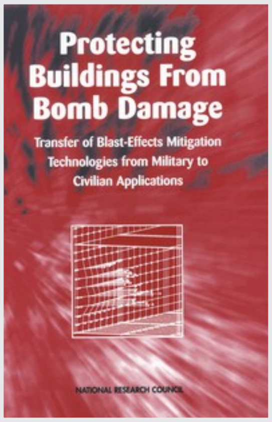

Protecting Buildings from Bomb Damage: Transfer of Blast-Effects Mitigation Technologies from Military to Civilian Applications (1995)

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Protecting Buildings From Bomb Damage

Transfer of Blast-Effects Mitigation Technologies from Military to Civilian Applications

Committee on Feasibility of Applying Blast-Mitigating Technologies and Design Methodologies from Military Facilities to Civilian Buildings
Board on Infrastructure and the Constructed Environment
Commission on Engineering and Technical Systems
National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Terms Used in This Report

Designing structures to withstand the effects of a deliberately placed explosive device can entail many types of protective measures. Some will increase the difficulty of placing a bomb close enough to a structure to damage it; others will physically strengthen all or parts of the structure while still others will aim to ensure the survival and rescue of the occupants in the event of a bomb explosion. Throughout this report, a number of terms are used to describe these measures. To facilitate the reader's understanding, an explanation of the most commonly used terms is provided below. Technical terms that are considered outside the normal usage of the lay reader are defined as they appear.

Blast-hardening of a structure refers to all measures that are taken, either in the design phase or in subsequent (retrofit) actions, to reduce or eliminate the effects of an explosion. This process is sometimes simply referred to as building "hardening." In the broad sense, it includes site selection and physical space planning (i.e., organization of spaces to minimize the effects of a blast on people and property).

Blast resistance is an effect of blast-hardening and refers to the ability of a structure to withstand an explosive event with minimum loss of life or property.

Blast-effects mitigation refers to the reduction in the severity of the effects of an explosion on a structure resulting from having taken specified blast-hardening measures.

Protective design technologies refer collectively to the techniques and methodologies that have evolved for addressing blast-hardening of buildings and other structures. This body of knowledge is the product of experimental studies, theoretical analyses, and advanced numerical simulation approaches developed primarily by the military for predicting blast loads and the responses of structural systems.

Executive Summary

The United States became a victim of terrorism on a grand scale when a powerful bomb exploded in the World Trade Center in New York City in February, 1993. This event, however, was only a precursor to the devastating attack against the Alfred P. Murrah Federal Building in Oklahoma City in April 1995. These events, and other lethal attacks elsewhere, have generated considerable concern over the ability of the United States to protect buildings and their occupants from the continued threat of bombings and other direct physical attacks. The issue of ensuring structural integrity from explosive blasts has been an active topic with the military and national security communities for years. Such concerns arose initially in response to bombing threats during World War II; however, they continued through the Cold War, and more recently these concerns have grown with the increase in terrorism worldwide. A large body of theoretical and empirical knowledge regarding explosions and their effects has been developed as a result of research and tests sponsored by U.S. government agencies, including the Defense Nuclear Agency and the uniformed services.

In response to a potential threat of terrorist bombing attacks against U.S. civilian structures, the Defense Nuclear Agency requested the National Research Council to examine whether design methodologies and construction techniques developed for the protection of military facilities could be beneficially applied to civilian architecture. The *Committee on Feasibility of Applying Blast-Mitigating Technologies and Design Methodologies from Military Facilities to Civilian Buildings* was established and charged with three tasks summarized as follows:

- review the existing knowledge on blast-effects mitigation technology,

- assess the applicability of this technology to civilian buildings and identify gaps in knowledge and needs for research and development, and
- recommend courses of action to implement technology transfer.

The committee was composed of recognized experts in architecture and architectural planning, structural engineering and blast-effects, computer modeling, terrorism, and commercial development. Most of the committee members have direct professional involvement with the planning and design of buildings with quantifiable risk (military facilities, embassies, etc.). In addition to the expertise of its members, the committee was assisted in its work by agencies, organizations, and individuals that provided information on current engineering and architectural practices.

This study, jointly sponsored by the Defense Nuclear Agency and the U.S. Army Corps of Engineers, is aimed at determining the applicability of defense-related efforts to civilian architecture and the potential to transfer this technology in a timely and cost-effective manner. The study does not examine the vulnerability of structures to an attack using toxic substances (such as the Sarin gas attack in Tokyo in March 1995).

The committee believes this is an appropriate time to restate what the Oklahoma City and World Trade Center attacks have made so abundantly clear: **the United States is vulnerable to a continuing threat of terrorist bombing.** The current awareness of this threat by both policy makers and the general public should facilitate acceptance of the desirability and timeliness of transfer and application of some military protective technologies to civilian architecture.

This report presents the findings of the committee's work and its recommendations for future action.

FINDINGS

1. Attacks against civilian buildings pose an unquantifiable but real threat to the people of the United States.
2. Blast-hardening technologies and design principles developed for military purposes are generally relevant for civilian design practice. However, because the knowledge base is incomplete, they must be adapted and expanded to be more specifically applicable, accessible, and readily usable by the civilian architect-engineer community.
3. Blast-hardening technologies developed by the military apply, for the most part, to building structural systems and must be expanded to include critical life-safety building subsystems.
4. Nonstructural architectural and engineering approaches can improve the blast resistance and response of civilian buildings.
5. Post-attack rescue and recovery operations can benefit from good emergency management planning, including rapid availability of building systems and

structural drawings and use of computer-based modeling and decision support systems to assess the extent of blast damage to the building's structural frame.

6. Buildings designed to be more bomb resistant through the use of increased mass in the lower levels will also benefit from increased resistance to dynamic forces from natural hazards such as hurricanes, tornadoes, and earthquakes.
7. Barriers exist to the effective transfer of relevant military technology to the civilian sector. These barriers include lack of professional education, classification of military technology, lack of established technology transfer mechanisms, and cost and financial issues.

Based on these findings, the committee developed a series of recommendations aimed at adapting and transferring technology already available from the military to civilian sectors. For those areas where knowledge gaps exist, the committee has suggested a program of applied research.

RECOMMENDATIONS

1. Adapt selected technical manuals, threat assessment methodologies, and relevant computer programs developed for military applications and disseminate them to civilian building-design professionals as one component of an integrated threat deterrent and blast-effects mitigation strategy (*Findings 1 and 2*).
2. Conduct experimental and analytical studies on the blast resistance of structural subsystems representative of conventional civilian building design and construction practice (*Finding 2*).
3. Conduct research and testing of common building materials, assemblies, equipment, and associated designs applicable to blast-resistant design of critical nonstructural building subsystems (*Finding 3*).
4. Establish a government/academic partnership whose purpose is to inform and alert design professionals regarding the range of measures that can and need to be taken to protect buildings from terrorist activities and the collateral benefits of providing such protective measures. This partnership should also take the lead in facilitating the transfer of this technology by interaction with the appropriate government and professional bodies (*Findings 4, 6, and 7*).
5. Explore the use of computer-based modeling and decision support systems to assess the extent of blast damage to a building's structural frame as part of the post-attack rescue and recovery operations (*Finding 5*).
6. Analyze all new civilian federal buildings, and existing buildings where appropriate, to determine reasonable ways of incorporating blast-hardening and other blast-effects mitigating features, and to document consequent building construction costs and financial performance (*Finding 7*).

1

Introduction

On February 26, 1993, the World Trade Center towers in New York City, two of the tallest buildings in the world and an instantly recognizable symbol of the United States, were the target of a terrorist car bomb. Six people were killed, scores were injured, and the damage to the structure and its contents would cost many hundreds of millions of dollars to repair. Two years later, on April 19, 1995, the Alfred P. Murrah Federal Building in downtown Oklahoma City was the target of an even more devastating and deadly attack.

Such bomb attacks have become a familiar feature of modern life around the world. In the past few years, there have been explosions in the financial center of London, and in Buenos Aires a multistory community center was destroyed, resulting in major loss of life. The technology to produce powerful explosives is relatively simple and inexpensive. Delivery can be as easy as parking a car or van under or near a building, or by walking into a building with a briefcase or package.

What can be done to mitigate the effects of explosions that do occur? Several federal agencies, including the Defense Nuclear Agency (DNA) and the U.S. Army Corps of Engineers (USACE), have for many years studied explosions and their effects on structures of various kinds. It is reasonable, therefore, to inquire about all the information developed for military use and how that information might be applicable to the civilian sector. The director of DNA, in cooperation with the director of the Waterways Experiment Station (WES), USACE, asked the National Research Council (NRC) to undertake a study to recommend policy and technical advice on transferring to the civilian sector the applicable security technologies developed by DNA, USACE, and other federal agencies.

SCOPE OF THE STUDY

In response to that request, the NRC established the authoring committee of this report and charged the committee with the following specific tasks:

- Identify, document, and review the body of knowledge on blast-mitigating technologies and the design methodologies used to minimize or mitigate blast-effects on internal building structures and relevant subsystems.
- Assess this body of knowledge as it might apply to conventionally designed existing civilian office buildings. Identify gaps in knowledge, needed research and development, and other appropriate actions to further develop and apply promising technologies and design methodologies in the civilian sector.
- Recommend steps, such as research and development, education and training programs, or policy changes within or applying to the military agencies, that would be needed to implement promising civilian applications.

This report considers non-nuclear explosions and their effects (including fire and smoke) on multistory commercial buildings and facilities; however, much of the information presented here should have wider applicability to civilian building design. Prevention of explosions through the use of perimeter access-control security systems to limit entry of bombs and to detect those that get through before they are detonated is discussed only superficially. There is an extensive body of knowledge concerning the design and application of active security systems which the committee has judged to exceed the scope of its charge. For similar reasons, the committee also did not address the potential effects of chemical or biological weapons.

At the outset, the committee was aware that techniques for hardened military construction, developed over many years by the U.S. Department of Defense, focus on maintaining the structural integrity of a principal facility at some designated threat level in order to sustain operation of mission-critical equipment and personnel within. Usually the facility is located and constructed in a way to reduce the likelihood of attack (e.g., buried missile silos, underground command centers) and further protected through controlled access, bomb detection, and other passive and active security measures. Moreover, since the primary structural envelope of a blast-hardened military facility is not intended to be breached by a bomb explosion at design threat levels, little consideration is given to the blast resistance and failure characteristics of critical building life-support subsystems such as lighting, communications, and ventilation.

Clearly, many of these design approaches are characteristic of military construction and are neither desirable nor practical for civilian buildings that provide ready access and a friendly atmosphere to the public and where prevention of injury and loss of life is of paramount importance under emergency situations. The more appropriate perspective for civilian buildings design professionals might be that, since little can be done to thwart the determined terrorist bomber, how can the building be designed and constructed in ways that can reduce hazards to people and enhance safe rescue and repair efforts? This question has been uppermost in the committee's deliberations in dealing with the second of the three tasks stated above.

ORGANIZATION OF THE REPORT

The succeeding chapters in this report address the study's charge in the following manner: Chapter 2 presents a fundamental background on the motives, methods, and immediate results of terrorist activities, including such topics as statistical patterns of recent terrorist acts, the types of damage to structures and critical building systems, and injuries that can be expected after a bomb detonates. Chapter 3 summarizes relevant knowledge on blast-effects mitigation and protective design technologies, including both empirical techniques and numerical simulations, which in the committee's judgment are applicable to civilian architecture. The scope of the committee's charge did not include an exhaustive assessment or review of the state of the art of all hardening and protective design methodologies. The committee did, however, elicit and receive numerous briefings from the sponsors and their principal contractors concerning all relevant past and current research and development in this area, and has utilized this information in generating its findings and recommendations. Chapter 4 explores the potential opportunities to transfer blast-effects mitigation technologies in such areas as architectural planning and design and placement of building systems, along with possible transfer agents and economic issues for the transfer process. The study's findings and recommendations are presented in Chapter 5.

2

Terrorism: Its Motives, Methods, and Immediate Results

Two years before the April 1995 bombing of the Alfred P. Murrah Federal Building in Oklahoma City, the February 1993 World Trade Center bombing had already marked a watershed in America's perceived vulnerability to terrorism[1] on its own soil. Prior to the World Trade Center bombing, modern terrorism was generally regarded as something that happened elsewhere: a problem of the unsettled Middle East and Latin America, which on occasion spilled over into the streets of London or other major cities. While Americans have often been targeted by terrorists abroad, this attack demonstrated that they can no longer believe themselves immune to terrorist violence within their own borders. The Oklahoma City bombing showed that the United States continues to be vulnerable to terrorist attacks.

Three bombings in July 1994 also underscored the attractiveness and vulnerability of civilian buildings as terrorist targets. On July 18, 1994, a massive car bomb destroyed the Jewish Community Center in Buenos Aires. One week later, another car bomb exploded outside a London apartment adjacent to the heavily guarded Israeli Embassy. Less than 12 hours later, a London building housing a number of Jewish community organizations was the target of still another car bomb.

This chapter presents a background on the motives, methods, and immediate results of terrorist activities, including such topics as statistical patterns of recent

[1] The State Department defines "terrorism" as premeditated, politically motivated violence perpetrated against noncombatant targets by subnational groups or clandestine agents, usually intended to influence an audience.

terrorist acts and the types of damage to structures and critical building systems, and of injuries that can be expected after a bomb detonates.

MOTIVES FOR TERRORIST ATTACKS

Terrorists' specific motives for attacking buildings are diverse, but they might be grouped into the following categories:

- to obtain publicity for the terrorist group and its cause,
- to exert political pressure or make a symbolic statement,
- to destroy some asset within or part of the building,
- to achieve financial gain through ransom or extortion,
- to advance a religious imperative,
- to kill or injure occupants, and/or
- to seek vengeance or revenge.

Publicity appears to be the most common objective, although any particular terrorist attack often combines several of the above-listed motives. While the actual intent of the World Trade Center bombers remains unclear, a major motive was no doubt publicity, together with a protest of U.S. support for conservative Arab governments and Israel, as the bombers explained in a letter they later sent to the *New York Times* claiming credit for the bombing.

In addition to a quest for publicity, a major motive for a terrorist attack is to exert political pressure or to make a symbolic statement. For this reason, buildings are often the objects of terrorist attacks because of their specific occupants. Targeted tenants in the U.S. and worldwide have included governmental agencies, such as in the Oklahoma City bombing, storefront military recruiting stations, diplomatic and consular facilities, post offices, defense contractors, banks, corporate offices, and commercial establishments.

Terrorists rarely appear to target a building simply to destroy the building itself or to damage some asset inside. While there is some indication that the World Trade Center bombers actually intended to bring down one of the twin towers (Wald, 1993), and the suicide bombers who attacked the U.S. facilities in West and East Beirut in the early 1980s sought—among other objectives—to destroy those structures, the damage sought in these and similar cases generally appears to have been a secondary goal, the primary goal being publicity and the exercise of political pressure. Perhaps the first well-publicized incident in which terrorists sought to destroy some specific asset inside a building was the 1946 bombing of Jerusalem's King David Hotel in what was then British-ruled Palestine (Hoffman, 1983). Jewish terrorists targeted the hotel, where the headquarters of the British administration and military command for Palestine was located, to destroy vital Jewish documents that had been seized by the British Army a month earlier and were believed to be stored on two floors of the west wing.

Terrorists as well as nonpolitically motivated individuals have also targeted commercial buildings purely for economic gain. Terrorist organizations and criminal gangs in Latin America and Northern Ireland, for example, regularly extort protection money from building contractors, owners, and tenants (Adams, 1986). In some cases, the extortion amounts demanded, and the damage caused to the property of those who refused to comply, have been extraordinarily high. In August 1980, for instance, after a Nevada casino did not respond to extortion demands, a homemade bomb caused more than $12 million in damages to the casino (Center for the Study of Terrorism and Political Violence, n.d.).

In many bombing incidents, it is often difficult to single out a specific motive for the attack. Although terrorist attacks on civilian buildings do not generally appear to have the sole intention of killing or injuring the occupants, in several instances, such as the bombings of the Alfred P. Murrah Federal Building in Oklahoma City and the Jewish Community Center in Buenos Aires, that was certainly a result. Similarly, attacks with apparent religious or vengeance overtones such as the World Trade Center bombing may have other motives as well. For example, suspicions have been raised that the World Trade Center bombing was masterminded by politically motivated agents who have little in common with the religious movement to which the convicted bombers belonged. Should this be the case, it would suggest that one organization with a particular agenda may manipulate another group with different objectives and motivations to carry out the act.

PATTERNS OF TERRORIST ATTACKS

Bombing has long been the most common terrorist tactic. Bombings account for nearly half (46 percent) of all international terrorist attacks carried out since 1968, a proportion that has rarely fallen below 40 percent or exceeded 50 percent in any year.[2] Terrorists' reliance on bombing is not surprising, given that bombs provide a dramatic, yet fairly easy and often relatively risk-free (to the perpetrator) means of drawing attention to the terrorist cause. Few skills are required to manufacture a crude bomb, surreptitiously plant it, and then be miles away when it explodes. Terrorist attacks typically involve only one or two persons and, in general, do not require the same organizational expertise, logistics, and knowledge required of more complicated or sophisticated operations such as kidnapping, barricade and hostage situations, assassination, or assaults against defended targets.

Armed attacks on buildings (including assaults with automatic weapons as well as hand grenades, bazookas, and rocket-propelled grenades, drive-by

[2] Forty-four percent of all terrorist attacks between 1968 and 1969 involved bombings, 53 percent involved bombings in the 1970s, 49 percent in the 1980s, and 39.5 percent between 1990 and 1993 (Center for the Study of Terrorism and Political Violence, n.d.)

shootings, arson, vandalism, and sabotage other than bombing) represent a distant second to bombing, accounting for 22 percent of all terrorist operations since 1968.[3]

Not surprisingly, the frequency of various types of terrorist attacks tends to decrease in proportion to the complexity or sophistication they entail. Hijackings are the third most common tactic, accounting for 12 percent of terrorist attacks,[4] followed by assassination (6 percent),[5] and kidnapping (1 percent).[6] The Sarin gas attack in Tokyo in 1995 represents a new method of attack, but it is too early to assess the likelihood of an increase in that mode of terrorism.

The choice of bombing as the preferred terrorist tactic in the United States is evidenced by Federal Bureau of Investigation statistics. Between 1982 and 1992, bombings accounted for 77.5 percent of all terrorist incidents in this country.[7] Most of the targets were commercial establishments (36 percent of all incidents), followed by military personnel and facilities (20 percent), federal and state government office buildings and property (19 percent), private residences (11 percent), diplomatic establishments (10 percent), and educational establishments (4 percent) (FBI, 1993).

Explosive-incident statistics compiled from the latest report by the U.S. Department of Treasury's Bureau of Alcohol, Tobacco and Firearms (ATF) are shown in Table 2-1 by type of target (ATF, 1993). These figures augment the FBI statistics by including bombing attempts in addition to actual bombings (explosive and incendiary) by both terrorist and nonterrorist perpetrators for the period 1989–1993. [8] Bombings of commercial buildings figure prominently in these statistics. Ease of access, entry, and escape figure prominently in terrorists' selec

[3] Armed attacks on buildings accounted for 18 percent of all terrorist attacks between both 1968 and 1969 and during the 1970s, 19 percent in the 1980s, and 32 percent between 1990 and 1993 (Center for the Study of Terrorism and Political Violence, n.d.).

[4] Hijackings accounted for 33 percent of all terrorist attacks between 1968 and 1969, 7 percent in the 1970s, 4 percent in the 1980s, and 12 percent between 1990 and 1993 (Center for the Study of Terrorism and Political Violence, n.d.).

[5] Assassination accounted for 3 percent of all terrorist attacks between 1968 and 1969, 9 percent in the 1970s, 13 percent in the 1980s, and 13 percent between 1990 and 1993 (Center for the Study of Terrorism and Political Violence, n.d.).

[6] Kidnapping accounted for just .01 percent of all terrorist attacks between 1968 and 1969, 9 percent in the 1970s, 10 percent in the 1980s, and 6 percent between 1990 and 1993. There were no barricade and hostage situations recorded between 1968 and 1969, though they accounted for 3 percent of all terrorist incidents during the 1970s, and just 1 percent in both the 1980s and between 1990 and 1993 (Center for the Study of Terrorism and Political Violence, n.d.).

[7] Followed by kidnapping (6 percent), arson (5 percent), robbery (3 percent), malicious destruction of property and hostile takeovers (2 percent each), acts of sabotage (1 percent), and hijacking (1 percent) (FBI, 1993).

[8] The data include bombings carried out by persons motivated by economic (profit) reasons, vengeance, or other personal grievances, rather than political causes and grievances. It is the political motivation that generally defines a terrorist from a nonterrorist act of violence.

tion of sites and methods of attack. In choosing a target, terrorists assess buildings' physical layouts and locations, more specifically, the patterns of public vehicular and foot traffic into and out of a building, physical security measures and visitors' entrance procedures, and the existence of multiple entry and exit points. The lightly guarded public parking lot beneath the World Trade Center was very likely a factor that made this structure—in contrast to the considerably older Empire State or Chrysler buildings, which lack such facilities—operationally attractive to the terrorists who bombed it. Similarly, the unrestricted public access in front of the Murrah Building in Oklahoma City and its relatively short setback distance from the street may have influenced the choice of that target.

TABLE 2-1 Analysis of Bombing Incidents in the United States by Target, 1989–1993 (Deaths, Injuries, and Number of Incidents)

	Killed					
Target	1989	1990	1991	1992	1993	Total
Residential	15	10	13	15	21	74
Commercial	2	1	1	0	9	13
Vehicles	8	1	8	5	6	28
Educational	0	0	0	0	0	0
Mail Boxes	0	0	0	0	0	0
Open Areas	2	5	3	0	5	15
Utilities	0	0	0	0	0	0
Law Enforcement	0	1	0	0	0	1
State and Local Governments	0	1	0	0	0	1
Federal Government	0	0	0	0	1	1
Banks	0	0	0	0	0	0
Military	0	0	0	0	0	0
Airports and Aircraft	0	0	0	0	0	0
Apartments[a]	0	0	0	4	4	8
Religious Facilities[a]	0	0	0	0	0	0
Energy Facilities[a]	0	0	0	0	0	0
Parks[a]	0	0	0	0	2	2
Medical Facilities[a]	0	0	0	0	0	0
Other[b]	6	3	2	2	1	14
TOTAL	33	22	27	26	49	157

[a] New target category added in 1992.
[b] Other category does not include accidental/noncriminal explosives incidents.
[c] Statistical information for 1992 and 1993 encompasses actual and attempted bombings. The years prior reflect only functioned bombs and incendiary devices.
SOURCE: ATF (1993).

	Injured					
Target	1989	1990	1991	1992	1993	Total
Residential	114	64	84	112	99	473
Commercial	52	69	34	60	1075	1,290
Vehicles	26	38	27	22	26	139
Educational	15	11	41	73	29	169
Mail Boxes	1	5	3	3	14	26
Open Areas	77	41	26	26	44	214
Utilities	0	1	1	0	0	2
Law Enforcement	4	2	3	4	8	21
State and Local Governments	1	2	1	2	0	0
Federal Government	0	0	1	0	2	5
Banks	0	1	0	3	0	4
Military	0	0	0	2	1	3
Airports and Aircraft	0	0	0	0	0	0
Apartments[a]	0	0	0	35	17	52
Religious Facilities[a]	0	0	0	14	16	30
Energy Facilities[a]	0	0	0	0	0	0
Parks[a]	0	0	0	1	3	4
Medical Facilities[a]	0	0	0	0	0	0
Other[b]	14	17	25	6	2	64
TOTAL	305	251	246	349	1,323	2,474

A building's physical location may similarly be a critical factor in target selection. Terrorists may be unable to gain access to their primary target site and therefore must settle for detonating a bomb inside or outside an adjacent building. A block of apartments in London's exclusive Kensington Palace area was bombed in July 1994 apparently because of its location adjacent to the well-protected Israeli Embassy.

Several facts suggest that the terrorist threat to buildings will remain significant. First, there is the relative ease with which access can be gained to commercial establishments. Such structures are necessarily open to the public, are subject to heavy daily pedestrian and vehicular traffic, and generally have few formidable access barriers. In contrast, other attractive terrorist targets—such as embassies, consulates, and military facilities—are often better protected and guarded, and sometimes physically and structurally reinforced. The latter are deliberately formidable targets, but an unintended effect of their "hardening" may be to displace the terrorist threat onto more vulnerable structures, such as commercial buildings. Another reason the terrorist threat to buildings will likely persist, as the Oklahoma City, the World Trade Center, and other numerous recent major bomb ings demonstrate, is that attacks on buildings (especially by bombing) are a proven means for terrorists to attract attention to themselves and their causes.

It is interesting to note that simple homemade devices fabricated by amateurs have proven just as destructive and lethal as more sophisticated terrorist weapons. The explosive device used at the World Trade Center, for example, was made out of ordinary, commercially available materials—including lawn fertilizer (urea nitrate) and diesel fuel—and cost less than $400 to make.[9] The device used in the Oklahoma City bombing was likely of similar construction. The

	Number of Incidents					
Target	1989	1990	1991	1992	1993[c]	Total
Residential	367	372	453	662	699	2,553
Commercial	205	262	297	369	335	1,468
Vehicles	284	294	286	426	408	1,698
Educational	76	86	93	151	167	573
Mail Boxes	204	352	495	789	872	2,712
Open Areas	81	124	91	126	146	568
Utilities	27	25	37	38	16	143
Law Enforcement	14	17	15	38	24	108
State and Local Governments	14	17	38	50	36	155
Federal Government	11	7	9	11	10	48
Banks	8	16	17	16	15	72
Military	4	2	8	5	8	27
Airports and Aircraft	2	1	3	2	2	10
Apartments[a]	0	0	0	146	98	244
Religious Facilities[a]	0	0	0	14	16	30
Energy Facilities[a]	0	0	0	4	7	11
Parks[a]	0	0	0	45	44	89
Medical Facilities[a]	0	0	0	12	14	26
Other[b]	87	89	157	85	63	481
TOTAL	1,384	1,664	1,999	2,989	2,980	11,016

[9] The World Trade Center bomb was composed of some 1,200 lbs of common sulfuric and nitric acids used in dozens of household products and urea used to fertilize lawns. The detonating device was a more complex and extremely volatile mixture of nitroglycerine enhanced by tanks of compressed hydrogen gases that were designed to increase the force of the explosion (see Barnes. 1994: Bernstein. 1994a–d: and Morganthau. 1994). Similarly, in April 1988 a Japanese Red Army terrorist was arrested while en route to New York City on a bombing mission. Found in his possession were gunpowder, hollowed-out fire extinguishers in which to place the explosive materials, and roofing nails as crude anti-personnel weapons (see BRI. 1988: Hanley, 1988).

sophistication of terrorist weapons, then, especially bombs and explosive devices, may well be in their simplicity. Unlike military ordnance, such as plastic explosives for example, the materials used in homemade bombs are readily commercially available; they are thus perfectly legal to possess until actually concocted or assembled into a bomb.

These ordinary materials are also far more difficult for authorities to trace or for experts to obtain a "signature" from. For foreign governments seeking to commission terrorist attacks, such homemade bombs also help enable the state sponsor to avoid identification and any possible military retaliation or international sanction. Furthemore, terrorists can improve their methods readily. As the World Trade Center bombers included a chemical engineer in their operations, future terrorists targeting a building may, for example, include a structural engineer in their plans to help ensure the collapse of the building. Terrorists study the "lessons" of comrades and other terrorist groups, and are often more sophisticated in their operations and know more about security-force tactics and countermeasures than their predecessors. Finally, again, the increase in internal security at many buildings in the wake of recent bombings may not eliminate the terrorist threat to buildings, but rather displace it to more accessible buildings.

BOMB DAMAGE TO BUILDINGS AND OCCUPANTS

A bomb explosion within or immediately nearby a building can have catastrophic effects, destroying or severely damaging portions of the building's external and internal structural framework, collapsing walls, blowing out large expanses of windows, and shutting down critical fire-and life-safety systems, such as fire detection and suppression, ventilation, light, water, sewage, and power. Loss of life and injuries to occupants can result from many causes, including direct blast-effects, debris impact, fire, and smoke. The indirect effects can combine to inhibit or prevent timely evacuation, thereby contributing to additional casualties.

The following sections describe examples of these damaging effects. Bomb damage to buildings depends, of course, on the type of building and the nature of the explosive device and its location relative to the building. Other factors determining damage relate to the specifics of the building's design and the immediate surroundings and the location and disposition of its occupants. The first section below describes the structural damage to a building from the direct effect of an explosion. Collateral damage to building subsystems is discussed, and the final section describes how injuries are sustained by people within the building. The nature of explosions and a more quantitative discussion of their induced physical behavior is presented in Chapter 3.

Structural Damage

Recent terrorist attacks against commercial buildings dramatically illustrate the influence of bomb placement and building design on the nature and extent of direct structural damage. The devastating car bomb attack against the Jewish Community Center in Buenos Aires (July 1994) illustrates the damage potential of an external explosion against a multistory building of masonry load-bearing construction. A similar attack against a multistory office building of more modern concrete column and slab construction at St. Mary Axe in London, (April 1992) inflicted a different type and level of damage. In marked contrast, a much larger car bomb detonated in an underground garage of the World Trade Center, a modern steel and concrete skyscraper (February 1993) did substantially less structural damage than was probably intended. The structural consequences of these terrorist attacks and bombings in Staples Corner, London, and Oklahoma City are briefly reviewed here.

Jewish Community Center, Buenos Aires

On July 18, 1994, a van loaded with about 275 kg of high explosive was detonated in front of the Jewish Community Center located in a densely constructed area of Buenos Aires. The explosive is thought to have been arranged to focus the blast on the building, 3 to 5 meters away. The exterior walls of this five-story building were of brick masonry construction, which supported the floor slabs. The air blast from the bomb totally destroyed the exposed load-bearing walls which, in turn, led to progressive failure of the floor slabs and virtually total collapse of the building. Figure 2-1 illustrates the resulting damage to the building. Such wall-bearing buildings are notable for their tendency to be brought down in this manner by localized damage.

St. Mary Axe, London

A car bomb containing an estimated 350 kg of TNT[10] was detonated in the densely built-up St. Mary Axe section of London near midnight on April 11, 1992, causing extensive damage to a number of neighborhood buildings. Figure 2-2 is a photograph of the damaged European Bank for Reconstruction and Development, a 10-story tower block atop a three-story pedestal, located at an estimated 115–160 m from the car bomb. This building was of modern concrete column and slab construction with nonbearing masonry walls on the lower three

[10] This estimate was obtained from newspaper accounts and does not necessarily represent official estimates.

Figure 2-1
The Jewish Community Center, Buenos Aires, showing vulnerability of brick masonry construction. Source: Embassy of Argentina, Washington, D.C.

Figure 2-2
St. Mary Axe, London, showing general damage to multistory office building of the European Bank of Reconstruction and Development. Photo reproduced courtesy of Safe Special Services Group.

floors. It was directly shielded from the explosion by another building and did not suffer significant structural damage; nevertheless, there was extensive glass damage and attendant hazard potential to personnel. [11]

Figure 2-3
St. Mary Axe, London, showing potentially lethal glass shards. Photo reproduced courtesy of Safe Special Services Group.

Window damage to the bank building illustrates the influence of glass size, strength, and orientation. Windows were completely broken on the two up-wind faces and survived almost completely on the down-wind faces.[12] All large windows in the first-floor pedestal (1.5 m × 2.8 m, 10-mm annealed glass) were blown in, and glass shards were thrown into adjacent offices to a distance of about 3 m, as illustrated in Figure 2-3. This office either did not have venetian blinds or the blinds were not lowered at the time of the explosion. Where blinds were in place in other offices, they effectively reduced the fragment hazard by

[11] Because the explosion occurred just before midnight when the offices were unoccupied, it is estimated that injuries were less extensive than if the explosion had occurred during the day.

[12] Windows that blew out on the down-wind faces were designed as smoke vent windows and were actuated by the internal explosion pressure.

capturing many of the glass shards and reducing the throw of others. Similar glass fragment behavior was observed on upper floors as well. It is also evident from this photograph that the blast effects of the explosion on the interior were of very low intensity, since only negligible disturbance of desk papers occurred. The only windows to survive on the up-wind face of the building were the second-floor podium windows (2.5 m × 2.5 m) that were made of toughened, 10-mm thick, double-glazed glass, and the picture windows on either side of the main entrance, which were laminated and survived the explosion but were crazed. Basement windows at street level were 33-mm-thick laminated glass and survived without crazing.

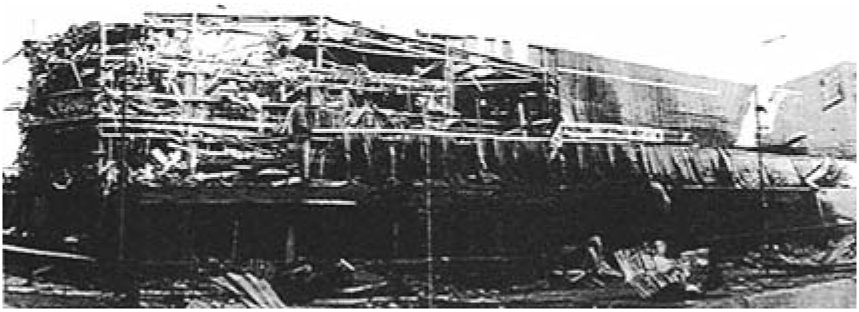

Figure 2-4
Staples Corner, North London, showing damage to a single-story steelframed warehouse. Photo reproduced courtesy of SAFE Special Services Group.

Staples Corner, North London

On April 11, 1992, an explosion occurred at Staples Corner. Figure 2-4 shows the resulting damage to a single-story steel-framed warehouse measuring 56 m × 57 m. The building's nearest corner was 17 m from the explosion and its farthest corner 95 m away. The building was clad with light-profiled steel sheeting on light purlins in the walls and roof and is a good example of frangible construction, that is, where the resistance of the cladding is much less than that of the supporting framework. Severe damage occurred to the cladding, sheeting, purlins, blockwork lining wall, and finishes and fittings in areas nearest the blast. However, the main steel frame sustained only minor damage. The stripped sheeting generally rebounded outward toward the bomb.

World Trade Center, New York City

The terrorist attack against the 110-story World Trade Center on February

26, 1993, involved a much larger car bomb than the London or Buenos Aires attacks. While damage and injuries in the World Trade Center bombing were extensive, they differed substantially from those in the other cases because of differences in bomb placement and building structure. The bomb, estimated to be about 900 kg of high explosive, was detonated against the south wall of the north tower in an underground garage two levels below grade. The most severe structural damage occurred to the subgrade levels, with the bomb crater measuring 24 m to 36 m across on some of the levels. Two levels of reinforced concrete slabs, about 280 mm thick, were blown out and the debris completely covered refrigeration equipment on the fifth subgrade level, rendering it inoperable. A shock wave propagated throughout the subgrade structure, causing the parking-level slabs to fail at column capitals and other "hard points." Steel columns that supported both the adjacent Vista Hotel and parts of the World Trade Center Plaza and concourse area, that before the explosion were braced by the closely spaced parking levels, stood naked as high as 21 m without definable lateral support. At the crater's edge, the slabs had sheared free of their supporting columns, settling several feet to form "ski jumps" into the crater. Elsewhere, multi-ton portions of concrete were literally dangling from reinforcing steel.

Figure 2-5 shows the aftermath of the explosion at the level of the detonation. The photograph was taken at the south end of the parking garage; the explosion occurred at the north end. Segments of the masonry wall along the

Figure 2-5
World Trade Center, New York City, showing the aftermath of the explosion within the parking garage. Source: ATF (1993).

south wall of the north tower were blown into the building; masonry work surrounding elevator shafts was blown into those shafts, causing the air locks to be breached, particularly for the north tower. With the loss of the air locks, smoke and dust-laden air was drawn into and upward through the towers by stack action, a phenomenon discussed in Chapter 4. Breaching of the air locks accounted for the majority of personnel injuries, as discussed later in this chapter.

While the intent of the terrorists may have been to bring down the tower, its structural integrity was never threatened. This achievement undoubtedly can be attributed to the ductility of the structural steel shell and the conservative requirements used in its design: to withstand a 240-kph wind storm, the loss of perimeter columns by sabotage, and the impact of a fully fueled 707 aircraft anywhere along the tower height. A more immediate reason the tower did not collapse is because the lateral (horizontal) blast pressure was not large enough to cause the column to fail in shear or combined axial load and bending. The adjacent column bracing and floor framing did fail due to the blast pressure. The adjacent Vista Hotel, less massively constructed, did sustain extensive damage, which threatened its structural integrity.

Alfred P. Murrah Federal Building, Oklahoma City

The bombing of the Federal Building in Oklahoma City on April 19, 1995, was the largest such terrorist attack in the United States to date (ENR, 1995). A car bomb, estimated to contain about 1,800 kg of high explosive and located 3–5 m from the north face of the building and about 12–15 m from the east end, caused 168 fatalities, numerous injuries, and an estimated $50 million in damage to about 75 buildings in the area. The Murrah Building was a nine-story tower of reinforced concrete slab and column construction measuring 61.5 m × 21.5 m. The frame had 10.7 m × 6.2 m typical bays, created by a column line along each face and one down the center. Four of the north-face columns, spaced at 12.3 m and unsupported for two stories, formed an atrium at street level. A 61.5-m-long third-floor spandrel beam transferred loads from the columns on floors above to the 8-m-tall exposed columns. The explosion destroyed three of the four front columns and a centerline column. With four columns shattered, the upper floors toppled northward as the 200-mm-thick slabs separated from centerline columns. As a consequence, 8 of the 10 bays along the northern half of the building collapsed into a heap. In the southern half of the building, two bays collapsed on either side of the failed center column. Inside the south entrance, slabs collapsed in adjacent bays on two floors. Photos are shown in Figures 2-6 and 2-7.

Damage to Building Subsystems

Certain building subsystems, if lost, render the building unable to protect the occupants or assist in their survival and otherwise make the building uninhabit

Figure 2-6
Alfred P. Murrah Federal Building, Oklahoma City, showing catastrophic effects on the building's north face.

Figure 2-7
Alfred P. Murrah Federal Building, Oklahoma City, showing detail of the reinforced concrete column and slab construction.

able or unusable. Typical of these subsystems are fire-detection and suppression systems; water and sewer service, including sanitation; means of egress, including corridors, stairs, lobbies, and exit doors; elevators; primary and emergency electrical systems; and rescue operation systems, including voice and data communications, ventilation, and smoke control.

A bomb detonation inside a building's parking garage probably would cause the most serious damage to building subsystems simply because several critical subsystems originate there, along with much of the control and distribution equipment. A garage-level detonation has a significant potential for fire and smoke production because the parked vehicles contain large amounts of combustible materials. Also, the fire-suppression system would likely be made inoperable, since it is exposed and very fragile.

The World Trade Center bombing, unfortunately, was a very good example of these observations: extensive damage occurred to communications, life-safety, electrical, and mechanical systems; the emergency generator plant shut down because of loss of cooling water; the elevator and stair shafts were breached; smoke from burning automobiles on the parking levels was forced up the shafts of both towers; and the underground tower's operations control center was put out of commission, leaving building occupants without important information.

Street-level explosions can also cause serious damage to critical building subsystems. Most urban office buildings have extensive street-level fenestration consisting of glass panes, some as large as 2 m × 4 m set in narrow aluminum extrusions. This assembly typically has little or no blast resistance, and a blast wave can enter the street-level lobby area virtually unattenuated. Consequently, extensive damage can occur to the fire control room usually located near the lobby, to elevators, to egress stairways, and to the service risers that pass through the street-level floor. Service risers generally are concentrated in one of a few vertical shafts or "chases" that rise up through the core of the building, usually contiguous with the elevator shaft(s). Typically they contain the heating and cooling hydraulic lines, domestic and sanitary systems, electrical distribution and communications lines, fire standpipes, and supply/return ducting and condenser water lines. Building codes require that these chases be fire-rated, but they are generally constructed of relatively light materials. Their blast resistance typically is poor and at least some of the service risers would likely be severed. The lateral distribution of services on the upper floors is accomplished by equipment and conduits above the ceilings of occupied spaces—systems that can be damaged by a street-level depending on the location of the service risers relative to the point of detonation. The ceilings are commonly constructed of loose fiber tiles laid in a lightweight gridwork and offer little to no protection.

Blast damage to the elevators from either a garage-or street-level detonation is usually extensive and most disruptive to occupancy in mid-to high-rise buildings. Elevator doors may collapse into the hoistway, and there will be damage to hoistway components directly from the explosion and from flying structural de bris. Elevator cabs that are at rest on the floor where the explosion occurs will be damaged, perhaps beyond repair. In multi-elevator banks, damage to only one cab or hoistway may cause the electrical and mechanical safeties to shut down the entire system, thereby preventing the surviving cabs from being operated manually or on fire service. Stairways used to evacuate the building in the event of a fire or explosion are similar in construction and vulnerability to the elevator shafts and would experience similar damage from a street-level blast. Collapse of the stairway shaft walls may make the stairway impassable, impeding or even preventing evacuation, and the situation is made still more serious because the main lobby level is often one means of egress from the building.

Hazards to People

Personnel injuries and loss of life can result directly from the bomb's explosion; blast pressure, impact of high-speed glass fragments or other structural debris, collapse of structural members, fire and smoke inhalation, or a variety of other causes associated with the general confusion that may follow an explosion and a possibly prolonged evacuation period. If the explosion is sufficiently close to a wall or floor, there can be gross disintegration, with either spalled pieces on the back side or the wall materials themselves being propelled as missiles. These missiles can injure people and damage property, and if structural support is sufficiently disrupted, the building may collapse. Except when people are trapped in collapsed building spaces, most injuries occur from missile penetration or from smoke inhalation.

Breaching of elevator and stairwell doors (more likely for street-level explosions) allows smoke to migrate upwards into the building, carried by the building's stack effect during winter months. Elevators are likely to be occupied throughout the day, and persons may be trapped within them, either as a result of damage to the elevator shaft or hoists, or as a result of loss of power or controls. In the World Trade Center bombing, the north tower air locks were destroyed and smoke and dust-laden air was forced to the upper floors, accounting for most of the over 1,000 personnel injuries.

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3

Review of Existing Knowledge for Blast-Effects Mitigation and Protective Design Technologies

INTRODUCTION

This chapter contains an assessment of the state of the art in blast-effects mitigation and protective design technologies and highlights blast-hardening capabilities developed by the military that are applicable to the civilian sector. The introductory section outlines the historical development of the existing knowledge base, the nature of explosions, and the induced physical behavior of materials. This is followed by a section on experimental and simple analytical approaches to blast-effects mitigation and structural design. The far-ranging needs of military organizations to protect key assets from enemy attack, together with the large cost and practical limitations of field testing, has led to a strong emphasis on developing analytical methods and advanced computer models for simulation of blast-effects on building structures. The third and fourth sections summarize applicable military design manuals and computational approaches, respectively, to predicting blast loads and the responses of structural systems. Although the majority of military design guidance is based on semi-empirical relationships, much of the existing knowledge of blast environments and the effects of high-intensity, short-duration loadings on the behavior of structures, systems, and components is embodied in sophisticated "first-principle" computer programs as well as in simplified, design oriented and semi-empirical software. Accordingly, the fifth section discusses specific computer programs, followed by a section on code validation which looks at comparisons of computational calculations of the response to an explosion to the actual experimental results. The final section of the chapter reviews the applications of the computational methods to terrorist threats.

Although not directly related to the subject of this study, two previous National Research Council (NRC) studies have dealt with terrorism and bombing: The first is *The Embassy of the Future* (NRC, 1986), which reviews the measures that could be applied to new foreign service buildings for all categories of threats, including bombs. The Department of State has since developed a large body of data and design guidelines related to countering terrorism through design. The second study is *Protection of Federal Office Buildings Against Terrorism* (NRC, 1988) which addresses the protection of existing domestic federal buildings from various threats, including bombs.

Historical Background

Explosive devices have been used for hundreds of years, yet comprehensive treatment of blast-effects and their mitigation appeared in the Western Hemisphere only during and after World War II. Following the war, the Office of Scientific Research and Development (National Defense Research Committee, 1946) produced the seminal, unclassified document on weapons and penetration capabilities. This report remains of value today. While the document is difficult to locate, some of the information it contains has been republished (Bangash, 1993). Of special interest in the latter publication is information that permits estimates to be made of the penetration resistance of structural elements of various materials to projectiles of many forms.

World War II was the first international conflict that resulted in massive destruction of cities, mostly with high explosives, which also inflicted enormous casualties. In the latter stages of that war, the use of two nuclear weapons demonstrated the destructive capability of such weapons (Glasstone and Dolan, 1977).

The accelerated arms race during the Cold War, from 1945 through 1990, led to research and development of modern nuclear weapons during this time period, and a major research program on protective structures and systems was established, largely sponsored by the Armed Forces Special Weapons Project, later renamed the Defense Atomic Support Agency, and thereafter the Defense Nuclear Agency (DNA). Throughout this period, DNA, in cooperation with the U.S. Air Force, the U.S. Navy, and the U.S. Army, conducted major test programs in laboratories and field test facilities. In addition, theoretical and experimental work sponsored by these agencies was carried out in various companies and universities.

In the United States a comprehensive program of research over the past half century was undertaken to increase the blast resistance of military structures such as weapons storage facilities and command, control, and communication facilities. Much of this research was in response to deployment of ballistic and guided missile systems. In addressing both the nuclear threat and the threat of conven tional weapons, a number of widely used manuals on protective structures were developed. These manuals reflect the improvements in engineering practice that occurred over the years (Newmark and Haltiwanger, 1962; Crawford et al., 1974; ASCE, 1985; Schuster et al., 1987). This progression of manuals concentrated on techniques for estimating the loadings from nuclear weapons explosions, attenuation of pressure effects in the air and ground, simple analytical techniques for design and proportioning of structural elements, guidelines for designing and analyzing equipment, and many other related topics.

Although nuclear weapons effects were the primary focus of protective design through the 1970s, related work was ongoing to develop quantitative procedures for the design of structures subject to accidental explosion. Extensive research and development programs, including numerous full-and small-scale structural response and explosive effects tests, form the empirical basis for *Structures to Resist the Effects of Accidental Explosions* (U.S. Departments of the Army, Navy, and Air Force, 1969). Several other manuals dealing with blast effects and the design of protective structures have also been developed for use by the military services (U.S. Department of the Army, 1986, 1990; Drake et al., 1989; U.S. Department of Energy, 1992). Although none of these manuals is dedicated solely to the subject of this report, taken together, they provide a range of structural data and design procedures for protective structures useful to designers and which have applicability to the design of more explosion-resistant buildings. Increased terrorist activity throughout the world and in the United States has also led to a number of specialized studies in recent years. These studies and a variety of design manuals are discussed later in this chapter.

Nature of Explosions

Explosive materials are designed to release large amounts of energy in a short time. The explosion arises through the reaction of solid or liquid chemicals or vapor to form more stable products, primarily gases. A high explosive is one in which the speed of reaction (typically 5,000–8,000 m/s) is faster than the speed of sound in the explosive. High explosives produce a shock wave along with gas, and the characteristic duration of a high-explosive detonation is measured in microseconds (10^{-6} s).

Explosives come in various forms, commonly called by names such as TNT, PETN, RDX, and other trade names (U.S. Department of the Army, 1986; McGraw-Hill Encyclopedia of Science & Technology, 1987). A common explosive employed in rack blasting, called ANFO, is composed of ammonium nitrate and diesel fuel oil—products that are readily available. Dynamite, of which there are many kinds, is also readily available, and theft and misdirection in shipping occur occasionally. The lethality of high explosives has been increasing since the nineteenth century (Johansson and Persson, 1970; Henrych, 1979; Baker et al., 1983; Dick et al., 1983; Fickett, 1985; McGraw-Hill Encyclopedia of Science &

Technology, 1987). For someone bent on destruction, high explosives are relatively easy to make or acquire, and detonation, though technically more complicated, is not difficult for someone with even modest training in explosives.

The effects of explosions on structures are directly related to stress-wave propagation as well as impact and missile penetration. In all close-in explosions, where shock waves must travel through the surrounding medium to cause damage to a facility, a realistic description of the wave-propagation phenomena is needed. The literature on these subjects can be divided into two groups: one group addresses the classical issue of wave propagation, with emphasis on linear-type problems, and the second group is more focused on nonlinear problems. (Various theoretical aspects of the explosive effects in materials are discussed in Achenbach, 1973; Whitham, 1974; Davis, 1988; Han and Yin, 1993; and Batsanov, 1994.)

The effects of an explosion are varied. For explosions close to the targeted object, the pressure-driven effects occur quickly, on the order of microseconds to a few milliseconds. The air-blast loads are commonly subdivided into (1) loading due to the impinging shock front, its reflections, and the greatly increased hydrostatic pressure behind the front, all commonly denoted as overpressure; and (2) the dynamic pressures due to the particle velocity, or mass transfer, of the air. It is customary to characterize the pressure loadings in terms of scaled range, as given by $Z = R/W^{1/3}$, in which Z is the scaled range, R is the radial distance between the explosion center and the target, and W is the explosive weight (normally expressed as an equivalent TNT weight). Units for charge weight and distance should be either pounds and feet or kilograms and meters. In the scaled-range concept, as long as the value of Z remains the same, the same parameters for the explosive effects (i.e., peak pressure, positive duration, etc.) should be obtained.

If an explosion is confined by a chamber or room, the gas pressure increases rapidly to a sustained level and then decays by venting out. Under these conditions shock reflections occur and the overall effect can be greater than that of the incident shock. The effects of internal explosions can be devastating to buildings and their occupants, which supports evaluation of the possibility of mitigating blast-effects by controlled venting. There is a considerable body of knowledge available concerning blast-effects mitigating techniques for buildings subject to accidental explosion (U.S. Department of the Army, 1990), which may have applicability to the design of civilian office structures.

There are three additional explosion-related phenomena relevant to this study, namely impact of objects propelled by the explosion environment (Jones, 1989), penetration of such objects (Zukas, 1990; Bangash, 1993), and ground-transmitted shock (U.S. Department of the Army, 1986, 1990; Drake et al., 1989; U.S. Department of Energy, 1992; DNA, 1995).

Induced Physical Behavior

If the explosion originates at a sufficiently great scaled range (i.e., a small charge or a large distance from a structure), then the structure will be loaded in a manner that leads to global deformation, meaning that all the elements provide some degree of resistance to the loading. The definition of the expected loading, and the provision of resisting elements to accommodate the loading, are the essence of dynamic design, analysis, and construction; these issues are addressed in the previously cited design manuals and by the computer codes discussed later in this chapter.

If the explosion is sufficiently close to a wall or floor (that is, with a small scaled range), there can be gross disintegration, with either spalled fragments coming off the front and back sides or wall fragments themselves being propelled as missiles. These fragments can injure people, damage property, and, if structural support is sufficiently disrupted, cause the building to collapse. At intermediate scaled ranges, both global and localized response, including severe cracking, with near-face disintegration and spalling on the rear face, can be expected.

When an explosion impinges on a structural element, a shock wave is transmitted internally at high speed; for example, dilatational waves (tension or compression) propagate at speeds of 2,700–3,400 m/s in typical concrete and 4,900–5,800 m/s in steel. At these speeds, reflections and refractions quickly occur within the material (within milliseconds), and, depending on the material properties, high-rate straining and major disintegration effects can occur. For example, under extremely high shock pressures, concrete, a relatively brittle material, tends to undergo multiple fractures which can lead to fragmentation. In steel, under similar conditions, depending on the material properties and geometry, yielding and fracture can be expected, especially if fabrication flaws are present, with fragmentation occurring in some cases. Primary, fragments are produced when a detonating explosive is in contact with a material such as concrete or steel. The initial velocity of the primary fragments depends in part on the detonation pressure. Secondary fragments are produced by the effect of the blast wave on materials not in contact with the explosive.

Openings such as doors and windows require special design considerations if intrusion of the explosive shock wave is to be averted, or damage mitigated. Where high levels of blast-effects mitigation are sought, labyrinth (and) entrances, possibly with blast doors, as well as ventilation blast valves, can be used. As described earlier, explosions in a partially or fully confined space, as a room or garage, can be even more devastating, with higher pressures than would occur in free air and a longer duration of loading. In such situations significant damage can be expected.

Other explosion-generated effects are also produced, such as fire (including smoldering fires), smoke, pressure damage to ears and other organs, and violent motion of the structure and its contents. Such shock-related motion can result in personal injury and equipment damage and cause the loss of lifelines such as utilities and communications cables.

EXPERIMENTAL AND SIMPLE ANALYTICAL APPROACHES

Theory and experiments are essential for predicting the blast effects of an explosion. Experimental data may be combined with certain aspects of explosion theory to properly characterize material behavior at high strain rates, which in turn can be employed in developing computational approaches for estimating structural and equipment reaction to an explosion. It is important to validate such computational approaches by experiment whenever possible.

Some military testing programs have concentrated on the effects of nuclear weapons, frequently employing specially designed high-explosive devices to simulate either close-in or far-field effects of nuclear blast waves. The large-scale ANFO testing program using full-scale structures conducted by the military is one example of data collection specifically addressed to the issue of analytic verification. In these tests, approximately 450 metric tons of ANFO charges were used to produce overpressure loadings below approximately 0.69 megapascals (100 psi) corresponding to a 1 kt nuclear weapon; other high-explosive techniques were employed occasionally to obtain higher pressures.

The most common method used in this type of testing has been to load reduced-scale structures with either weapons or special high-explosive devices. In many cases, testing conditions permit only one structural scale and charge per study rather than a range of scaled sizes and charge weights, and, for a variety of reasons, comprehensive post-test studies often have not been conducted. Although the voluminous data available from weapons-systems test procedures and related military experiments may require extensive analysis and interpretation before the results can be fully incorporated into the knowledge base, this data provides a rich source of information not readily available elsewhere.[1]

The Accident Data Base of the Department of Defense Explosives Safety Board (DDESB) is another valuable source of empirical data on explosive events. The DDESB accident reports analyze damage sustained by structures in accidental explosions and can provide considerable insight into the performance of structural elements following an explosion.

[1] The majority of tests were conducted to determine the survivability of existing or proposed blast-hardened U.S. facilities: other tests were conducted to determine the vulnerability of possible enemy facilities, hardened or otherwise. From a survivability perspective, test objectives dealt with determining margins of strength of fully described facilities, whereas from a vulnerability perspective, the objectives concerned failure modes of facilities whose characteristics were known only approximately. Thus, what was conservative in one type of test, tended to be unconservative in the other, and extreme care must be taken in evaluating specific results for application in civilian practice.

The ability to design and construct safe buildings depends on an understanding of how such buildings behave under severe loads (i.e., cause-and-effect relationships). Unfortunately, past experiments, performed mainly by the military, have shown that supposedly identical high-explosive devices frequently produce significantly different loading environments. Consequently, progress in designing structures subject to explosive loading has been difficult to attain. A program of precision testing and code simulations in which loads are well defined and the outcome is well documented and assessed is clearly a prerequisite to further progress in designing blast-resistant buildings.

The results of full-scale tests for strengthening existing civilian structures against terrorist attack were recently reported at an international symposium (Fouks, 1993). Results were obtained for windows, doors, and light ceilings and roofs, and appear to be limited to failure pressures; no computational analyses of these tests have been reported. The suitability of these results for computer program validation (as discussed later in this chapter) is questionable because of limited data. Two companion papers report on measures to increase the blast resistance of walls and ceilings (Eytan and Kolodkin, 1993) and windows and doors (Kolodkin and Eytan, 1993). There has also been extensive test programs on windows in the United States and the United Kingdom.

Over the years, as a result of research coupled with test programs, computational approaches have been developed for estimating the responses and behavior of simple structures subjected to blast loading. In turn, based on experimental data, field-test observations and analytical procedures, a number of technical design manuals were developed, as described in the next section.

TECHNICAL DESIGN MANUALS

Structures to Resist the Effects of Accidental Explosions, TM 5-1300 (U.S. Departments of the Army, Navy, and Air Force, 1990). This manual appears to be the most widely used publication by both military and civilian organizations for designing structures to prevent the propagation of explosion and to provide protection for personnel and valuable equipment. It includes step-by-step analysis and design procedures, including information on such items as (1) blast, fragment, and shock-loading; (2) principles of dynamic analysis; (3) reinforced and structural steel design; and (4) a number of special design considerations, including information on tolerances and fragility, as well as shock isolation. Illustrative computations are also included in many cases. Guidance is provided for selection and design of security windows, doors, utility openings, and other components that must resist blast and forced-entry effects. The manual contains a valuable listing of relatively current references. Distribution is unlimited.

A Manual for the Prediction of Blast and Fragment Loadings on Structures , DOE/TIC-11268 (U.S. Department of Energy, 1992). This manual provides guid ance to the designers of facilities subject to accidental explosions and aids in the assessment of the explosion-resistant capabilities of existing buildings. It includes chapters on air blast; cratering and ground shock; fragment ballistics, including a thorough description of secondary debris hazards, secondary explosions, and the dynamic properties of materials. It is intended to be used in conjunction with other structural design manuals and provides a comprehensive listing of references. Distribution is unlimited.

Protective Construction Design Manual, ESL-TR-87-57 (Air Force Engineering and Services Center, 1989). This manual provides procedures for the analysis and design of protective structures exposed to the effects of conventional (non-nuclear) weapons and is intended for use by engineers with basic knowledge of weapons effects, structural dynamics, and hardened protective structures. Chapters cover topics such as uncertainties in protective design, air-blast effects, fragment protection, loads on structures, resistance of structural elements, and dynamic responses of structures. Distribution is limited.

Fundamentals of Protective Design for Conventional Weapons, TM 5-855-1 (U.S. Department of the Army, 1986). This manual provides procedures for the design and analysis of protective structures subjected to the effects of conventional weapons. It is intended for use by engineers involved in designing hardened facilities. It includes chapters on air-blast effects, fire, incendiary and chemical agents, loads on structures, and auxiliary systems (piping, air ducting, and electrical cable). Distribution is unlimited.

Design of Structures to Resist Nuclear Weapons Effects, Manual 42 (ASCE, 1985). This manual was prepared for civilian use, and has been widely distributed throughout the world. It contains information on weapon detonation characteristics, radiation shielding, blast and shock-loadings, applicable limit-load theory, simplified dynamic analysis procedures, and design procedures for structures as well as equipment. Even though the procedures emphasized are perhaps oversimplified, the manual has a broad audience. Distribution is unlimited.

The Design and Analysis of Hardened Structures to Conventional Weapons Effects (DAHS CWE) (DNA, 1995). This new Joint Services manual, written by a team of more than 200 experts in conventional weapons and protective structures engineering, supersedes U.S. Department of the Army TM 5-855-1, *Fundamentals of Protective Design for Conventional Weapons* (1986), and Air Force Engineering and Services Center ESL-TR-87-57, *Protective Construction Design Manual* (1989). The manual is based on state-of-the-art design information and methods for protective structures and includes new, recently analyzed and validated test data from the DNA test programs on conventional weapons effects, as well as design examples. Selected sections of the manual have unlimited distribution, but the manual as a whole has limited distribution.

In parallel with this effort, a DAHS CWE hypertext system based on the DAHS CWE hardcopy manual is being developed. This electronic hypertext version is intended to transform the manual into an interactive computer product complete with text, figures, graphs, tables, equations, and a number of stand-alone computer codes such as BLASTX and FOIL (discussed later in this chapter). All DAHS CWE system software and codes will be produced and distributed on CD-ROM and will eventually operate on both DOS-and Unix-based platforms. The hypertext system is expected to be completed in the fall of 1995.

Security Engineering, TM 5-853 (U.S. Department of the Army, 1993). The Department of Defense has recently shown an increased interest in applying systems engineering approaches to the design of military facilities for increased physical security against a range of threats, including terrorist attack. A three-volume security engineering manual has been developed that is intended for new construction and provides designers with guidance for protecting assets within facilities against a range of criminal, protester, terrorist, and subversive threats. Distribution is limited.

Terrorist Vehicle Bomb Survivability Manual (Naval Civil Engineering Laboratory, 1988). This manual contains information on vehicle barriers and blast survivability for buildings. It provides information to aid owners in protecting their property, assets, and personnel against terrorist vehicle bombs. This manual includes information on access control, vehicle barrier systems and testing, and sample blast vulnerability analyses. Distribution is limited.

Structural Design for Physical Security—State of the Practice Report (ASCE, 1995). This report is intended to be a comprehensive guide for civilian designers and planners who wish to incorporate physical security considerations into their designs or building retrofit efforts. Individual chapters are devoted to threat determination, load definition, structural systems behavior and design philosophy, structural components behavior and design, security window design, door design, utility opening design, and retrofitting existing structures. Publication is expected in 1995.

Balanced Survivability Assessment (Cicolani, 1994) DNA has developed and uses a method of survivability assessment that also appears applicable to architectural design, particularly for retrofitting existing buildings. This method incorporates a comprehensive systems approach to survivability assessment. Its elements include consideration of a full-threat spectrum analysis, assessment of the capabilities of all the physical systems of the facility to meet the threat (systemwide and single-point assessment), with assessment identification of the likelihood of failure and consequences on mission readiness and capability. It appears to the committee that this approach could be adapted to civilian application with relative ease.

COMPUTATIONAL TECHNIQUES

During the past 25 years, powerful computer programs have been developed for predicting blast loads and the resulting structural response. This section discusses the methods used in and the validation of these programs. To provide the nonexpert reader with some background on the need for validation, the classifications of semi-empirical and first-principle programs and linear and nonlinear problems are introduced. The purpose of this discussion is to support the theme that since blast evolution and response problems are highly nonlinear, validation of the computer programs by experiments is a necessity. The section also notes that a considerable degree of expertise is needed to use these programs effectively. DNA and other military organizations have conducted numerous tests and experiments for validating these computer programs over the years, and the need for validation is discussed later in this chapter. However, the structures in these validation tests and experiments were generally representative of military applications. It is not clear how relevant these previous tests are to civilian structures which are typically lighter in construction yet at the same time more structurally complex than the military structures tested.

First-Principle and Semi-Empirical Methods

Computer programs for the prediction of blast-effects can be subdivided in two groups: *first-principle* and *semi-empirical*. In first-principle programs, mathematical equations are solved that describe the basic laws of physics governing a particular problem. These principles are conservation of matter, momentum, and energy. In addition, mathematical relationships called constitutive equations, which describe the physical behavior of materials, are needed. If these equations are solved accurately with suitable mathematical models, they should predict the blast loads and structural response. However, there are several barriers to accurate prediction of the effects of an explosion through the use of first-principle programs. Among them are the following:

- In the calculation of blast due to explosions in air, the response of the air often involves complicated phenomena, such as dust-air mixtures, boundary effects, and turbulence. Turbulent flow, for example, cannot be calculated without the addition of models governed by empirical parameters.
- Calculation of the pressures imparted by a detonating explosive on the

structure involves multiscale phenomena that are very difficult to deal with; such phenomena also occur in the structure during failure.

- In the calculation of structural failure, the behavior of the materials is neither well understood nor readily characterized; in other words, accurate constitutive equations are not available for the materials, particularly in fracture or fragmentation.

While these deficiencies in first-principle codes are often compensated for by the use of engineering judgment, the main objective of first-principle techniques is to provide predictions in new domains where the experience that makes engineering judgment possible is not available.

Semi-empirical computational methods are based on simplified models of physical phenomena, which are developed through analysis of test results and application of engineering judgment. These methods rely on extensive data and case studies. They involve fewer equations and require far less computer time, which makes them more practical than first-principle codes for design purposes.

The computer programs applied in the evaluation of explosive effects cover two physical disciplines:

- computational fluid dynamics (CFD), which is used for the prediction of the air blast caused by the explosion and the pressures applied to surfaces exposed to the propagating air blast; and
- computational solid mechanics (CSM), which deals with the prediction of the response of structures to loads.

The pressures and the response of the structure are interrelated, and in many cases "coupled" analyses of the fluid and structure (where the fluid solution is obtained interactively with the structural solution) are needed. Coupled CSM-CFD solutions entail the use of much larger computer programs and are more costly, but they can provide more accurate predictions.

Linear and Nonlinear Problems

Computer models and programs have become indispensable in engineering design and development. The complexity and dependability of the models varies dramatically. To provide a perspective for blast programs, this section introduces several classifications.

An important classification of computer simulation models and analyses is whether the governing equations and response are linear or nonlinear. Linear analysis is applicable when the displacements of a structure or medium are small and the stresses can be related to the deformation by linear relationships. Examples of linear analyses include acoustic-wave propagation and stress analyses of structures and machines under normal operating loads (referred to as "elastostatics"). In a linear analysis there is usually almost no need for validation of a computer program because the equations are very robust, and modern computer programs can accurately predict the linear behavior if sufficient resolution is achieved in the model.

Nonlinear analysis, however, is needed when the displacements of a medium or structure are large and when the strains and stresses exceed the range in which linear relationships hold. Behavior such as fracture, fragmentation, and flow due to high-pressure sources is also nonlinear. Thus the problems of blast evolution and structural response are highly nonlinear and there are many mathematical and physical complications and phenomena whose underlying physics are not well understood. For the nonlinear computations required for most blast-effects problems, validation of computer programs by experiments in similar scenarios is essential. Without adequate validation, a nonlinear computation is generally of marginal usefulness, underscoring the importance of precision experiments mentioned earlier in this chapter.

Finite-Element and Finite-Difference Methods

Two types of discretization methods are widely used: *finite-element* (and *finite-volume*) *methods* and *finite-difference methods*. In finite-element methods, the domain of the problem is subdivided into subdomains called elements, which are interconnected by nodes. The dependent variables, such as the displacements, are then interpolated in each of these elements so that they are expressed in terms of their nodal values. Finite-element methods have the versatility to deal with complicated geometries. Finite-volume methods are quite similar to finite-element methods, except that the mathematical approximation procedure is different.

In finite-difference methods, the discretization is accomplished by superimposing a network of nodes or grid points on the geometry. The arrangement of these grid points is usually structured, which diminishes the versatility in dealing with complex geometries, but these methods generally offer higher calculational speeds.

Ease of Use of Programs

At present, use of these programs requires considerable expertise in computational mechanics generally and familiarity with the specific programs used. Some of these programs are evolving research tools that are successfully used only by the developing organization or perhaps by a few similar organizations. They lack the documentation and user-friendliness for engineers who cannot readily interact with the developers of the programs. Even the more highly developed and user-friendly programs are not readily usable by nonexperts for several reasons:

- Many parameters need to be input, including artificial viscosities and choices among methodologies, and their selection requires considerable experience.
- The development of inputs requires construction of detailed finite-element or finite-difference models, which entails selection of the features of the physical sites that are important and a knowledge of how to model them.
- Considerable skill is required to evaluate the output, both as to its correctness and its appropriateness to the situation modeled; without such judgment, it is possible through a combination of modeling errors and poor interpretation to obtain erroneous or meaningless results.
- Conversely, the generality of these programs and the relative ease with which details of a physical system can be incorporated in the simulation model, even by those without the requisite expertise, can lead to unwarranted confidence in the validity of specific results.

Therefore, successful computational modeling of specific scenarios by engineers unfamiliar with these programs is difficult, if not impossible. Current research is seeking ways to make these and other sophisticated computer programs more intuitive and user-friendly. The committee learned of one such effort to develop a powerful methodology which facilitates simulation-based design by providing the user with an expert system to assist in the development of the model and specification of the parameters required for a computational simulation (SAIC, 1994). Such tools would make the programs developed for blast-effects simulation more accessible to engineers who are not experts in the programs themselves.

Another impediment to the use of these programs is the magnitude of computational resources required. Some of the simulations take 20–100 hours on the most powerful supercomputers, such as the Cray C-90. Small-scale, two-dimensional calculations can often be made on workstations in a matter of minutes or hours, but the time required grows rapidly as the model increases in detail.

Other Applications of Numerical Simulation Techniques

Computational methods are proven techniques that are used extensively in commercial engineering design and evaluation. For example, in the automotive industry, crashworthiness design is based on computer simulations which can predict passenger acceleration levels, and hence whether the crash can be survived without serious injury. CFD programs, similar to those used for blast prediction, are used to design the air flow for cooling the engine compartment and for drag reduction. The use of computer models in the automotive industry has reduced the numbers of prototypes that must be built during the design cycle and thus shortened the time required from inception of design to production. The automotive industry is able to amortize the cost of computer modeling over the large number of units produced. Nonlinear computational mechanics is finding increasing application in design manufacturing processes, such as sheet-metal forming, extrusion, forging, and casting, and to simulate prototype tests, such as drop tests for electronic products and durability tests of safety-critical components. The methods used for prediction of blast effects and structural damage are identical to those used in manufacturing and some of the same computer programs are used in both areas.

COMPUTER PROGRAMS FOR BLAST AND SHOCK EFFECTS

Computational methods in the area of blast-effects mitigation are generally divided into those used for prediction of blast loads on the structure and those for calculation of structural response to the loads. Computational programs for blast prediction and structural response use both first-principle and semi-empirical methods.

The governing equations of physics include conservation of momentum, conservation of energy, measures of stress and strain, and laws governing the relation between stress and strain, which depend on the physical properties of materials involved. To some extent, prediction in solids is simplified as compared to fluids, since there is no counterpart to turbulence; however, the dynamic behavior of solid materials generally is far more complicated than fluids, particularly when the structure fractures or fragments.

Most explosion-induced structural response calculations are made in an uncoupled manner. This involves calculating blast loads as if the structure (and its components) were rigid and then applying these loads to a responding model of the structure. The shortcoming of this procedure is that when the blast field is obtained with a rigid model of the structure, the loads on the structure are often overpredicted, particularly if significant motion or failure of the structure occurs during the loading period. An example of this was the overprediction of pressures in a numerical simulation using the FEFLO program (see below) after the World Trade Center bombing.

A current, active area of research is addressing the need for coupled calculations. In coupled calculations, the CFD model for blast-load prediction is solved simultaneously with the CSM model for structural response; that is, for a coupled calculation, the blast prediction program is linked with a structural response program. By accounting for the motion of the structure while the blast calculation proceeds, the pressures that arise due to motion and failure of the structure can be predicted more accurately. Several efforts in this direction are now under way. Under DNA sponsorship, FEFLO has been coupled to DYNA3D and its adaptivity features added to DYNA3D. This change allows FEFLO to be used for the blast calculation and DYNA3D) for the structural response calculation.

Table 3-1 summarizes a partial listing of computer programs that are currently being used to model blast-effects on structures, with more detailed descrip

TABLE 3-1 Representative Computer Programs Used to Simulate Blast Effects and Structural Response

Summary of Computational Codes				
Name	Purpose	Type	Corporate Author	Reference
BLASTX	Blast prediction	Semi-empirical	SAIC	Britt and Lumsden, 1994
CTH	Blast prediction	First-principle	Sandia National Laboratories	McGlaun et al., 1990
FEFLO	Blast prediction	First-principle	SAIC	Baum et al., 1994
FOIL	Blast prediction	First-principle	Applied Research Associates, Waterways Experiment Station	Windham et al., 1993
HULL	Blast prediction	First-principle	Orlando Technology, Inc.	Gunger, 1992
SHARC	Blast prediction	First-principle	Applied Research Associates, Inc.	Hikida et al., 1988
DYNA3D	Structural response	First-principle	Lawrence Livermore National Laboratory	Whirley and Engelmann, 1993
EPSA-II	Structural response	First-principle	Weidlinger Associates	Atkatsh et al., 1994
FLEX	Structural response	Firm-principle	Weidlinger Associates	U.S. Department of Energy, 1992
ALEGRA	Coupled analysis	First-principle	Sandia National Laboratories	Budge and Peery, 1993
ALE3D	Coupled analysis	First-principle	Lawrence Livermore National Laboratory	American Society of Mechanical Engineers, 1993
DYNA3D/ FEFLO	Coupled analysis	First-principle	Lawrence Livermore National Laboratory/ SAIC	Löhner et al., 1995
FUSE	Coupled analysis	First-principle	Weidlinger Associates	Sandler and Rubin, 1990
MAZe	Coupled analysis	First-principle	TRT Corporation	Schlamp el al., 1995

tions of the codes presented in Appendix B. Code validation has occurred in all cases, with the rigor of a particular validation depending on such factors as code maturity, urgency of application, availability of funding, etc. Software availability to the private sector varies, with some codes being currently available for sale (e.g., FLEX), others classified as "export-controlled" (CTH), and some having limited availability due to national security classification. Corporate authors can provide availability information for particular codes. Except for a few cases where the code can be run on a personal computer (e.g., FLEX), these codes are generally of sufficient complexity to require workstation or mainframe hardware.

CODE VALIDATION

Prediction of the blast-induced pressure field on a structure and its response involves highly nonlinear behavior. Computational methods for blast-response prediction must therefore be validated by comparing calculations to experiments. It is important to note, however, that experimental validation applies only to the class of events (or domain of applicability) encompassed by the experiments. For example, an experiment involving explosive loading of an unreinforced concrete wall subject to a blast pulse of 20.67 megapascals (3,000 psi) peak pressure and with a duration of 10 ms could be used only to validate a computer program for predictions for structures with similar characteristics and stiffness loaded over a similar pressure pulse.

During the past 30 years, many experiments and tests have been conducted by the Department of Defense for the purpose of code validation. At the beginning of this period, CFD and CSM developments were in their infancy, and few experiments were designed specifically to validate individual codes; tests mainly focused on determining response modes and failure mechanisms of representative military structures. The response of this class of structures may be significantly different from conventional civilian structures for the reasons mentioned earlier.

DNA recently conducted a series of experiments to evaluate the effects of penetrating weapons on hardened, reinforced concrete structures and to validate first-principle blast and structural response programs. The test structure had reinforced concrete walls and horizontal slabs 45–60 cm thick and consisted of a series of rooms interconnected by corridors and doorlike openings. Tests were carried out at full scale and at one-third and one-sixth scale; in each experiment a high-explosive charge (representing the penetrated weapon) was detonated in one room, and blast pressures and response measurements were obtained in adjacent rooms.

For this series of tests, the first-principle codes FEFLO, HULL, and SHARC (Hikida et al., 1988) were used for both blast propagation and structural response analyses. Initially, all calculations were two dimensional in that only the plane of the test structure was modeled. The results of the computations exhibited subtle differences, which were slight in the source chamber but showed substantial pressure differences in adjoining chambers. This result was attributed to the large effect of turbulence on the transmitted pressures triggered at the doorways. Subsequently, full three-dimensional calculations were made with both first-order (HULL) and second-order (FEFLO) programs. The former, without adaptivity[2], underpredicted the pressures in the adjoining chambers, but did exhibit the delay in the pressure spikes observed in the experiments; the FEFLO calculation compared quite well with the measurements.

The response of the structures was determined in an uncoupled manner with FLEX, DYNA3D, and TRT computer programs, using computed pressures as a loading on the structures. The predictions of failure did not match the experiment in any of the analyses. The discrepancy was ascribed to the difficulties in modeling the tensile failure of the concrete, an area of modeling that is still not well in hand.

Recent tests performed by DNA on shallow-buried structures to validate an application of the DYNA3D and FLEX programs provide an example of the accuracy with which the deformation of a structure can be predicted when the structure remains homogeneous (i.e., does not encounter any tearing, fracture, or fragmentation). The tests were intended to study the interaction between the structure and the surrounding soil for different types of soil. A cylindrical structure was tested in both clay and sand. The cylinder and the surrounding soil were modeled in detail, and the pressures measured on the surface of the soil during the experiment were applied to the top surface of the model. The computations were made prior to the release of experimental response data, so there was no opportunity to "tune" the analysis. A comparison of the computed shapes of the cylinders in the sand and clay blackfills are shown in Figure 3-1. The deformation can be seen to depend markedly on the surrounding medium; the deformations in clay are much larger and exhibit a different pattern of deformation. The computation accurately predicted the difference in the response in soil and clay and the magnitude of the deformation, illustrating the predictive capabilities of first-principle programs in certain instances.

Some programs, under certain conditions, have produced results in excellent agreement with observations. In other cases, the differences between observed and predicted results have been great. This points to the need not only for ongoing testing but also for care in the selection of an appropriate model and input parameters and equal care in the interpretation of the results. Once a model has been validated over an experimental range, its real value lies in the richness of the predictive domain thus established. For example, the effects of attributes such as various window shapes, geometrical configurations, percentage of reinforcement,

[2] Adaptivity refers to the ability of a simulation model to initiate modifications to the analytic procedure(s) during program execution based on the model's "sensing" the results of the ongoing analysis.

and other variables can be studied by computer programs once they are validated. The designers of civilian structures can make use of these validated results in the quest for improved building performance.

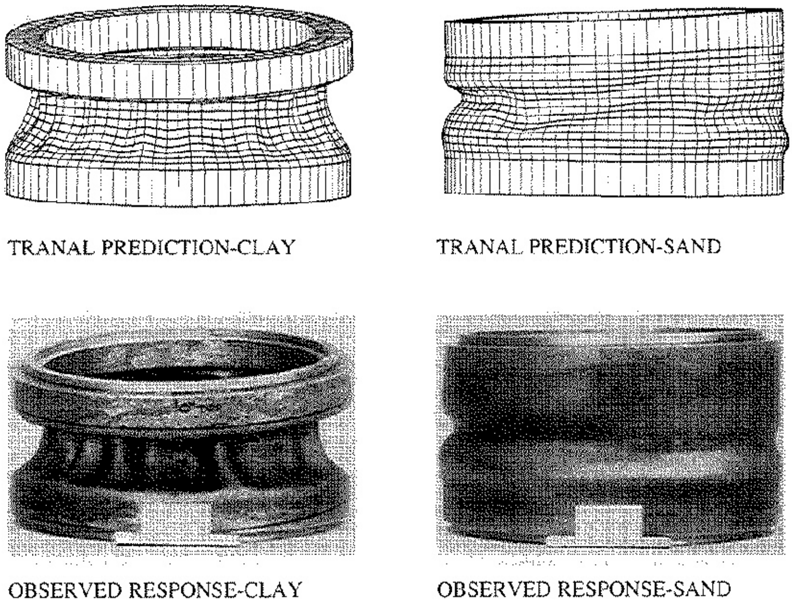

Figure 3-1
Comparison of predicted and observed deformation of a buried structure inclay and sand backfills.

APPLICATIONS OF COMPUTATIONAL METHODS TO TERRORIST THREATS

Several of the programs described above have already been applied to the evaluation of terrorist threats and events. The FEFLO code was used to analyze the explosion in the World Trade Center (Baum et al., 1994). This computation required 10,000,000 equations and approximately 150 hours on the Cray C-90. The model of the geometry of the area affected by the explosion was extremely detailed; even the cars in the parking lot were modeled. Nonetheless, in the later stages of the calculation, after the shock passes and turbulence develops, even this detailed a mesh was found to be inadequate for resolving the turbulent flow field. This calculation overestimated the blast loading because it did not account for the failure of the floors, the modeling of which would require coupling the program with a structural response program.

Several other analyses of the World Trade Center bombing were done with different suites of codes. One analysis using the CTH, BLASTX, and FLEX programs focused on interpreting explosive effects on the floor and roof slabs and failure patterns of the floor slabs. The analyses coupled the blast prediction with the floor response and showed that the principal mechanisms that limited the damage were due to the decrease in pressure and impulse that resulted from the progressive venting of the gas pressure and the large displacement of the slabs. Good correlations were obtained between computed and observed damage patterns in floor and ceiling slabs. Another analysis used BLASTX and some simple computer models of the floor slabs, but BLASTX proved inadequate for this class of problems because the long spanwise dimensions of the parking floors led to significant overpredictions of the impulse.

The CTH, BLASTX, and FLEX suite of codes was also used to develop guidelines for the protection of U.S. embassies against explosions from terrorist attacks (Clemens and Watt, 1987; Nelson and Watt, 1989). Tests were conducted with a one-third scale model to validate the computational results. Both internal and external explosions were considered. The predicted peak displacements of the exterior wall were within 15 percent of the measured values, but the final displacements differed by almost a factor of two. Nonetheless, the analyses were used to develop guidelines for structural design, including layout and anchorage of beams and slabs, and recommendations for mitigating progressive collapse due to detonation of explosives hand-carried into the building. The CTH and FLEX codes were also used by Weidlinger Associates to perform a vulnerability study of a hotel due to a car bomb explosion in the JFK Airport east parking garage, and to develop protection schemes for the Rockefeller Center control room against the threat of briefcase bombs (Baron and Hinman, 1994). The FLEX and FUSE (Sandler and Rubin, 1990) codes were used to develop procedures for blast-hardening areas of a federal court building to explosions from package bombs; a similar study was made for the World Trade Center control center prior to the bombing.

SUMMARY OBSERVATIONS

Over the past 50 years, design procedures have been developed for structures subjected to explosive blast loads. These procedures are based largely on synthesis of test data and simplified computational models and apply for the most part to the type of hardened structures found in military construction. These design procedures are codified in a variety of manuals and computer programs. While this body of knowledge can serve as a foundation for designing civilian buildings to be more blast-resistant, substantial effort will be required to make the methods more directly applicable and useful for civilian design professionals.

The available computer programs for prediction of blast-effects and structural response have been described and classified in several ways. From the viewpoint of a user, the most important classification is whether the programs are semi-empirical or first-principle in nature. First-principle codes are more generally applicable, but they require the user to be well versed in structural dynamics and explosive behavior. For both classes of computer programs, validation by tests is imperative. To date, very little test data have been obtained for structures representative of civilian building design and construction practice. Application of these programs to blast-resistant design strategies in civilian buildings is of limited usefulness without appropriate experimental validation.

Extending this technology to civilian design and construction practice affords a valuable opportunity to both solidify and advance the state of knowledge in this field. There are difficulties in understanding and mathematically modeling structural behavior in transition regions of response from predominately flexural behavior into domains dominated by boundary or punching shear, and ultimately to material disintegration. Also, material constitutive relationships are less well understood in these transition regions. Nevertheless, computations can give valuable information about the magnitude and type of damage. The pressures resulting from complex, nonspherical explosive charges (e.g., car bombs) are not well understood and carefully controlled experiments are vital for a better understanding and validation of computer programs. Wherever possible, tests of civilian buildings and component types should be conducted at sufficiently large scale to allow the use of actual design details, materials, and construction practice.

Despite some success in re-creating the observed effects of actual bombings and the cited examples where numerical codes were applied to specific design problems, it is not clear that the routine application of these programs to civilian buildings will become widespread. The cost and complexity of the analysis, coupled with uncertainty regarding threat levels and the low probability that a specific building will actually become a target, all suggest that they will not. However, where these programs could prove very valuable is in testing a wide range of building types and structural details over a broad range of hypothetical explosion events. The knowledge gained from such testing, verified by experimentation, could transfer directly to civilian practice through manuals and other design aids, and ultimately into building codes, in much the same way as the application of seismic design principles has become routine.

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4

Blast-Effects Mitigation Potential for Commercial Buildings

This chapter explores opportunities to apply blast-effects mitigation techniques to commercial buildings. Such opportunities may occur in several areas: in the architectural planning process, specifically, for example, in site selection or physical space planning; and in the design and placement of critical building systems, such as electrical and communications systems. Also discussed are special considerations for blast-effects mitigation in commercial buildings, such as below-grade vulnerabilities and the stack effect in high-rise buildings (two areas of vulnerability shown dramatically in the World Trade Center bombing). Where issues applicable to civilian buildings are addressed by military technical literature, these are pointed out as potential transfer opportunities.

ASSESSING THREATS TO CIVILIAN BUILDINGS

In the aftermath of attacks on civilian buildings in the United States, many building owners must now consider the following questions when deciding whether their property might potentially be a target of terrorism:

- Who or what is the threat?
- Is a bomb a possible choice of weapon?
- What are the most likely scenarios or tactics for introducing a bomb into or near the building?

If an owner decides that there is reason to believe the property could be a target for a terrorist bomb, then the consequences of taking action should be considered:

- What resources, including technologies, are available to respond to the threat?
- What are the costs of applying those technologies?
- What will building tenants and occupants tolerate in the way of inconvenience or added expense for security measures?

U.S. Department of the Army (1993) Technical Manual TM 5-853 (*Security Engineering*) provides a systematic methodology to analyze "aggressor threats and tactics," including a system for rating potential risks and developing appropriate responses. The Defense Nuclear Agency (DNA) has developed an integrated systems approach, the balanced survivability assessment method, to evaluate the survivability of facilities against a wide spectrum of threats. Both of these techniques are directed primarily at military needs, though they could be used effectively for civilian applications. Answers resulting from these analyses would need to be weighed in the context of the functional and financial goals of the building owner.

ARCHITECTURAL PLANNING PROCESS

Having decided that a proposed or existing building requires protection from attack, the owner must assess what can be done to mitigate the effects of an explosion should one occur.

Blast-hardening refers to all measures to reduce or eliminate the effects of an explosion. This included techniques such as physical space planning, that deliberately use architectural location and organization of spaces and other nonstructural features to minimize the effects of an explosion on people and property.

These options are discussed in U.S. Army Technical Manual TM 5-853 to a limited degree, though the planning techniques in this manual are strongest in the area of supporting access control to the facility.

All such options can be applied in the normal design of a building, just as designers now routinely incorporate seismic, wind, and fire protection features and systems in buildings. The architectural planning process itself involves less technology than awareness and design skill, although technology may be needed to validate or revise empirical planning and design assumptions. In considering opportunities for technology transfer, it is useful to discuss here these planning techniques and consider how they might supplement or be supported by the technologies of hardening.

Improving the performance of conventionally designed civilian buildings following an explosion begins with site selection and the architectural planning process. One of the first steps in protective planning for a new facility is to select a building site that allows access to the facility to be easily controlled so as to make delivery or placing of an explosive as difficult as possible. Locations to avoid, for example, include congested urban areas where it is difficult and costly to secure distance between the building and uncontrolled public rights-of-way. Preferably, the site, its entrances, and the building itself should all be placed out of alignment with potential high-speed approaches by vehicles, such as would be the case of an entrance drive opposite a street.

Distance between the building and streets or parking areas where potential vehicle bombs could be detonated is one of the most effective means of minimizing damage from explosions. The cost of land, however, must be considered in this measure. Control of surrounding streets and adjacent off-site parking is ideal, but rarely available to civilian commercial building owners.

As to the building itself, earlier chapters discussed some technically sophisticated tools, especially computer codes, for designing structures to respond acceptably to explosions. The following discussion explores less technical design approaches that, when applied with common sense, can economically reduce the effects of an explosion on the people and contents of the building. Of course, hardening parts of a building may also be necessary.

Many planning and design response options could be considered for a new building or retrofitting an existing structure. All the following options could be applied to new or retrofit situations.

Identifying potentially hazardous functions, such as mail-and freight-receiving and handling facilities. If a letter or package in freight is considered a likely means of introducing a bomb into a building (such as buildings housing celebrities who might be targets and who receive large volumes of unsolicited mail), providing such facilities in either a hardened area or a remote location, perhaps off site, might be considered, even at the cost and inconvenience this might involve. (TM 5-853 addresses bombs introduced through mailed or shipped packages in considerable detail.)

Controlling or eliminating hazardous material storage on site. Fuel storage, trash holding, paint shops, and pressure vessels can contribute to the fire and smoke generated in an explosion, and might be located remotely from areas vulnerable to the introduction of a bomb, from means of egress, and from life-safety systems such as fire pumps.

Locating vulnerable functions away from uncontrolled public traffic areas to minimize blast-effects on occupants. High-profile potential targets (and facilities for the particularly vulnerable such as children, the elderly, or handicapped) might be placed in remote, inconspicuous locations rather than, say, at the front of the building over the entrance. Offices and other continuously occupied spaces including day care centers can be located, for example, on the sides of the build ing away from streets or on interior courtyards. Street frontages can be reserved for circulation, nonvital equipment, storage, or other uses that could even be sacrificed to an explosion and absorb the initial shock. (TM 5-853 addresses this strategy briefly.)

Providing dispersed, concealed, and controlled access to utility service entrances, fuel delivery, and storage facilities, and providing decentralized internal electrical and telecommunications distribution centers. Frequently, these important utilities enter buildings near one another, are easily identified, and are relatively easily accessed by unauthorized persons. An explosion in the area of the utility service entrances could destroy all services in one stroke if they are all close together. (TM 5-853 is concerned with the vulnerability of utility openings to forced entry or introduction of chemical and biological agents, but not with protection of the utilities themselves.)

Furnishing redundant electrical and telecommunications supplies when necessary. Where it is impossible or not cost-effective to locate utilities out of harm's way entirely, redundancy of vital systems, such as switchgear, primary feeders, power generators, sprinkler mains, and fire pumps, may be advisable. Wherever possible, the alternative source should be located in a protected area and remote from the primary source.

Determining the practicable application of physical security systems . A wide assortment of surveillance, access control, and access-denial products are available to use to reduce the risk of bomb deliveries by persons or vehicles. These products are identified in such manuals as TM 5-853 and in commercially available sources.

Enhancing areas of refuge. Modern multistory buildings are allowed by many building codes to use "horizontal exits" in addition to the usual exit stairways. This concept permits large floor areas to be compartmented by fire and smoke barriers, so that persons fleeing fire and smoke in one area may move horizontally to an adjacent area. Occupants can either continue to exit by stair or remain in the area of refuge as long as necessary. Incapacitated persons need not negotiate fire stairs, at least immediately. As a result of an explosion, lower floors and means of egress from the building may be so severely damaged or filled with smoke that refuge areas may be needed for some period of time before rescue can be attempted successfully. The construction of the walls and partitions surrounding such areas might be strengthened to resist breach by flying debris. Additional accommodations to this situation can include emergency medical equipment, blankets, toilets, drinking water, radios, and flashlights in a designated area of each compartment.

Continually assessing existing conditions against the availability of new technologies that mitigate blasts-effects. Any building owner or occupant who believes the building may be a target for bombings should undertake systematic threat and vulnerability assessments periodically and decide on any new courses of action if new technologies are available. The Balanced Survivability Assessments technique developed for military applications by DNA would provide an excellent basis for this task after being adapted to civilian situations.

Controlling or eliminating parking and loading under or within the building. Vehicle parking and loading operations within or under an occupied building pose a major hazard, since vehicle bombs can be very large and powerful. Vehicle bombs may also elude detection, especially in high-volume facilities where inspection of vehicles with any regularity or thoroughness may be operationally and financially unacceptable. Where parking or loading cannot be excluded, limiting the number of vehicles, such as those of tenants only, and providing machine-readable identifiers, vehicle-weight sensors, and spot checks are often acceptable compromises.

Having a well-developed emergency operations plan to aid occupants after an explosion. Essential components of an emergency plan are the appointment of trained wardens, conducting practice drills, and regular review and update of emergency procedures. These measures are seldom appreciated by occupants in a peacetime environment and in situations other than high alert. They are often neglected or abandoned as soon as the sense of real urgency is lost. Disaster planning and emergency operations are two areas which can potentially return enormous dividends in terms of lives saved and suffering averted. A sample of the considerable literature in this field is included with the references to this chapter.

Relocating functions and installing or upgrading fire-and life-safety features such as smoke control and evacuation. Fire-and life-safety code requirements are becoming more stringent, especially for new buildings in urban locations. Periodic review of a facility's fire-and life-safety features and upgrades to new building standards seem prudent in any case, but such measures are more urgent for a facility that could be a target of terrorism.

Avoiding architectural features that magnify blast-effects. If there are architectural features that focus or increase blast-effects, they should be identified and avoided. (TM 5-853 indicates that re-entrant corners tend to cause blast pressures to build up.) Research is needed in this area to determine what other building configurations may have these properties.

Incorporation of controlled venting and other measures to mitigate the effects of internal explosions. There is a considerable body of knowledge on techniques to mitigate the effects of an internal explosion which has been developed as protection against accidental explosion in military, explosive, and chemical environments. (For example, U.S. Department of the Army [1990] Technical Manual TM 5-1300 (*Structures to Resist the Effects of Accidental Explosions*) discusses the use of blast valves for the controlled release of blast pressure from accidental explosions; Air Force Engineering and Services Center [1989] ESL-TR-87-57, [*Protective Construction Design Manual*] discusses the same topic for blasts resulting from weapon detonations.) Other methods of blast-effects mitigation available are blow-out panels for pressure relief and the use of "frangible" or sacrificial elements designed to fail to reduce the amplification of shock pressures. Temperature-reducing systems to retard the development of high overpressures are also available. Research on these techniques is needed to determine their applicability to civilian office structures where the survivability of the occupants is the paramount objective.

Designing windows that minimize the effects of blasts or applying such technologies as high-strength glazing or fragment curtains. A number of studies have been done on security windows resistant to explosions (Chapter 7, vol. 3, of TM 5-853, and Chapter 5 of the American Society of Civil Engineers [1995] task group draft report on *Structural Design for Physical Security* provide important design guidance). Recently, research has been exploring more-robust window assemblies, including glazing for resistance to hurricane-blown debris. High-strength glazing materials, including glass block, tempered glass, and polycarbonates, and laminated and film-backed glass and fragment-entrapping meshes for fragment control are already in use for both security and storm resistance, but more research is needed to develop better assemblies and distribution of impact loads.

Designing elevator and stair shafts to resist smoke penetration by pressurization or compartmentation. Elevator entrances and cabs are currently not resistant to smoke penetration. In a fire or explosion emergency, persons may be trapped in elevators and overcome by smoke. Research is needed to explore the possibility of sealing elevators against smoke penetration and to meet fire-resistance standards. At the present, the only option is isolation of shafts in smoke or fire compartments. Pressurization of stair shafts is a design problem, especially in tall buildings where shafts must be interrupted to decrease the height of pressurized chambers and to control pressure levels.

SPECIAL CONSIDERATIONS FOR HARDENING EXISTING BUILDINGS

Since there are many more existing buildings than planned new buildings, it is understandable that building owners and management would be more interested in ways to protect existing buildings. *Structural Design for Physical Security*, Chapter 8, "Retrofitting Existing Structures," (ASCE, 1995) discusses some approaches for possible improvements to existing structural systems.

Sometimes little or nothing can be done to protect existing buildings from explosions, such as older wall load-bearing structures in congested urban settings where closing adjacent streets to vehicle traffic cannot be done. Defensive precautions, such as threat and vulnerability assessments, access control, and good intelligence and law enforcement, are always useful, but there are limitations to what building technologies can offer, and in some of these cases, the only option may be relocation.

In addition to the architectural planning techniques discussed above, there are other means to harden typical existing civilian buildings against terrorist attacks. One consideration in commercial structures is that hardening features may be quite apparent when installed after the fact in an existing building, and most commercial building occupants do not want the appearance or the function of the building to be changed or to advertise their presence, if they are potential targets, by obvious security measures.

Hardening a monumental structure such as the U.S. Capitol Building without changing its appearance or function would be technically challenging and extremely costly. Of course, many federal buildings have large security systems including on-site enforcement personnel. Yet the attack on the Murrah Federal Building in Oklahoma City demonstrates the vulnerability of most governmental buildings. Other prominent buildings, such as places of worship, communications centers, courthouses, and office buildings, are not as security conscious as airports, banks, and museums.

In addition to the planning techniques discussed in the previous section, structural reinforcement of some building elements may be possible through the use of:

- additional mass;
- additional strength, through modification of boundary conditions (e.g., supports to walls or floors), reduction in spans, or reduction in loaded areas;
- replacement of weak components;
- redundancy of structure;
- strengthening of exterior curtain wall (by attention to windows or doors); and
- strengthening of interior partitions.

However, some of these techniques may present problems. For instance, consider the addition of mass. Loading from TNT is dynamic in nature, while adding mass to a building component has an effect where damage is caused by impulsive loading. Also, the addition of mass contributes to the weight of the building, which often places greater demands on the existing framing and foundations. It is usually difficult and expensive to add additional foundation capacity.

Adding strength and stiffness to the structure is also difficult, especially when attempts are made to decrease spans. Such approaches usually require additional columns or walls and clearly are not suitable for inherently long-span structures such as courtrooms, trading floors, retail sales floors, convention centers, sports arenas, performing arts centers, museums, or worship areas.

Reduction of loaded areas usually refers to earth beams placed against the exterior walls of the building. This solution has possibilities, depending on the site conditions and the exterior wall material, but it is certainly not a universal solution. Modifying boundary conditions also has its limits, especially when dealing with reinforced concrete structures.

Wall load-bearing buildings are sometimes easily brought down by localized damage. Structural load-bearing members may need to be examined for their participation in the load-bearing system and to ascertain that they exhibit reasonable redundancy. Structural redundancy has potential, especially in precast structures or masonry-bearing wall structures. The designer may ensure that, when certain key elements (columns or walls) of a structure are damaged or destroyed, alternate load paths are provided so that the building will not undergo progressive or total collapse. Often this retrofit procedure only requires additional means of tying the structure together.

For significant blast resistance, substantial and compact structural forms—such as box-type construction, with strong walls, roof, and floor—are often preferred. The building material most commonly used throughout the world, because of its relatively low cost and ease of fabrication, is concrete. Although concrete is a relatively brittle material, it is rendered ductile through steel reinforcing. For resistance to high pressures, care with the details of reinforced columns, connections, and walls is required; special reinforcing may include closely spaced ties throughout the element, with attention given to the reinforcing and tie-in to other walls and slabs at the edges where much of the resistance is developed. In some cases, the use of fiber-reinforced (metal or polymer) concrete can be effective. Quite obviously, anticipated loading conditions will influence the design, but reinforced concrete structures can be expected to be relatively thick (10^2 to 10^3 mm) to provide the mass and strength to resist blast pressures.

Steel structures also need special attention where they are employed to resist intense blast loading or are expected to respond in an inelastic manner. Of particular concern are those connections that, if they fail, can lead to instability of the structure, and possibly collapse. For both steel and concrete structures, the de signer should consider redundancy in supporting members, to help ensure the survivability of the structure even if some columns or other critical members are severed.

Although current design procedures provide guidelines on how to enhance the breaching resistance, it is often impractical to protect against breaching and direct shear effects by conventional means. Alternative reinforcement details should be employed when heavy shear (diagonal, punching, or direct) is expected. Special materials and combinations of materials (e.g., high-strength concrete, perhaps combined with fiber reinforcement, and layering with energy-absorbing material) might possibly be employed in such situations.

Strengthening exterior curtain walls may be quite effective against a bomb placed outside a building. Assuming the structure can resist the loading from the bomb, substantial damage can be avoided by not letting the blast wave into the building. Typically, doors and windows are the weak points. Windows can now be protected to some degree by several means: polyester fragment retention films, polyethylene terephthalate (PET) backing or interlayer, heat-strengthened and tempered glass, polycarbonate-sheet and urethane/glass composite glazing, and polyvinyl butyrate (PVB) interlayer or combined PVB-PET laminated glazing. Security windows and glazing are discussed in the U.S. Army Technical Manual TM 5-853 and *Structural Design for Physical Security*, Chapter 5, (ASCE, 1995).

Various available shutter designs can decrease blast loading on the windows, although they are only useful with advance notice of a threat. Nylon and Kevlar® mesh curtains can also be used inside the windows to contain blast fragments, or special blast windows can be purchased.

Special blast doors are available, though they can be too massive for high-frequency applications. Security doors are generally marketed for ballistic and forced-entry resistance, and while these doors are suitable for regular high-frequency use, their performance under blast conditions is unknown. Although these solutions have some impact on appearance, they can often be acceptable. (Security doors are also discussed in TM 5-853.) More research is needed on these assemblies, research that might also benefit design of windows and doors for protection from projectiles during high winds such as hurricanes.

Selected metal stud and drywall interior partitions can be replaced with steel plate on hot-rolled steel framing. Steel-plate shear walls have been used in buildings before, to resist horizontal loads when thick, reinforced, concrete shear walls occupy too much space. Drywall interior partitions can also be replaced with reinforced masonry walls with a spray-on concrete/steel mesh or Kevlar® or ballistic nylon. When these interior partitions are tied into the existing structure, they increase the stiffness of the building, with minimal impact on the appearance or function of the interior space.

Because of the high cost of retrofitting existing buildings for blast-effects mitigation, developing improved methods of monitoring and controlling the flow of people into and out of facilities may prove to be the most cost-effective way to frustrate terrorist bombing attempts for the long term.

VULNERABILITIES OF CIVILIAN STRUCTURES

The trend in new civilian building design for the last 50 years has been toward the use of lighter but stronger materials. This has led to more economical buildings, with the structure accounting for less of the floor area and lower first costs. During this same period of time, engineers have developed a greater understanding of building performance when a structure is subjected to dynamic horizontal and vertical forces associated with wind and earthquake. In a situation involving earthquake loading, the design forces decrease as the weight of the building decreases. Seismic design calls for the building to possess adequate strength (force and ductility-resistance characteristics) so as to resist the repetitive seismic motions in a manner that protects human lives and leaves the building usable, or, at the most, with damage that is easily repairable. When designing for wind and earthquake loads, therefore, it is advantageous, especially for the upper levels, to use lightweight nonstructural building materials such as metal stud and drywall partitions instead of masonry.

The dynamic loading on buildings caused by explosions differs in important respects from dynamic loads imposed by earthquake and wind. These latter loads are of relatively low intensity, long duration (seconds to minutes), and essentially oscillatory (periodic in nature). Explosive loads, by comparison, are extremely large initially, act for very short durations of time (milliseconds), and are non-oscillatory (aperiodic). For explosive loads localized in the lower levels, characteristic of terrorist bombing incidents, the lower levels of a structure should be massive to effectively resist the large, short-duration loading. This goal is generally in keeping with seismic requirements where significant strength is called for in the lower levels.

Sound engineering judgment, of course, should be used in the design of buildings to withstand short-duration explosive incidents. During the design process, particular attention should be paid to the following factors, because under certain conditions, or in combination with other factors, they may positively or negatively impact building performance following an explosion:

- the use of lightweight materials—especially in nonstructural applications;
- the use of very long spans;
- the use of live-load reductions permitted by codes;
- the vulnerability, especially of precast systems, to progressive collapse;
- the strength of the exterior cladding and its effect on the structural system;
- the effect of the loss of an individual column; and
- the behavior of ductile framing systems.

A discussion of the design and behavior of structural components typically used in modern civilian buildings subjected to a transient blast-wave form is contained in Chapter 4 of *Structural Design for Physical Security* (ASCE, 1995).

Although not specifically addressed to blast-effects, design for lateral loading for wind and earthquake is the subject of two important military publications (U.S. Department of the Army, 1986, 1991; and two civilian publications (ASCE, 1993; FEMA, 1994) as well as the three Model Building Codes.

VULNERABILITIES OF NONSTRUCTURAL BUILDING SYSTEMS

Recent instances of buildings that have suffered the effects of an explosion, such as the World Trade Center, have demonstrated that if the structure of the building survives and does not progressively collapse, the greatest problems are experienced during evacuation and rescue, when fire and smoke control and other critical building systems may not provide the necessary support.

Most buildings are designed to resist events of seismic origin, fire, flood, wind, snow, and similar natural and human-caused events. Long experience with these perils has permitted rational codification of how a building and its systems must perform to achieve several critical goals to allow:

- the maximum number of occupants to escape,
- the minimum number of injuries and fatalities to be sustained,
- the protection of property, and
- emergency personnel to control or prevent further destruction of the building while these objectives are accomplished.

Few civilian buildings in the United States are designed to withstand the effects of an explosion within or adjacent to the structure, although the design features for more common emergencies will also help to achieve the same objectives in the event of an explosion. After any disaster—fire, flood, or bomb explosion—a building's systems are major factors in the recovery period when evacuation, and, ultimately, reoccupancy and return to normal operation are the principal objectives.

A modern building can be thought of as a set of interdependent systems and subsystems, rather than as a group of autonomous elements such as wall, floor, roof, and so forth. The structural system is probably the most vital, since failure of even part of this system may directly and immediately threaten all other systems. Extreme examples include the nearly total destruction of the Alfred P. Murrah Federal Building in Oklahoma City and the U.S. Marine barracks in Beirut. The structural system and its protection has therefore been extensively studied, and technologies for designing this system to resist failure following an explosion are discussed in Chapter 3 in this report.

Nonstructural building systems have been given less attention in blast-ef fects mitigation technology. However, the survival of some of these systems is essential to the rescue and evacuation of building occupants and to the recovery of the building to normal use. Therefore, the roles of these nonstructural systems in civilian buildings are addressed here.

Three general types of nonstructural systems are defined for the present discussion.

1. The first type of nonstructural system consists of those systems that may be critical for survival and evacuation during and immediately after an explosion:

- ***The electrical system*** supports lighting to aid in evacuation, fans that may be designed for smoke exhaust, occupied elevators at the time of an explosion, fire pumps, and numerous control systems that may ensure the function of security and communications systems.
- ***Communications systems*** allow building occupants to be notified of the nature of the emergency and instruct them in evacuation and provide contact with outside rescue and emergency forces.
- ***Plumbing systems*** deliver water for extinguishing fires, provide for hygiene and drinking during entrapment situations, and are used in administering first aid.
- ***Ventilation systems*** provide pressurization and exhaust to control and contain smoke.
- ***Circulation systems***, including corridors, stairs, doors, and ramps, provide the means for occupants to escape and emergency personnel to enter the building.

All of these systems must be operational and support each other in their various tasks to enhance the likelihood of survival of individuals not killed by the explosion itself.

2. The second group of nonstructural building systems may not in themselves play active roles in survival or rescue activities following an explosion, but they may attenuate, propagate, or contribute to the effects of an explosion:

- Exterior wall systems consisting of interdependent subsystems:

- wall construction—precast panels, metal panels, masonry, framed, and so forth—that is basically supported by the structural system;
- sash supported by the wall system;
- glazing supported by the sash, although polycarbonate glazing could hold the sash together;
- sun-control system supported by the sash or soffit which could contain glass fragmentation, if in the form of a film or mesh, or contribute fragments, if in the form of blinds.

- Interior partition system

- metal runners and studs supported by the structural system;
- drywall panels supported by the studs and perhaps holding them together following an explosion;
- finish materials supported by the drywall, and, in the case of some fabrics, possibly holding the drywall together under the effects of an explosion.

- Interior ceiling system:

- suspension grid supported from the structural system;
- ceiling panels supported on the grid system;
- lighting fixtures supported on the grid system:

- Interior mechanical and electrical distribution systems:

- heating, ventilating, and air-conditioning terminal units and ductwork supported by the structural system and perhaps easily dislodged by an explosion;
- electrical conduit usually hung under the structural system and possibly severed by structural failure or directly damaged by an explosion if it occurs nearby (exposed or ruptured power lines may pose a threat to occupants and emergency personnel, or contribute to fire);
- piping for water and gas under pressure usually hung under the structure, and, like conduit, possibly destroyed by the structure if it fails or is breached by the explosion itself (loss of fire-fighting water not only loses the fire-extinguishing function, but can pose a threat of flooding to occupants, other systems, and rescue personnel).

These systems may perform in any number of ways in an explosion, either absorbing some of the shock, shielding people or property from fragments, or becoming lethal fragments themselves. In the case of an exterior explosion, loss of the exterior wall allows greater damage to the interior of the building. Strengthening the exterior wall and window systems has been studied, and design information is available in the TM 5-853 manual and elsewhere. However, little research appears to have been done on how these and other assemblies might be protected from the effects of an explosion in order to reduce the possibility of damage to critical systems.

On the other hand, breach of any part of the building's envelope or of the enclosure of a space in which an explosion occurs will relieve pressures, possibly to the benefit of the building and its occupants. The effects of venting are discussed in the U.S. Department of the Army Technical Manual (1990) TM 5-1300 (sec. 2-14). The BLASTX computer code, discussed in Chapter 3 of this report, provides computational methods to predict the effects of explosions in vented conditions.

3. The third type of system assures the continued functioning or rapid repair of certain building systems for the continued beneficial use of the structure after the building sustains serious damage. The definition of this type of system de

pends to some extent on the user's objectives and expectations, the type and location of the building, the season during which the event occurs, and what recovery-time interval is sought. Examples of this type of system include:

- Mechanical temperature conditioning, as may be essential for computers supporting other systems, for certain laboratories and medical functions, and for food or other low-temperature storage needs.
- Elevators.
- Water and sewer service.
- Security and perimeter control, such as may be needed to protect secure information, or sensitive or vital facilities, or to control inmates or prevent looting.

Additional choices will have to be made according to the circumstances, financial considerations, and priorities of the building user or owner.

BELOW-GRADE VULNERABILITIES IN CIVILIAN BUILDINGS

Many modern buildings and complexes have parking, loading, and service areas within the building, and because vehicles are capable of surreptitious transport of large explosive charges, the location of critical systems in such areas as basements, where the above-mentioned functions are often placed, is a common vulnerability. This arrangement often reflects the desire to reserve above-ground building areas for occupancies that benefit from access to daylight, and in some cases, it also reflects the desire to maximize the above-grade envelope permitted by zoning. (See also "Architectural Planning Process" discussed above.)

Primary electrical switchgear is commonly located in a below-grade room (which is at a garage level in many buildings) simply because large commercial electric service is usually delivered underground. Although this equipment is housed in a separate, controlled access room, the enclosing construction is designed to meet fire codes only and is poorly equipped to withstand an explosion. If the room is located adjacent to or in the midst of the vehicle parking area, some of the main feeders from this equipment are also potentially exposed to an explosion from a vehicle bomb. If the building has a secondary power source from an alternative substation or even a power grid, the switchgear for that service is also typically placed in a similarly vulnerable location, if not in the same vicinity.

If the building or complex has emergency power generation on site, the generator(s) might be located remotely from the main switchgear, but the generator controller and automatic-transfer switching equipment is typically mounted in the same room as the switchgear. An explosion that breaches the switchgear room also renders the emergency system inoperable, leaving the building with neither primary nor backup electricity.

The generators themselves are usually situated for ease of heat and exhaust rejection on an outside wall in an areaway or even in a separate structure. In some buildings, however, the generators are also located in basement areas, making them subject to the same vulnerabilities noted above. Generator and switchgear rooms below grade are also vulnerable to water damage or flooding if an explosion ruptures water piping in the vicinity and there is insufficient drainage or pumping capacity.

Building control centers for refrigeration and other building operating systems may also be located below grade in or near the central mechanical equipment room, if it is also below grade. This arrangement is vulnerable to the same risks in the event of an explosion. If this control center also includes security, communications, fire alarm, and other systems, its loss could be catastrophic.

Buildings with early (nonenhanced) fire-detection and annunciation systems may have the main fire-panel controller and power supply in the switchgear room also. Buildings with enhanced systems have their fire-control panel located just inside the lobby doors for rapid access by fire officials, but in this location, the panel may be vulnerable to an explosion in the lobby area.

As is typical of other commercial utilities, voice and data communications services usually enter a building underground, into a room that may also contain the main distribution frames. In some cases, this room also houses the electronic switching equipment that routes calls within the building and is the interface with the local telephone exchange. If the switching equipment is owned by a private telephone service provider, it may serve several adjacent buildings as well. A below-grade location adjacent to areas accessible to vehicles is vulnerable in the same way as the primary electric power service room.

The main water and sewer services are also located below-grade level, and are usually co-located with the building's fire pump, siamese connection, standpipe, and sprinkler manifolds. This equipment may be enclosed in a room, but also may be placed behind a chain-link barrier that is intended only to discourage tampering and vandalism. Again, if this equipment is within or adjacent to vehicle parking areas, it may be lost in an explosion, and in addition to the loss of the services of water supply for fire and hygiene, the probability of flooding and interruption of other systems is high.

Mechanical heating, cooling, and ventilation equipment may be located below-grade, at, or adjacent to, parking levels, especially if the building is subject to height or setback restrictions or other zoning constraints. This equipment and its attendant piping and ductwork are mostly in enclosed rooms, though the rooms are usually not resistant to blast-effects. However, air ducts are connected to the fan housings to bring outside air into the system and to distribute it into the building above, and chilled and hot water lines pass into and out of the room. Any of these ducts or pipes that traverse an area exposed to an explosive source is vulnerable to loss. Most modern buildings are totally dependent on mechanical systems, and the loss of these systems can jeopardize recovery of vital functions that permits rapid reoccupancy and resumption of the building's business.

Shafts for utilities are typically adjacent to stair and elevator shafts and subject to many of the same vulnerabilities. Utilities can also be severed in these shafts by explosion-generated debris.

The most serious damage to building systems, then, can probably be accomplished from a vehicle-transported bomb that is detonated in a building's basement areas, simply because a number of critical building systems are typically found in this location, as is much of their control and distribution equipment. A garage detonation also has significant potential for fire and smoke because of the large amount of combustible materials present in and on the vehicles that may be parked there. Any basement vehicle parking areas, therefore, should be given particular attention when considering blast-hardening features or access control and detection, perhaps even at the expense of other measures when available funds are limited.

PROTECTING NONSTRUCTURAL SYSTEMS

Blast-resistant, reinforced concrete walls can be constructed to decrease the effects of an explosion in or around buildings, including protection of many of the critical systems discussed above. Since little research has been done on the protection of systems or behavior of common building assemblies following an explosion, the following discussion is limited to a few of the planning techniques available to design professionals to remove at least parts of these systems from harm's way.

As a general principle, critical services should be decentralized and, wherever possible, separated from garages, loading docks, and vehicle routes. Where emergency or alternative systems exist, they should be kept as remote as possible from primary systems.

Although there are some first-cost economies in placing the electric switchgear, emergency generator controls, and fire panels in the same room, this practice places the building at greater risk of losing three critical systems in a single event. Physically decentralizing critical systems and their components may help one or more of these systems survive or may reduce the extent of damage to them, thus reducing the time needed to repair and restore them. Rooms containing critical systems may be placed behind or nested within other rooms deeper in the building to achieve greater distances from areas of vehicle access. Of course the same logic can be applied to noncritical systems as well.

A design precaution may be to keep critical services away from exterior walls that face possible locations for a bomb at the building's exterior. A more drastic solution would be to place as many services as possible in floor raceways or in access floors, where they would be less exposed to explosions. Some hardening at little or no cost can be achieved during building design by locating lower floor chases behind protective building elements where they are less likely to be in the line of an approaching blast wave. It may also be useful to orient the elevator lobby's lengthwise axis perpendicular to the anticipated location of an explosion, such as a parking place along the building's street frontage.

Garage-level auxiliary rooms, such as those housing the primary electric service, are usually constructed of concrete masonry units that have poor resistance to side-loading, and it is doubtful that these assemblies could withstand a nearby explosion even if retrofitted with interior or internal bracing. Blast-response technology may permit the design of a device, baffle, or room shape that can deflect the shock wave away and toward a less critical building component or a component that is known to successfully resist blast-effects, such as underground perimeter walls.

Some protection can be afforded to elevators and stair shafts by not having them be continuous from upper stories to basement levels. Separate elevators and stairs can be provided for the below-grade floors. This design is often desirable for security reasons as well. However, existing buildings have few if any options other than to construct stand-off barriers to keep vehicles as far as possible from elevators and stair shafts.

STACK EFFECT IN HIGH-RISE BUILDINGS

The vast majority of the injuries caused by the World Trade Center bombing were not the result of direct impingement of fire or explosion, but from smoke and dust inhalation. Smoke and dust were driven upward through both towers by stack action, filling the stair shafts and many of the floors.

The stack effect in tall buildings is similar to the behavior of a chimney: the colder, heavier air outside of the chimney pushes the warmer, lighter air inside of the chimney to the top; this action stops when the flue is closed.

Each of the towers of the World Trade Center is like a chimney, with the warm air inside of the building pushed up by the cold air outside, generating an upward flow through the towers, particularly during the cold winter months. To minimize this air flow, an air lock was constructed around each of the two towers. Passing through the revolving doors is, in effect, passing through the air lock.

With the detonation of the bomb, much of the masonry wall along the south wall of the north tower at the basement level, where the explosion occurred, was blown into the building. Other masonry work surrounding the shuttle elevator shafts was blown into those shafts. (Similar but lesser damage was done to the south tower.) In this way, the air locks were breached, particularly for the north tower. With the loss of the air locks, the smoke-and dust-laden air from the bombed area was drawn into and upward through the towers by stack action. The problem was aggravated in areas where tenants broke windows.

It is conjectured that had the air locks survived the explosion, the smoke-laden air would have been confined to below-grade areas of the complex and would not have been forced into the towers, and perhaps several hundreds of millions of dollars of nonstructural damage would have been averted and per sonal injuries would have been greatly reduced. Much less smoke was found in the south tower where the air locks remained largely intact. Controlling stack effect in tall buildings is mechanically complex and worthy of further study.

ECONOMIC CONSIDERATIONS

It is reasonable to expect that blast-hardening a building will cost an owner additional money, whether the building is in the design stages or already exists. A blast-hardened building may cost more to operate and maintain as well, especially for increased security staff.

For a building still in the concept or design stage, additional first costs may include services of consulting experts, perhaps some testing or modeling, and the increased expense of nonstandard design, nonstandard construction practices, and, possibly, the purchasing and use of unusual materials.

Existing buildings would entail these same costs plus the cost of retrofit demolition and perhaps the loss of some usable or rentable area occasioned by the relocation of subsystems or the creation of buffer spaces.

For this discussion, properties may be divided into two broad classes: those constructed by an owner for the owner's use and those expected to perform as a financial investment. The economic factors in these two classes differ according to the owner's objectives.

Buildings constructed by and for an owner include owner-occupied office buildings, such as corporate headquarters, warehouse and distribution facilities, process and production plants, and civilian government buildings. The facility typically does not need to compete financially directly with other similar facilities. The owner does not expect a return on the investment through leasing or renting these facilities to a second party, although some building owners may reduce their own floor space needs and rent or lease out other portions to lower their costs.

When such a facility is being planned, the concern for protecting it against attack is based on the owner's assessment of risk. This assessment may depend on the owner's potential attractiveness to an attacker, perhaps for offering a controversial product (tobacco) or service (abortion), or for suffering an unpopular public image (a petroleum company or a multinational corporation that operates in many foreign countries, where it must try to satisfy diverse and often conflicting social and cultural expectations).

While any owner must weigh the costs of protection against the perceived threat, this type of owner may be more willing to install security, because in an owner-occupied building convenience or preference of the occupants are less of a concern than for a commercial building requiring access by the general public. Since ease of public access is not a major determining factor, in this case the owner is also more likely to emphasize physical security measures to intercept an attacker through access control. Rather than taking measures to mitigate damage from a successful attack, this type of owner may be more interested in avoiding disruption of whatever processes are taking place at the facility. This type of owner may also not be as concerned with space utilization as a commercial owner would be, and may be able to make more use of design strategies such as buffer space against outside walls and increased stand-off distances.

Since the degree of occupant satisfaction is a prerogative of the owner, fenestration and other fragile building components can be reduced or eliminated, which could, in fact, result in lower direct costs of construction, operation, and maintenance than would have been the case for a building of conventional design and construction.

On the other hand, buildings constructed as financial investments are expected to provide a return on their costs by generating revenues as a direct result of their use by others. Commercial office buildings, retail and mixed-use centers, and recreational facilities are typical of this class of structures. Moreover, these investments are made in a very price-competitive environment where even small-cost excursions can and do affect investment decisions.

Appendix A compares the financial performance of a speculative commercial office building and the financial performance of the same building after it has incurred the additional costs of protection against attack. The discussion and accompanying cost models conclude that the construction premium for blast-hardening does not materially impact the financial performance of a commercial building. The committee believes that reasonable blast resistance can be accomplished for about a 5 percent premium in construction cost which equates to an increase of the lease premium of about 3.5 percent.

However, there are still financial and other barriers to incorporating blast-hardening features in such buildings. Commercial developers and their investors are wary of anything that alters the traditional financial profile of a building or that injects an unknown element in its liquidity potential, refinancing value, or market position, or other factors that could in any way impact the property's performance as an investment.

Since every element in the development of an investment-grade property must pass a rigorous cost/benefit analysis to ensure that the added element does not dilute the anticipated return on investment, the decision to add a nonrevenue element, such as blast-resistant construction, to a building would be much more likely if there were some cost-recovery mechanism available. Some of these mechanisms could be tax credits, reduced insurance costs, or more favorable lender terms. However, none of these mechanisms are available today, nor are they being contemplated. The most attractive and likely incentive for including blast protection in an investment property would be finding a long-term tenant, such as a government agency, that is sensitive to security issues and is willing to pay a higher rent for a blast-hardened building.

Such a long-term lease would allow the developer to recover his costs. It also delays the time when it becomes necessary to find a replacement tenant with the same security concerns, or to compete for another tenant against properties with lower cost bases and operating expenses. Finding a tenant who is willing to pay higher rent may mean advertising or promoting the property as blast-resistant, and most developers would be reluctant to do this because the advertising could be interpreted as a challenge and might actually invite an attack on what otherwise is an unremarkable target. Development and publication of security measures or blast-effects mitigating technologies may also carry the risk of liability potential, so the dissemination of technology may have to be done in a way that does not put the source at risk. Casualty insurers are most affected by damage to a property caused by an explosion, because of both repair costs and insured lost revenues. The potential for terrorist activity at a specific building can affect its insurability when an insurer believes that a tenant of the building is a high-profile target.

A positive side of the economics of effective blast-hardening is the reduction in personal injuries or deaths with inevitable claims and the reduction in repair costs and lost revenues following an explosion. To the extent that the structure and its systems are able to resist blast-effects, occupants are better protected, repairs are more easily made, and the time the building is nonfunctional is reduced, along with the revenue losses to the occupant businesses. Additional benefits are possible to the extent that blast-hardening features improve a building's resistance to accidental explosions, which can result from the improper storage of chemicals, or fuel or gas leaks, for example.

Representatives of the building industry, such as the Building Owners and Managers Association, generally corroborate the observation that there is a low level of continuing public concern about terrorist attacks on commercial buildings in the United States. In the case of the World Trade Center, public attention and concern were very high in the months that followed, only to subside as time passed. Time will tell if interest in the Oklahoma City bombing will be brief, or if a sustained level of concern will develop into widespread demand for blast-resistant measures in commercial buildings.

AGENTS FOR TECHNOLOGY TRANSFER

Successful transfer of relevant military technology to the civilian sector must overcome several significant barriers: inadequacy of professional education, inaccessibility of information, and lack of financial incentives. Agents for affecting this technology transfer must be selected with these barriers in mind. As already noted, specialized knowledge and resources are required to effectively realize the blast-effects mitigation potential for commercial buildings. Today, a select number of architect-engineer firms specializing in hardened military design and construction are also engaged in civilian building design and thus possess the requisite capabilities. Many of the design-oriented computer programs described in Chapter 3 were developed by research-oriented firms who frequently assist archi tect-engineer teams in the application of their design tools. However, if these technologies are to gain widespread acceptance, a major effort must be made to broaden the educational and experiential base within the profession.

The agents for technology transfer are many and normally take months or years to be developed and disseminated. Past experience suggests that documents or reports that address certain aspects of the problem will become available; an example is the ASCE (1995) document currently being developed. Over time, if demand is sufficient, a series of such guideline documents could be expected. The sponsors for such documents could be technical societies, governmental laboratories, or contracted documents could be supported and funded by any number of sources. These guideline documents, even though not referenced in building codes, can normally be used in building design or retrofit. The guideline provisions normally far exceed code requirements, however, the professional would have to be sure that adopted procedures are not in violation of any building code procedures or other local, state, or federal ordinances. In time, such material will naturally find its way into texts and special courses in universities and colleges. This evolutionary process has occurred in many subdisciplines. In the civil engineering field, such design topics as wind, earthquakes, and other natural phenomena, offshore platforms, major pipelines, and criteria for nuclear power plants have evolved in this general manner.

The schools of architecture, construction, and engineering in our country's universities have a unique ability to transfer technology through education, and they must be part of the process. So too must the professional societies, such as the American Institute of Architects, the American Society of Civil Engineers, the National Society of Professional Engineers, the American Society of Heating, Refrigerating, and Air Conditioning Engineers, the Association of General Contractors, the Association of Building Contractors, and the American Society for Industrial Security.

Federal and state governments are also good candidates as agents of technology transfer, since they have a long-term concern to protect their own commercial office buildings. They are not subjected to all of the code issues that pertain to the private sector, and hence could incorporate blast-effects mitigation technology in their office buildings at a faster rate than the private sector. Also, the initial additional cost is not as great a concern when balanced against long-term objectives. Because the same designers typically work on both government and civilian office buildings, technology transfer would be much quicker. This same transfer technique is being used to introduce the metric (SI) system of units into civilian design and construction. Government agencies are requiring the SI units for their building projects and hence building designers who want to do the work are quickly making the necessary conversion.

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5

Findings and Recommendations

Terrorism is a reality which the United States must recognize and confront. Events over the past two years demonstrate that the United States is vulnerable to terrorist bombing. An awareness and acceptance of this threat by policy makers, building owners, and the general public is necessary for the application of blast-effects mitigation technologies and design methodologies to be effective. Prior to the bombing of the Alfred P. Murrah Federal Building in Oklahoma City (which occurred as the committee was completing its work), blast hardening measures seemed unlikely to have wide appeal within the civilian building community because of the relatively low level of public awareness of, and sensitivity to, the potential vulnerability of buildings in the United States to terrorist bombing attacks. At this time, the committee cannot speculate whether public attitudes will change over the long term as a consequence of the Oklahoma City bombing, and no such assumptions are made in arriving at the committee's findings.

The specific findings reached by the committee regarding applicability of the technology and blast-effects mitigation potential for commercial buildings, future research requirements, and technology transfer opportunities have been presented throughout the report and are summarized below.

FINDINGS

1. **Attacks against civilian buildings pose an unquantifiable but real threat to the people of the United States.**

   The historical record suggests that bomb attacks against civilian buildings will continue as the terrorist's tactic of choice. The hitherto generally low level of awareness of, and sensitivity to, the potential vulnerability of buildings in the United States to terrorist bombing attacks may have changed dramatically as a consequence of the Oklahoma City bombing, but only time will tell.

2. **Blast-hardening technologies and design principles developed for military purposes are generally relevant for civilian design practice. However, because the knowledge base is incomplete, they must be adapted and expanded to be more specifically applicable, accessible, and readily usable by the civilian architect-engineer community.**

   The committee found that the techniques of analysis and design for blast resistance and structural response developed for military purposes have general relevance to civilian architecture. Much of the existing knowledge on hardening of structures to high explosives has been documented in military engineering design manuals, as have the principles of threat assessment, critical asset determination, architectural planning, and related decision processes. Similarly, the military has produced an array of powerful computer programs for the estimation of blast-effects and the resultant structural response. However, civilian architecture differs from its military counterpart by typically being lighter in construction, while at the same time more structurally complex. Therefore, transfer of these technologies to civilian practice will require both modification of the design manuals to account for the fundamental differences between structural types and selective application of the most promising computer programs to civilian design problems. It must be noted that the more sophisticated programs are generally difficult to use and require a level of expertise and scale of hardware generally not found in the commercial architect-engineer sector. Considerable skill in computer modeling is required to analyze the structure and evaluate the output. Without experienced engineering judgment, it is quite possible to obtain erroneous results. Successful implementation of these approaches will require testing and validation of typical civilian structural types over a range of hypothetical explosions. Work will also need to be done to broaden or recast the planning manuals and other literature to make them fully usable for civilian settings.

3. **Blast-hardening technologies developed by the military apply, for the most part, to building structural systems and must be expanded to include critical life-safety building subsystems.**

   Protection of nonstructural systems in civilian buildings is vital to survival and rescue of occupants and can significantly accelerate recovery of a building to its intended function. The effects of fire and smoke are not included in the current blast-effects mitigation manuals, but this subject is covered in publications of the National Institute of Standards and Technology (NIST) and the National Fire Protection Association (NFPA) and is the subject of continuing research. Little attention has been paid to blast resistance of critical life-safety building subsystems such as lighting, communications, and ventilation.

4. **Nonstructural architectural and engineering approaches can improve the blast resistance and response of civilian buildings.**

   Representative of these approaches, for example, are building siting, controlled parking beneath structures, strategically situating high-profile occupants in inconspicuous locations, interior space planning, etc.

5. **Post-attack rescue and recovery operations can benefit from good emergency management planning, including rapid availability of building systems and structural drawings and use of computer-based modeling and decision support systems to assess the extent of blast damage to the building's structural frame.**

   The experiences from the World Trade Center and the Alfred P. Murrah Federal Building demonstrated the perilous nature of rescue and that competent management of emergency services of many types can be vital to the rapid evacuation of occupants, securing medical treatment for the injured, and reducing panic. Particularly important is the need to know the condition of remaining structural elements and the availability of drawings to support this determination would greatly aid the safe access to and removal of victims. Where drawings have been produced on computer, the availability of pre-engineered computerized models of the building structure would permit real-time analysis of a damaged building to identify potential hazards and suggest effective means of reinforcement while rescue operations proceed.

6. **Buildings designed to be more bomb resistant through the use of increased mass in the lower levels will also benefit from increased resistance to dynamic forces from natural hazards such as hurricanes, tornadoes, and earthquakes.**

   Although the dynamics of explosions and natural phenomena differ in significant details, the increased strength provided by structural solutions to potential blast-effects will resist natural forces as well.

7. **Barriers exist to the effective transfer of relevant military technology to the civilian sector. These barriers include lack of professional education, classification of military technology, lack of established technology transfer mechanisms, and cost and financial issues.**

   The committee has found that there are several serious barriers to technology transfer from the military to the civilian sector. The first major barrier is education. The current academic and professional training of architects and engineers does not adequately prepare the design professions, either technically or philosophically, to incorporate blast-hardening principles in civilian structures. Thus a strong educational commitment is required by university schools of architecture, construction, and engineering, as well as by professional engineering societies, if the potential for technology transfer is to be realized.

Another barrier is that much of the military technology is classified, and these security classifications will have to be removed before the technology can be transferred. Traditionally, the process of declassifying government testing programs and research results has been slow.

The third barrier is the lack of established mechanisms to transfer applicable technologies and techniques for structural hardening and blast-effects mitigation from the military to the civilian sectors. Near-term agents offering the best opportunity for technology transfer are federal and state governments and professional engineering societies. It is essential to involve the country's university schools of architecture, construction, and engineering if this technology is to be accepted by the design professions. Design guidelines from professional organizations and government will probably be the first vehicles incorporating counter-terrorism design principles. In the long term, the three Model Building Codes in the United States, the Standard Building Code, the Uniform Building Code, and the BOCA National Building Code, may reflect or incorporate certain blast-mitigating measures that are also applicable to other more common hazards, such as fire, smoke, wind, and seismic conditions.

The final major barrier to the application of these technologies is the negative impact of blast-hardening technology on financial performance. The additional construction costs created by the use of this technology, whether in the design stage of a new building or in retrofitting an existing building, may be a major barrier to adopting blast-hardening principles and procedures in the private sector. Thus the cost and other financial issues related to providing structural hardening and blast-effects mitigation treatment of a prototypical commercial office structure may not be supportable on an economic basis at this time.

It is generally agreed (and supported by the design manuals cited in this report) that thoughtful architectural planning and proper engineering design can accomplish significant improvement in building performance for minimal additional cost. The accuracy of this assertion will need to be demonstrated on a case-by-case, project-by-project basis. However, for those commercial buildings, and certain government buildings, whose financial performance is not the sole or primary decision factor, the application of available technologies and physical security measures should be considered on a case-by-case basis. While retrofitting existing buildings with hardened and reinforced construction is more costly and disruptive than incorporating these features in the original design of a new building, many of the planning and other blast-effects mitigation techniques can be applied to existing as well as new construction. Where the threat potential is sufficiently high, and where economic first-cost is not the primary driver, military design and construction principles can be beneficially applied.

Based on these findings, the committee developed a series of recommendations aimed at adapting and transferring the already available technology from the military to the civilian sectors. For those areas where knowledge gaps exist, the committee suggests a program of applied research to address those areas.

RECOMMENDATIONS

1. **Adapt selected technical manuals, threat assessment methodologies, and computer programs developed for military applications and disseminate them to civilian building-design professionals as one component of an integrated threat deterrent and blast-effects mitigation strategy (*Findings 1 and 2*).**

The most attractive candidates for technology transfer are the design principles, guidelines, and methodologies incorporated in the following:

- *Structures to Resist the Effects of Accidental Explosions Manual* , 1990, Army TM 5-1300, Navy NAVFAC P-397, AFR 88-22, Departments of the Army, the Navy, and the Air Force (approved for public release; distribution is unlimited).
- *Security Engineering Manual*, 1993, TM 5-853 (currently restricted to official use only).
- *Design and Analysis of Hardened Structures to Conventional Weapons Effects Manual*, 1995 (DAHS CWE)
- Threat Analysis and Vulnerability Assessment, developed by the U.S.

Army Corps of Engineers, and Balanced Survivability Assessments developed by the Defense Nuclear Agency.

A unique opportunity exists for the Defense Nuclear Agency to influence ongoing development of an electronic hypertext version of the Joint Services DAHS CWE manual. This effort is intended to convert the manual to an interactive computer program complete with text, graphs, tables, equations, and stand-alone computer codes. Distribution of this product is intended to be on CD-ROM for both DOS-(WINDOWS) and Unix-based platforms. This is precisely the type of engineering design aid that should be tailored to the needs of the civilian building-design community and widely disseminated.

However, before these manuals can be fully adapted for use by the civilian sector, a program of applied research (as described in Recommendations 2 and 3), directed at the critical structural and nonstructural subsystems, components, and materials normally found in civilian buildings, will need to be undertaken.

2. **Conduct experimental and analytical studies on the blast resistance of structural subsystems representative of conventional civilian building design and construction practice (*Finding 2*).**

A base of knowledge regarding the performance of structural subsystems will be required to extend and adapt existing blast-resistant design principles, guidelines, and computer programs to the needs of civilian design professionals. This knowledge base will also serve to validate first-principle computer programs, extend the applicability of semi-empirical programs, and provide a basis for evaluating the conservatism in the explosive loading and structural resistance incorporated in current military design manuals and computer design programs.

A very strong experimental and analytic capability already exists in this country and abroad that could facilitate future research and development in the area of blast-effects mitigation. This includes various test sites throughout the United States, from indoor laboratories for small-scale component testing to very large ranges for field testing of full-scale structures. The United Kingdom has a facility for full-scale testing of structures indoors and has expressed an interest in working with the Defense Nuclear Agency and other U.S. research agencies involved in blast-effects mitigation activities. Cooperative efforts also should be sought with foreign governments actively engaged in bomb-resistant civilian building design with whom the United

States already has relevant data exchange agreements (e.g., United Kingdom, Israel, Norway).

Such test facilities are usually well equipped with both high-quality instrumentation and trained technical support staff. Although in the past, U.S. facilities have been operated primarily in support of defense activities, arrangements could be made to enable the civilian sector to gain access to selected testing sites. In particular, the committee notes that several federal agencies, including Defense Nuclear Agency and U.S. Army Corps of Engineers, Waterway Experiment Station, have the intellectual and programmatic infrastructure in place to carry on a program of research and development of new blast-effects mitigation knowledge and to assist other agencies and industry in the beneficial application of this knowledge.

3. **Conduct research and testing of common building materials, assemblies, equipment, and associated designs applicable to blast-resistant design of critical nonstructural building subsystems (*Finding 3*).**

The following specific areas of investigation are recommended:

i. Behavior of common non-load-bearing assemblies under various blast intensities to determine whether their design can be enhanced to reduce production of damaging fragmentation and vulnerability to fragmentation loading. For example, research could be conducted on developing interior partition assemblies, such as metal stud and drywall that could be bonded together for less fragmentation following an explosion.

ii. Survival of ducts, conduit, and other distribution sources. Investigate whether certain materials and assemblies offer improved survival potential and whether design techniques employed in military construction (including shock isolation) can be cost-effectively applied to civilian building design and construction. A study of protective designs might be developed for plumbing distribution piping and for investigating new materials that could be used, including protective jackets. The study could explore whether increased ductility of the piping or joints is beneficial.

iii. Protection of equipment and machinery. Blast-hardened walls are not always feasible to protect equipment or maintain air locks to prevent smoke propagation in tall buildings. A study is needed to determine the survival potential of commonly used building systems and equipment under various blast conditions. These include generators, chillers, switchgear, pumps, motors, etc. Designs for housings that could offer improved protection to equipment should be investigated, including lightweight shields or assemblies that could protect machinery, or maintain an air lock, even after partial failure. For example, a generator might be able to survive the explosion if a shield could minimize debris and fire from reaching the generator and its controls. A wall system might buckle, but hold together well enough to maintain an air lock. In this connection, it would be useful to prepare a summary of known information from the military and related efforts. Equipment resistance arising from studies under the SAFEGUARD missile defense program, including vulnerability shock data for equipment and lifelines, nuclear power plant design and construction, and other specialized industrial projects are examples that could be used for civilian applications.

iv. Research is needed to find ways of making elevator cabs and shafts less susceptible to smoke infiltration.

4. **Establish a government/academic partnership whose purpose is to inform and alert design professionals regarding the range of measures that can and need to be taken to protect buildings from terrorist activities and the collateral benefits of providing such protective measures. This partnership should also take the lead in facilitating the transfer of this technology by interaction with the appropriate government and professional bodies (*Findings 4, 6, and 7*).**

This partnership is not envisioned as a single organization, but rather as an institutional network to foster cooperation between the public and private sectors and academia and industry to establish appropriate technology transfer mechanisms; such a network can also be used as a vehicle to introduce departments in architecture, engineering, and construction schools to the protective technology and procedures currently available and under development.

5. **Explore the use of computer-based modeling and decision support systems to assess the extent of blast damage to a building's structural frame as part of the post-attack rescue and recovery operations (*Finding 5*).**

The immediate objectives of post-attack rescue and recovery will be influenced by an engineering assessment of the building's safety and the requirements for safe and rapid removal of debris and temporary shoring of specific structural elements. This assessment could be improved substantially if validated computer-based modeling and decision support systems are made available as an immediate and practical aid for the assessment process. In turn, this will require the availability of building plans and all relevant structural design data, as well as the ability to rapidly model the post-attack status of the damaged building structure. The analytical capability for such assessment exists, but needs to be adapted and made available for post-attack operations.

6. **Analyze all new civilian federal buildings, and existing buildings where appropriate, to determine reasonable ways of incorporating blast-hardening and other blast-effects mitigating features, and to document consequent building construction costs and financial performance (*Finding 7*).**

These analyses will contribute to a broader appreciation of how blast-hardening planning and design can mitigate the effects of terrorist bombings, provide a database on architectural design solutions applicable to the commercial sector, and will assist in the formal education of design professionals. Until such time as this capability develops in the civilian architect and engineer community, several federal agencies, including Defense Nuclear Agency and the U.S. Army Corps of Engineers, Waterway Experiment Station (and their contractors), currently possess technical resources and expertise to assist in the analysis of existing and proposed civilian buildings to determine the need for (and cost of) blast-effects mitigating measures.

Appendixs

Appendix A

Financial Performance of a Commercial Office Building

For the purposes of this analysis, it is assumed that the building under consideration is a typical speculative mid-rise commercial office building that has been conventionally constructed. The building is located in a developed American urban area, is mid-life in age, has a rentable area of 250,000 square feet, and is occupied by a single tenant with a five-year, full-service lease. The building appraises at its cost basis, and its debt is a nonamortizing mortgage with a loan-to-value ratio of 0.8 and 9 percent interest. The building and land are privately owned so the project is subject to all applicable taxes. The financial profile for this building is given in Table A-1, and the figures used in the analysis are the averages shown in the column labeled "Average."

The U.S. national average cost to build a conventionally constructed, speculative commercial office building in an urban location is approximately $83.50 per square foot (/sf) including land, development costs, core and shell construction, and tenant improvements (build-out) (see Table A-2).

The analysis makes the assumption that blast-hardening the subject building will increase the owner's cost basis by 5 percent. This figure is highly dependent on numerous factors, and while the argument could be made that 5 percent is an arbitrary assignment, the more important aspect of the analysis is to examine the sensitivity of blast-hardening costs to the financial performance of a commercial property.

Blast-hardening will increase soft costs, core and shell construction, and build-out, but land cost would not be affected. The blast-hardening premium is therefore applied to the project costs before adding the cost of land. Referring again to Table A-2, it can be seen that a 5 percent blast-hardening cost would

TABLE A-1 Conventional Building Income and Expense Analysis (U.S. national average for an urban, commercial office building in the 100,000-300,000 sf range, 1993 dollars)

Income and Expenses	Average	Low	High	Conventionally Configured	Blast-Hardened	Unoccupiable
INCOME						
Office rent	16.29	9.95	19.97	4,072,500	4,189,381	0
Retail rent	17.18	8.78	26.79			
Other rents	4.62	2.76	10.02			
Total Rent	16.13	9.89	19.65	4,072,500	4,189,381	0
Parking Income	0.86	0.30	1.18	215,000	215,000	0
Miscellaneous Income	0.20	0.02	0.18	50,000	50,000	0
Total Income	16.82	10.41	20.21	4,337,500	4,454,381	0
EXPENSES						
Cleaning	1.07	0.72	1.23	267,500	267,500	66,875
Repairs/maintenance	1.24	0.82	1.56	310,000	325,500	162,750
Utilities	1.87	1.46	2.18	467,500	467,500	116,875
Roads/grounds/security	0.48	0.27	0.64	120,000	132,000	132,000
Administrative	0.97	0.62	1.23	242,500	254,625	254,625
Total Operating Expense	5.57	4.46	6.46	1,407,500	1,447,125	733,125
Taxes and Insurance	2.29	1.02	3.02	572,500	595,400	595,400
Total Operating + Fixed	7.87	5.72	9.49	1,980,000	2,042,525	1,328,525
Debt Service	5.95			1,487,500	1,532,125	1,532,125
Leasing Expense	1.46	0.20	2.07	365,000	365,000	0
Total Expense				3,832,500	3,939,650	2,860,650
NET INCOME				505,000	514,731	(2,860,650)
Operating + Fixed/sf				7.92	8.17	5.31
All Costs/sf				15.33	15.76	11.44
Cash Flow per Business Day						(11,433)

NOTE: National average data from BOMA *Experience Exchange Report* (1994:86) represent approximately $3.13/sf increased cost for a total construction cost of $86.63/sf. Assuming a 10 percent return on investment, this incremental cost requires a full-service rent premium of about 3.5 percent to recover the increased construction cost.

TABLE A-2 Return on Investment Analysis ($/sf)

	Conventional Building	Blast-Hardened Building
Construction Cost		
Shell and core	43.50	45.68
Tenant improvements	11.00	11.55
Development (soft) costs	6.25	6.56
Miscellaneous	1.75	1.84
Subtotal construction costs	62.50	65.63
Land	21.00	21.00
Total Building and Land for a Triple Net Lease	83.50	86.63
Net effective rent rate to achieve 10% return on investment	8.35	8.66
Blast-Hardening Premium for a Full-Service Lease		3.74
Add back		
Operating expenses and taxes	7.92	8.17
Net effective rent rate to achieve 10% return on investment	16.27	16.83
Blast-Hardening Premium		3.46
Assumptions 1. Land is owned by the project partnership 2. The partnership desires a return on investment of 10% 3. Blast-hardening increases investment by 5%		

NOTES: Construction costs from *Means Building Construction Cost Data* , 50th Edition, 1992. National average square foot costs, mid-rise office building, escalated to 1993 dollars. Operating expenses and taxes are from Table A-1.

Blast-hardening may also increase a building's operating costs through increased inspection and maintenance of blast-hardening features. These may be specialized services that are of limited availability and therefore more expensive than inspection and maintenance services would be in a building not so equipped. Furthermore, a tenant with concerns about terrorist activity may also require increased security measures such as perimeter and zone access control. Such security measures may include a uniformed guard service to screen and process visitors and the operation of a facility to X ray incoming mail and deliveries.

Ordinary operating, repair, and maintenance expense for a building as described above would be approximately $7.92/sf. Table A-1 attempts to compare operating costs between a conventional and blast-hardened building by making assumptions about which operating-cost elements could be affected. These assumptions result in a new operating cost of $8.17/sf or an increase of slightly more than 3 percent. The lease escalation would increase by $0.25/sf if all of these additional costs were borne by the owner and passed on to the tenant. Certain lease forms, particularly with government tenants, may disallow certain costs that could be otherwise escalated to a commercial tenant, which means the ownership must bear these costs directly.

Taken together, increased construction, operating, and repair and maintenance expenses can represent approximately $0.81/sf ($0.56 in lease rate plus $0.25 in escalations) in increased cost to a tenant desiring to occupy a blast-hardened building. For the sample building used in this analysis, the incremental cost would represent $1,012,500 over the five-year lease term.

Table A-1 also attempts to examine the operating cost of the subject building should the building sustain sufficient damage that it cannot be occupied. Certain fixed costs would continue unchanged while others would be reduced or eliminated altogether. The most damaging effect is the complete loss of revenue due to the abatement of rent. Most commercial leases require the owner to abate rent in the event the tenant cannot occupy the building for the period that the building is unoccupiable. Note that the building's cash flow under these circumstances becomes negative at about $11,400 for each business day that it cannot be occupied, and this does not include revenue losses suffered by the occupant businesses because of reduced or suspended operations. While it is common to insure against loss of revenues, most policies have a limit on either the number of days covered or a cap on the total amount that will be paid. Loss of revenues from a building that experiences damage to such a magnitude that it cannot be occupied will most probably exceed the policy limits before operations are restored.

Overall, the construction and operating and maintenance costs of a blast-hardened building are not significantly different from a conventional building when using the assumptions of this analysis. If the model shown in Table A-2 is indexed through different construction premium assumptions, the change in lease-rate premium is small in comparison.

Assumed Cost Premium	Resulting Lease Premium
3%	2.69%
5%	3.46% (used in the analysis)
7%	4.23%

One percent change in the construction-cost premium produces a 0.385 percent change in the lease-rate premium. This negative sensitivity tends to lessen the importance of validating the construction-cost premium assumption.

Appendix B

Computer Code Abstracts Provided by Code Developers

ALE3D

Lawrence Livermore National Laboratory

ALE3D is a three-dimensional finite-element code that utilizes arbitrary Lagrangian-Eulerian techniques to simulate fluid dynamics and elastic-plastic response on an unstructured mesh. The grid may consist of arbitrarily connected hexahedra, beam, and shell elements. The mesh can be constructed from disjoint blocks of elements which interact at the boundaries via slide surfaces.

The basic computational cycle consists of a Lagrangian step followed by an advection step. In the advection step, nodes in selected materials can be relaxed either to relieve distortion or to improve accuracy and efficiency. ALE3D thus has the option of treating structural members in a Lagrangian mode and treating materials which undergo large distortions in a ALE mode, all within the same mesh/problem configuration. The code has a range of equation-of-state and constitutive descriptions that are appropriate for modeling hydrodynamic shock phenomena. Several options are available for describing explosive detonations. ALE3D is currently being applied to a number of studies involving the effects of explosive events.

ALE3D has been distributed under a collaborative licensing agreement. At the request of the U.S. Department of Defense, it is being treated as an export-controlled code. The code currently runs on essentially all workstations and Crays. A graphics post-processor, MESHTV, is provided with the code. Mesh generation requires INGRID or TRUEGRID or any other mesh generator that can provide an output file in DYNA3D format.

ALEGRA

Sandia National Laboratories

ALEGRA is a solid dynamics code developed at Sandia National Laboratories for modeling the near-field and far-field transient response of complex bodies to explosions, impacts, or energy deposition. It combines the structural analysis algorithms found in Sandia's Lagrangian PRONTO code with the large deformation shock physics algorithms found in Sandia's Eulerian CTH code. This allows ALEGRA to accurately model the near-field large deformations of an explosion with an Eulerian mesh and the far-field structural response with a Lagrangian mesh. ALEGRA can model both three-dimensional and two-dimensional problems. It has simulated several problems including the response of containment vessels to explosive loading, the stresses in a machine tool cutting bit, and the transient response of an explosively loaded, fluid-filled storage compartment.

ALEGRA uses an explicit, time-stepping finite-element formulation and an arbitrary connectivity mesh composed of three-dimensional hexahedral and shell elements or two-dimensional quadrilateral elements. ALEGRA was designed using object-oriented software engineering concepts and is written in C++, C, and FORTRAN. ALEGRA runs on workstations and massively parallel computers.

Reference: Budge, K.G., and J.S. Peery. 1993. RHALE: a MMALE shock physics code written in C++. International Journal of Impact Engineering 14:107–120.

BLASTX

Science Applications International Corporation

BLASTX (version 3.0) code calculates the propagation of blast shock waves and detonation product gases in multiroom structures. The code provides predictions of the pressure-time and temperature-time histories in these structures. The 3.0 version includes: (1) a variety of room shapes that may be used throughout a structure, (2) an interactive menu-driven input module, (3) an enhanced version of the burning, venting, and wall-failure models from the Naval Surface Warfare Center INBLAST code, (4) failure models using the total shock and quasi-static gas pressure on a wall, (5) heat conduction to walls, (6) a more accurate model of shock propagation through openings, and (7) modeling of blast-effects within and outside of explosive storage magazines. The code uses dynamic memory allocation so that structures ranging from a single room to many rooms may be treated.

Reference: SAIC. 1994. International Blast and Thermal Environment for Internal and External Explosions: A User's Guide for the BLASTX Code, Version 3.0. (SAIC 405-94-2).

CTH (SHOCK PHYSICS)

Sandia National Laboratories

CTH is a multimaterial, large deformation, strong shock-wave, solid mechanics code developed at Sandia National Laboratories. CTH has models for multiphase, elastic-viscoplastic, porous, and explosive materials. Three-dimensional rectangular meshes, two-dimensional rectangular and cylindrical meshes, and one-dimensional rectilinear, cylindrical, and spherical meshes are available. It uses second-order accurate numerical methods to reduce dispersion and dissipation and to produce accurate, efficient results. CTH runs on most Unix work-stations and supercomputers. Preprocessing and color graphic postprocessing programs are provided.

PCTH is a massively parallel version of the CTH code. It runs on Intel and nCUBE massively parallel computers. It supports only three-dimensional meshes. It is heavily used to model problems much larger than possible with workstation or Cray computers. PCTH has several material models appropriate for strong shock and large deformation calculations. SESAME tabular and analytic equations of state model the nonlinear behavior of materials in the high-pressure regime. SESAME can model solid, liquid, vapor, liquid-vapor, solid-liquid, and solid-solid phase changes. An elastic-perfectly-plastic model with thermal softening is available. The Johnson-Cook, Zerilli-Armstrong, and Steinburg-Guinan viscoplasticity models are available. In addition, the Johnson-Holmquist brittle strength and failure model is available for modeling brittle materials such as ceramic or concrete. High-explosive detonation can be modeled using programmed burn, Lee-Tarver, Forestfire, and a history variable model developed at Sandia. The Jones-Wilkins-Lee analytic and SESAME tabular equations of state can model the high-explosive reaction products. Fracture can be initiated based on pressure or principal stress. A model moves fragments smaller than a computational cell with statistically correct velocity. This model is very useful for analyzing fragmentation experiments and experiments with witness plates.

CTH uses an Eulerian solution scheme where the mesh is fixed in space and the material flows through the mesh. CTH uses monotone, second-order convention schemes to flux all quantities between cells. It has a high-resolution material interface capturing scheme that prevents numerical breakup and distortion of material interfaces. These numerical methods reduce the dispersion and dissipation found in first-order accurate Eulerian codes.

CTH is written in FORTRAN77 and a small amount of C code. CTH runs on virtually all Unix-based systems such as those from Cray, Sun, Hewlett Packard, SGI, IBM RS6000, DEC/Ultrix, and Convex. PCTH is written in C++, C, and FORTRAN. It runs on Intel and nCUBE massively parallel computers.

All variables can be displayed in two-and three-dimension plots and as a function of time with CTH's postprocessing programs. The plots can be displayed on color and monochrome X-windows-based workstations. They can be printed on color and black-and-white PostScript printers. CTH is an export-controlled code.

Reference: McGlaun, J.M., S.L. Thompson, and M.G. Elrick 1990. CTH: a three-dimensional shock physics code. International Journal of Impact Engineering 10:351–360.

DYNA3D

Lawrence Livermore National Laboratory

DYNA3D, first developed in 1976 and continually updated thereafter, is a nonlinear, explicit finite-element code for analyzing the transient, dynamic response of three-dimensional solids and structures. The code is fully vectorized and is available on several computer platforms. DYNA3D includes solid, shell, beam, and truss elements to allow maximum flexibility in modeling physical problems. Many material models are available to represent a wide range of material behavior, including elasticity, plasticity, composites, thermal effects, and rate dependence. In addition, DYNA3D has a sophisticated contact interface capability, including frictional sliding and single surface contact. Rigid materials provide added modeling flexibility. A material model driver with interactive graphics display is incorporated into DYNA3D to permit accurate modeling of complex material response based on experimental data.

Reference: 1989. DYNA3D User's Manual: Nonlinear Dynamic Analysis of Structures in Three Dimensions. UCID-19592, Rev.5. Livermore, California: Lawrence Livermore National Laboratory.

EPSA-II

Weidlinger Associates, Inc.

The EPSA-II code is a finite-element program for the response of shell structures. It is primarily aimed at metallic structures in fluid media and has been used extensively for underwater structures, such as shock loading of submarine hulls. Both small-scale and prototype structure tests have been conducted to validate the program.

Reference: Atkatsh, R.S., et al. 1994. EPSA-II Theoretical Guidebook, Rev. G. New York: Weidlinger Associates.

FLEX (FINITE-ELEMENT)

Weidlinger Associates, Inc.

FLEX is a three-dimensional explicit, time domain finite-element code designed to analyze the response of continua and structures subjected to dynamic or static loads. Weidlinger Associates has developed and supports the code. New revisions are released once or twice a year. The code has been applied to a wide range of problems including geotechnical, seismic-wave propagation, soil-structure interaction, accidental explosion, and weapon effects. The accuracy of the program has been verified against both analytic solutions and other codes. The code contains sophisticated nonlinear constitutive models to represent soil, rock, and reinforced concrete subjected to high-stress environments such as blast loading. Beam, bar, shell, and continuum element types are available for modeling. Both nuclear and conventional explosion pressure functions are included in the code. An embedded scripting language is included to allow the construction of templates for particular classes of problems. These templates allow unsophisticated users to define and run a model by inputing only the key problem parameters. The template generates the grid, computes the solution, and evaluates the results using the expertise of the individual constructing the template. Fully integrated color graphics and PostScript hardcopy allow for all aspects of the model to be displayed at any time during a calculation. On-screen movies can be created and displayed. The code runs on most classes of hardware, including personal computers, Unix workstations and Cray supercomputers. The program and its derivative versions are currently being used by a number of organizations, including governmental agencies, academic institutions, and commercial companies.

Reference: Vaughan, D.K., and E. Richardson. 1994. FLEX User's Manual, Version 1-h.4. New York: Weidlinger Associates.

FEFLO

Science Applications International Corporation

The FEFLO family of codes is based on high-order monotonicity, preserving algorithms and the adaptive unstructured grid methodology developed by SAIC and George Mason University. Time-accurate or steady-state solutions for complex geometries with multiple moving bodies are reliably obtained over a wide range of flow regimes. Combined with the configured definition tools, FECAD and FRGEN, highly accurate solutions to real problems are achieved on a time scale compatible with the design cycle.

FECAD: Configuration definition for geometry, materials, and boundary conditions. Features include import of surface data (CATIA, CADAM, IGES, BRLCAD); workstation-based interactive mouse-driven modules; surface-oriented object library; mesh generation for fluid or structural dynamics computa tional meshes; functions for translation, rotation, scaling, surface lofting, automatic part merging, and extensive diagnostics.

FRGEN: Automatic mesh generation for adaptive unstructured surface and volumetric grids. Features include interactive background grid specification; variable grid-spacing density and stretching; point line and volumetric sources; and extensive grid-quality diagnostics. Executes on mainframes or workstations.

FEFLO: Compressible or incompressible Euler and Navier-Stokes codes using either an implicit or explicit formulation. Features include automatic mesh adaptation to physical or geometric features, moving bodies, and equations of state.

FEMOVIE: Solution animation allowing for multiple cameras, moving viewer frame, complex viewer trajectories, and zoom/pan.

FEPLOT: Complete three-dimensional package for interactive diagnostics including tracers, streamlines, arrows, contours, iso-surfaces, and cut planes of all-fluid conserved and derived quantities.

Reference: Baum, J.D., H. Luo, and R. Löhner. 1995. Numerical Simulation of Blast in the World Trade Center. AIAA-95-0085. AIAA 33rd Aerospace Sciences Meeting, Reno, Nevada, January.

FOIL

Applied Research Associates, Waterways Experiment Station

The first-principle code FOIL is an efficient analytic ground-shock prediction code that calculates ground-shock parameters (radial stress, impulse, velocity, displacement, and hoop stress versus time; peak radial stress, impulse, velocity, displacement, and hoop stress versus range; time of arrival of peak and time of initial arrival versus range) due to the detonation of conventional explosives in backfill materials. Predictions for fully coupled bombs are based on analytic fits to first-principle, one-dimensional spherical calculations of a spherical source of 188.8 kg of H6 explosive detonated in 20 backfill materials. The standard explosive is H6; cube-root scaling is employed to allow the use of the equivalent explosive concept to predict for explosives other than H6. A coupling-factor concept is employed to allow for effects of depth of burial less than fully coupled as defined in Army Manual TM5-855-1.

The purpose of this code is to provide the Department of Defense community with improved ground-shock prediction techniques for use in decoupled structural analyses for the design of hardened structures.

The equations in FOIL are formulated based on the theory of spherical flow fields in locking solids, and the backfill models/properties have been validated by comparisons of calculation results with recent test data. FOIL in turn closely replicates the first-principle calculation results and hence the test data, whereas previous empirical-based analytic prediction techniques as defined in the current military design manuals do not.

Reference: Windham, J.E., H.D. Zimmerman, and R.E. Wacker. 1993. Improved Ground Shock Predictions for Fully Buried Conventional Weapons. Proceedings of a special session of the Sixth Internal Symposium on the Interaction of Conventional Munitions with Protective Structures, Panama City, Florida, May.

FUSE

Weidlinger Associates, Inc.

The FUSE code is a newly developed hydrodynamics shock and structural dynamics code based on a Lagrangian treatment of material motion and deformation. This approach allows the numerical analysis to proceed without the nonphysical numerical diffusion of dissimilar materials (such as high-explosive gas and solid structures) across their mutual interfaces. The procedure involves a new computational technique to avoid the adverse effects of large distortion on conventional Lagrangian codes. The code is currently being generalized to three dimensions and to include structural (shell) elements. It can be run on supercomputers, workstations, or even personal computers.

FUSE is capable of dealing with arbitrary deformations and motions of materials of any properly posed constitutive type. It can accurately represent the shock-wave propagation and gas expansion resulting from explosions, as well as their effects (in terms of structural loading). The code, which is under continuing development at Weidlinger Associates, is used to analyze multidimensional and multimaterial physical problems. One-dimensional spherical and two-dimensional cylindrical geometries are currently available, with the three-dimensional version nearing completion. The code is based on a new algorithm which allows each element to be cycled at its own time step. This permits the Lagrangian procedure to accommodate any large distortions which may arise. (A small displacement, two-dimensional version of the code is also available.)

Aside from the time-step cycling, FUSE utilizes several other novel computational techniques. A new procedure for handling shocks replaces the artificial viscosity procedure commonly used in hydrodynamic codes. This procedure not only properly computes shocks, but works just as well for acoustic waves, avoiding the usual numerical dispersion and dissipation associated with all of the standard shock algorithms. A new approach is also utilized to follow the kinematics of finite deformation in a physically and numerically objective way for solid materials.

Another important aspect of the new code is the nature of its discretization scheme. This scheme differs from the standard finite-element approach in that the codes carry only acceleration/velocity information, but do not carry position or deformation data. These instead are carried at the element centers only. Further, the laws of conservation of mass, momentum, and energy are exactly satisfied (to the numerical accuracy of the computer) for the discretized system.

FUSE has several mechanical and thermodynamic constitutive models available for representing solid as well as fluid behavior. Solids can be represented by CAP (elastic-non-ideally-plastic) models, as elastic-ideally-plastic, or viscoplastic materials. Simplified analytic equations of state are available for air and water, and the Jones-Wilkins-Lee equation of state is available for modeling high-explosive reaction products. Various failure models are available, including one specifically designed to represent the cavitation of water.

FUSE documentation is sparse as the code is new and still relatively young in its development. Its use in problems involving water shock is documented but a users guide is not yet available. The existing versions of the code require extensive training, but future versions are expected to be much more user-friendly.

FUSE uses a graphics package which permits snapshots to be displayed on X-windows-based workstations, and all quantities can be displayed graphically as functions of time. Color and black-and-white PostScript files are available for hardcopy output.

The FUSE code allows the numerical analysis of very general, nonlinear dynamic problems involving arbitrary materials and geometry changes. It is well suited for defining explosive loadings on structures and for determining the resulting effects.

Reference: Sandler, I.S., and D. Rubin. 1990. FUSE Calculations of Far-Field Water Shock Including Surface and Bottom Effects. New York: Weidlinger Associates. Distribution limited to SAIC.

HULL

Orlando Technology Inc.

The HULL code is a comprehensive system of finite-difference algorithms which solve the nonlinear partial differential equations descriptive of an elastic/plastic/hydrodynamic continuous medium. The code is modularized to treat two- and three-spatial dimensions in either Euler, Lagrange, or linked reference systems. The numerical techniques are fully second order in space and time for both modules.

HULL uses a material library for definition of material properties. This methodology allows the user to add experimental or theoretical descriptions for a material to the library along with the equation-of-state type to be employed. Elastic-plastic behavior is modeled with a Von Mises flow rule. Isotropic and orthotropic materials can be modeled. Phase changes account for the energy of sublimation and fusion. The Mie Grunieson equation of state is most widely used for metals and composites. The code can treat failure through criteria for ultimate stress, ultimate strain, or a triaxial stress versus stain failure surface. HULL has been used to investigate the effects of conventional ordnance and other high-rate deformation phenomena for over a decade.

Reference: Gunger, M. 1992. Progress on Tasks Under the Sympathetic Detonation Program. WL/MN-TR-91-85, Shalimar, Florida: Orlando Technology, Inc.

MAZE (MULTIPHASE ADAPTIVE ZONING)

TRT Corporation

The MAZe computational fluid and solid dynamics code was originally developed to simulate problems of interest to the Defense Nuclear Agency (DNA), mainly for weapon-effects scenarios such as nuclear and conventional explosions and dust clouds. The code evolved from the previous DNA-sponsored codes DICE and CRALE. More recent defense-related applications have included incendiary weapons, electrothermal-chemical guns, simulations of collateral effects from explosions in facilities containing nuclear, chemical, or biological agents, and hypersonic flow over missiles. The code has also been broadened to model such nondefense applications as turbo machinery, diesel engines, and asteroid and comet planetary impacts. MAZe has been validated against laboratory and field-test experiments for most of these applications. The code has modern numerical features such as adaptive zoning and total variation diminishing differencing, and also has models for a wide variety of physical processes, such as multiple interacting phases (gas/solid/liquid) and multiple reacting chemical species. The code also models solid materials and fluid-solid interactions, either directly in the code or by coupling to a finite-element structures code. Explosion-structure interactions with severe structural damage and cratering may therefore be simulated. High explosives that have been modeled include Tritonal, C-4, ANFO, LX-10, and others.

References: Schlamp, R.J., P.J. Hassig, C.T. Nguyen, D.W. Hatfield, P.A. Hookham, and M. Rosenblatt. 1995. MAZe User's Manual. Los Angeles, California: TRT Corporation.

SHARC

Applied Research Associates, Inc.

The second-order hydrodynamic advanced research code (SHARC) is a library of routines that is used to solve the equations of motion for inviscid, nonconducting, compressible fluid flow. The method of integration is time marching, explicit and fully second-order accurate in space and time. The solution is fully conservative and zone-centered in a rectangular Eulerian mesh in two or three dimensions. Multiple materials and two-phase flow are readily handled. Many physical models and equations of state are included in the library. A preprocessing code, developed by Leon Wittwer at Defense Nuclear Agency, is used to construct a FORTRAN-compilable code by selecting subroutines and lines of code from the library. The selections are based on input conditions and parameters defined by the user as part of the problem definition. The code, thus constructed, is designed specifically for the problem of interest, on the machine of interest, and is extremely efficient of computer resources.

Some of the physical models available include high-explosive burn in two or three dimensions, a two-equation turbulence model for compressible nonsteady flow, a nonequilibrium chemistry package, and a capability for including nonresponding structures within the flow. Points within the grid may be designated, at the start time, which monitor the hydrodynamic parameters as a function of time. Several models are available for calculating the effects of dust or particulate matter, and an extension of these models can be used to predict the influence and effects of fragments from conventional munition. Automatic rezones are included which can expand the overall grid or follow shocks or other regions of interest.

SHARC includes a general problem-initiation program. Initial conditions can be established from a wide variety of other codes or from previous SHARC calculations. A selection of ambient atmospheric conditions is available. Boundary conditions may be transmissive, reflective, or specified by feed-in conditions as a function of time.

A full set of postprocessing and graphics is included in the library. Selections of histograms, contours, color graphics, and vectors are available for all hydrodynamic parameters. Plots can be made of parameters as a function of position at a given time or as a function of time at a given position. Plots are also available as a function of time for specified points which move with the flow. A brief description of the solution method and results of a number of sample problems can be found in the reference cited below.

Reference: Hikida, S., R. Bell, and C. Needham. 1988. The SHARC Codes: Documentation and Sample Problems. SSS-R-89-9878, September. Albuquerque, New Mexico: S-Cubed division of Maxwell Laboratories. Distribution limited.

Appendix C

Committee Briefings

Presentations Made to the Committee on Feasibility of Applying Blast-Mitigating Technologies and Design Methodologies from Military Facilities to Civilian Buildings at its July 11–12, 1994, and August 31–September 2, 1994, Meetings

1. Defense Nuclear Agency and U.S. Army Corps of Engineers Expectations of the Study and Presentations

- Overview of Experience and Activities

- Defense Nuclear Agency, *Kent Goering*
- Waterways Experiment Station, *Jim Balsara*

- Project Objectives, *Kent Goering*, DNA
- Blast and Shock Technology Overview, *Kent Goering*, DNA
- Relevant Programs

- Army Retrofit, *Dave Coltharp*, WES
- Conventional Weapon Effects, *Mike Giltrud*, DNA
- Anti-Terrorism Technology Applications, *Doug Sunshine*, DNA

2. Threat Scenarios, *Gail Solin*, CIA
3. The Bombing of the World Trade Center, *William Faschan*, Leslie E. Robertson Associates

4. Recent Efforts to Define Blast-Mitigation Technologies, *Ted Krauthammer* , Pennsylvania State University
5. Defense Nuclear Agency and Waterways Experiment Station, *Kent Goering*

- World War II Conventional Bomb Damage
- Fire Smoke/Subsystems
- Retrofitting (Chapter 14 of DAHS CWE Manual)
- 6. Security Engineering Design Process, *John Trout*, U.S. Army Corps of Engineers Omaha District Design Stage
- 7. Blast Mitigation and Office Building Subsystems, *John Basch*, Lerch Bates Hospital Group, Inc.
- 8. WTC Recovery Program-Lessons Learned, *Robert Harvey*, New York Port Authority
- 9. DNA Contractor Perspectives

- Blast Mitigation Analysis and Design Technology Transfer, *Mel Baron* , Weidlinger Associates
- Evaluation of Blast Computational Methods-Lessons Learned from the World Trade Center Analysis, *Jim Drake*, Applied Research Associates
- Simulation-Based Design, *William Grossman*, SAIC
- Simulation Methodologies for Predicting Damage and Failure as Utilized at Sandia Laboratories, *Paul Hommert*, Sandia National Laboratories
- 10. Balanced Survivability Assessments, *Angelo Cicoloni*, Springfield Research Facility Retrofit Stage
- 11. Foreign Government Experiences

- United Kingdom Case Studies, *Jim Mackenzie*, Waterway Experiment Station
- The Israeli Homefront Command Approach to Hardening of Civilian Structures, *David Coltharp*, Waterway Experiment Station

Appendix D

Biographical Sketches of Committee Members

EUGENE SEVIN, chair, is an independent consultant. He formerly served with the U.S. Department of Defense as Deputy Director, Missiles and Space Systems; Office of the Under Secretary of Research for Acquisition and Technology; and as Assistant to the Deputy Director of Science and Technology, Defense Nuclear Agency. Dr. Sevin was professor of mechanical engineering at the Technion, Israel Institute of Technology, and head of the mechanical engineering faculty at what is now Ben Gurion University, Israel. He was also adjunct professor of applied mechanics at the Illinois Institute of Technology, and Director of Engineering Mechanics Research, IIT Research Institute. He holds a Ph.D. in applied mechanics from IIT. Dr. Sevin is a member of the National Academy of Engineering and of several professional engineering societies.

STUART L. KNOOP, AIA, vice chair, is a registered architect, and President of Oudens and Knoop, Architects, P.C. of Chevy Chase, Maryland. He has 34 years of experience as an architect, 25 of those years in his own practice. He is a member of the American Institute of Architects, the American Society for Industrial Security, and the Construction Specifications Institute. Since 1977 he has been involved in design for security, particularly for the U.S. Department of State's Office of Foreign Buildings Operations for which he and his firm designed more than 60 security upgrades of existing embassies and consulates worldwide. This experience led to his service on the Committee on Research for the Security of Future U.S. Embassy Buildings for the National Research Council.

TED BELYTSCHKO is Walter P. Murphy Professor of Civil and Mechanical Engineering at Northwestern University, where he has taught since 1977. Previously he taught at the University of Illinois at Chicago. His primary research interests are computational mechanics and finite-element methods. He has served on National Research Council committees on computational mechanics, instrumentation (large shake-table) evaluation, and underground structures. He obtained B.S. and Ph.D. degrees from the Illinois Institute of Technology. He is past Chairman of the Applied Mechanics Division of the American Society of Mechanical Engineers and the Engineering Mechanics Division of the American Society of Civil Engineers. He is a Fellow of the American Society of Mechanical Engineers, American Academy of Mechanics, and the American Association for the Advancement of Science, and a member of the National Academy of Engineering.

GARY G. BRIGGS is Senior Vice President and Chief Operating Officer of Consolidated Engineering Services, Inc., which provides technical and consulting services for operations, maintenance, and facilities management, including mechanical plants and operations, fire safety and security, elevators and escalators, structures and envelopes, and energy management. These services are provided to over 100 properties including office buildings, residential units, retail malls, and recreational facilities. Mr. Briggs has a B.S. degree in physics from Drexel University.

WILLIAM J. HALL is professor emeritus of civil engineering, University of Illinois at Urbana-Champaign and a consultant. He served on the faculty of the University of Illinois from 1954 to 1993; he was head of the Department of Civil Engineering from 1984 to 1991. His higher education includes the University of California at Berkeley, Kings Point, the University of Kansas at Lawrence where he received a B.S. degree, and the University of Illinois where he received an M.S. and Ph.D. degrees. In 1948–1949 he was an engineer with the Sohio Pipeline Co. At the University of Illinois he was engaged in instruction and research, with a specialty in structural engineering and structural dynamics and research emphasis on properties of steel materials, blast and shock, and earthquake engineering. Professional involvement with many large projects includes the Trans-Alaska Pipeline, nuclear power plants, many agencies of the federal government (defense—protective structures, missile systems, and nuclear materials), and with the National Research Council. He is an honorary member of the American Society of Civil Engineers and a member of National Academy of Engineering.

BRUCE HOFFMAN is Chair and Senior Lecturer at the Department of International Relations, St. Andrews University, Scotland, and director of the university's Centre for the Study of Terrorism and Political Violence. He was formerly a member of the senior research staff in The RAND Corporation's International

Policy Department, and Director of the Strategy and Doctrine Program in RAND's Army Research Division. He previously served as Associate Director of both that program as well as of the International Security and Defense Strategy Program in RAND's National Security Research Division. Dr. Hoffman holds degrees in government, history, and international relations and received his doctorate from Oxford University. He has taught at both Oxford University and the University of Buckingham. In November 1994 Dr. Hoffman received the U.S. Intelligence Community Award Seal Medallion, the highest level of commendation awarded to a non-U.S. government employee. The award recognizes sustained performance of high value which distinctly benefits the interests and national security of the United States.

THEODOR KRAUTHAMMER is professor of civil engineering at the Pennsylvania State University. He obtained B.Sc. and M.Sc. degrees in mechanical engineering from the Technion, Israel Institute of Technology, and a Ph.D in civil engineering from the University of Illinois at Urbana-Champaign. His research and technical activities are in the area of structural behavior under severe static and dynamic loads. His work includes the development of design recommendations for enhancing structural performance and safety and the evaluation of facilities following hazardous loading events. He is a member of national and international professional organizations and serves on 11 technical committees of the American Society of Civil Engineers, the American Concrete Institute, the National Research Council, and the Federal Highway Administration. He is the founding Chairman of the American Concrete Institute Committee 370 on Short Duration Dynamics and Vibratory Load Effects, and a member of the American Society of Civil Engineers Task Committee on Structural Design for Physical Security. Dr. Krauthammer has written over 180 research publications and has been invited to lecture on these publications in the United States and abroad. He has been a consultant to industries and governments worldwide.

WALTER P. MOORE JR. is the Thomas A. Bullock Endowed Chair for Leadership and Innovation in the departments of Civil Engineering and Architecture at Texas A&M University. He is also the Director of the Center for Building Design and Construction and the Center for Construction Education at Texas A&M. He is the Chairman of the Board of Walter P. Moore & Associates, a consulting engineering firm specializing in structural, civil, and traffic engineering, which is headquartered in Houston, Texas with branch offices in Dallas, Atlanta, and Tampa. He is a registered professional engineer in 24 states and a member of the National Academy of Engineering.

BARBARA A. MYERCHIN is a partner at Strategic Science and Technology Planners, a strategic planning, programming, and lab planning firm located in Arlington, Virginia. She has over 25 years of professional experience in the public and private sector including background and knowledge in construction of hardened military structures and U.S. embassies worldwide. She has first-hand experience in the planning and design of security systems, including the electronic security systems installed for the 1984 Olympics in Los Angeles. Ms. Myerchin received a B.S. in civil engineering from Tennessee Tech, and is a graduate of the Industrial College of the Armed Forces at Fort McNair. She is a registered professional engineer in Tennessee and Virginia, and a member of the Society of College and University Planners.

LESLIE E. ROBERTSON is Director of Design and Construction in the structural engineering firm of Leslie E. Robertson Associates, R.L.L.P. After receiving a B.S. degree from the University of California at Berkeley, he worked at Kaiser Engineering, John Blume & Associates, and Raymond International prior to establishing Leslie E. Robertson Associates, R.L.L.P. In addition to a B.S. degree, he has received four honorary doctorates. In 1994, Mr. Robertson was granted the license of First Class Architect and Professional Engineer in Japan, the only non-Japanese engineer so honored. His election to the National Academy of Engineering was in recognition of his expertise and contributions to the field of structural engineering. He has served on the National Research Council Committee on Research for the Security of Future U.S. Embassy Buildings.