR concretes used projectiles with the same mass and dimensions as the projectile used for the experiments into the VHSC concrete. Target fabrication for the CSPC, HSPC, and HSFR experiments was similar to that for the VHSC concrete except that the targets were approximately 1.37 m in diameter. The average unconfined compressive strengths of the VHSC, CSPC, HSPC, and HSFR concretes used to fabricate targets in these tests were 159, 35, 104, and 90 MPa, respectively. Typical compressive strength values for VHSC can be higher, on the order of 185 MPa, depending on the materials and processing used. Additional material property data are presented in Table 3.

Also in Figure 3, results from the penetration experiments are compared to depth of penetration which was calculated using a spherical-cavity expansion model developed by Forrestal and Tzou [12]. The model separates the target response into elastic, cracked, and plastic (EKP) regions, with the plastic region being closest to the projectile. The target is described by density, yield strength, slope of the yield surface, tensile strength, and linear bulk modulus. The tensile strength of the material determines the influence of the cracked region on the depth of penetration. Values for these model parameters were determined for each concrete based on referenced data [2, 4, 13]. The results from the cavity-expansion calculations agree well with the experiment results (see Figure 3).

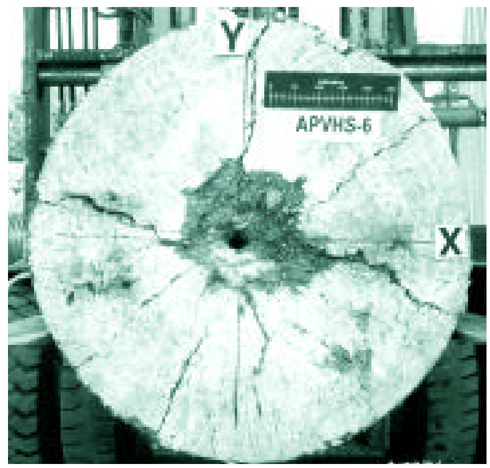
Another model presented by Forrestal and Tzou separates the target response into elastic and plastic (EP) regions only. This model was used to illustrate the influence of the cracked region on the depth of penetration[12]. Results from the two models are compared in Figure 4. Use of the EP model results in less depth of penetration than the results from the EKP model. The influence of the cracked region is greatest for the higher-strength concretes. Results from the calculation using the EP model represent a limit to the depth of penetration that could be expected as the tensile-yield strength approaches the compressive-yield strength.

The depth of penetration from experiments into the HSPC and HSFR concretes was about 30% less than that from experiments into the CSPC concrete, while the penetration depth observed in VHSC is about 50% less. So, one could expect approximately a 50% reduction in penetration by using the VHSC concrete versus conventional concrete. Post-test photographs of the target faces in Figure 5 show the visible damage to the targets for experiments at a striking velocity of about 800 m/s. The amount of visible damage to the HSPC concrete target is about the same as that for the CSPC concrete target, even though the depth of penetration is about 30% less. The

a. CSPC concrete

b. HSPC concrete

c. HSFR concrete



d. VHSC concrete

Figure 5. **Front-face Damage to Targets Impacted at Approximately 800 m/s.**

addition of steel fibers in the HSFR concrete resulted in a significant decrease in visible damage, and still resulted in a depth of penetration about 30% less than the CSPC concrete. The visible damage to the VHSC concrete target is comparable to the damage to the HSFR concrete target.

CONCLUSIONS

These new VHSCs are useful for force protection and infrastructures in need of blast and penetration resistance. Their performance, especially in spall resistance and increased deflection without failure, mesh well with design requirements calling for reduced flying debris in buildings and prevention of progressive collapse.

Development of this new class of very-high-strength concretes, based on use of small-particle component materials and particle-packing theories, has led to materials with improved penetration resistance. Although the direct-tensile strengths remain low at approximately 10 MPa, the compressive strengths of these concretes are very high, near 200 MPa. Additionally, the flexural toughness of the concrete is greater than 250 times that of conventional, non-fiber-reinforced concrete.

Penetration-resistance experiments conducted on the VHSC indicated approximately 50% less penetration than into CSPC concrete, and 30% less penetration than into HSPC and HSFR concrete. Inclusion of fibers into these concretes does not significantly improve the penetration resistance of a given strength of concrete, but does provide for greater resistance to visible damage surrounding the penetration crater. Results from calculations using the spherical-cavity expansion model with elastic-cracked-plastic regions agreed well with the experimental results.

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ENDNOTE

* In this discussion, density (or in some contexts "denseness") means the relative amount of volume in the freshly mixed product occupied by solid particles and not the mass per unit volume of the product.

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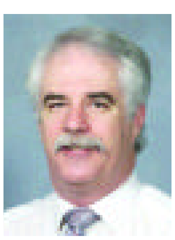

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AMPTIAC Celebrates Its 6th Birthday

On November 1st, AMPTIAC's staff took a few minutes out of their busy day to mark the IAC's sixth birthday. The six years have flown by, but are replete with accomplishments. We are proud of our success serving the DOD materials and processes community and look forward to continued service in the future.

AMPTIAC

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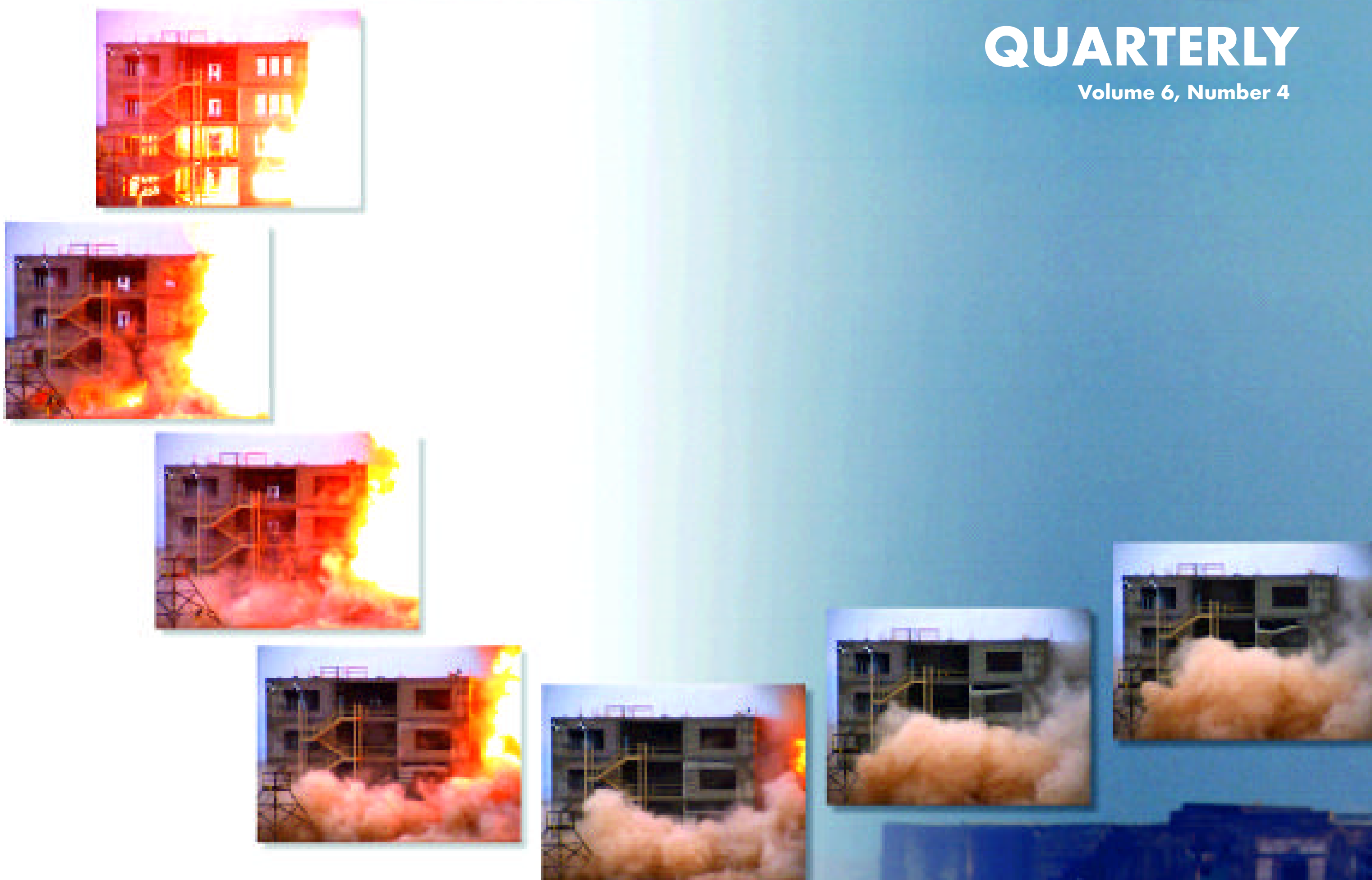

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