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Protective design of concrete buildings under blast loading

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Abstract

Designing buildings to resist failure due to blast loads is an extremely complex procedure. It is a process that has been investigated for many years, yet it warrants further research. Several issues related to the design of concrete structures to survive blast loads are discussed in this paper. General design issues of "terrorist-proof" buildings show how the threat of harmful blasts is affecting the thought process in designing government and public buildings as well as international and high-visibility organizations. Understanding the loads produced by explosions is an integral part of dealing with blast-resistant design. Case studies of buildings subjected to blasts reveal how actual structures have handled the dynamic loads. Current research on the subject is also reviewed.

1 Introduction

With the recent increase in public awareness of possible terrorist attacks in the United States and worldwide, many organizations and agencies are currently trying to secure methods of constructing facilities that will survive blast loads due to explosions. Beginning during the era of World War I, the military took an interest in the ability of concrete structures to resist bomb blasts. Since World War II, the Department of Defense has funded many research and testing programs on reinforced concrete structures and elements under blast loading. During the 1960s, an extensive research program was funded by the department to develop criteria for the analysis and design of blast-resistant structures. A majority of the early academic research in the field of blast design was done at the University of Illinois at Urbana-Champaign and at the Massachusetts Institute of Technology. This resulted in the Tri-Services Manual designed by the Army as "TM 5-1300: Structures to Resist the Effects of Accidental Explosions," which was subsequently revised in 1990 [1]. This revision incorporates the research conducted over the

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intervening period. Volume 4 of the manual addresses reinforced concrete design.

2 Anti-terrorist design

In an effort to minimize the threat of terrorist attack on government and public buildings, architects, engineers, and planners are trying to establish guidelines for "anti-terrorist design." Recommendations range from general design issues to specific details. Before designing blast resistance into a structure, some evaluation needs to be done to determine the feasibility of such a design. This should include an estimate of what sorts of rational threats may be imposed on the building. The possible aggressors and their likely tactics should be considered. Once a plausible threat is determined, the associated structural loads of such an attack can be calculated [2].

The United States had already begun implementing anti-terrorist planning in the design of its foreign embassies. In the Fall of 1984, Congress passed a bill to spend over $350 million to "fortify" the posts. Through carefully designing new embassies and increasing security measures at others, the government began determining what makes a building safe from attack [3].

Typically, explosive blasts lose their intensity as they move away from their source. Therefore, where possible, the most common cost-effective approach to keeping buildings safe is to increase the standoff distance, i.e., to keep potential bombs away from the building. Careful site planning and design can help in this matter. One non-architectural item that helps the most in improving safety is increasing the number and quality of security personnel.

3 Considerations for blast-resistant design

The foremost concern for blast-resistant design is human casualties due to structural collapse. The sources of dynamic excitation in a building under blast and earthquake loads are totally different in nature because blast loading is fast, localized and occurs at a much greater frequency than earthquake loading. However, there are some shared goals. In general, structures should be ductile enough to absorb the forces of an explosion without collapsing. Another crucial element is the need for redundancy in structural design. Unlike seismic zones, however, buildings can resist blasts better with more mass. The energy of a blast is more easily absorbed by a more massive structure. This qualifies reinforced concrete to be the principal material of choice for blast-resistant design.

One of the leading causes of injury following an explosion is flying shards of glass. Nadis recommends keeping window coverage to no more than 15 percent of wall area between supporting columns [4]. Developments in laminated glass are producing stronger windows less prone to breaking into large pieces.

Due to the limited budgets of many construction projects, the additional costs of buildings for providing blast resistance may apparently seem prohibitive. However, the average cost of designing for blast resistance in new structures is far less expensive than the cost to retrofit an existing structure to similar standards.

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3.1 Blast load sources

An explosive blast produces waves in the air and the ground, creating "shock waves" and "ground waves." The principal damage mechanism of an explosion is a supersonic shock wave that propagates radially from the blast source like a bubble. This imposes high-intensity, short-duration pressures on all surfaces in its path. This article primarily deals with air-transmitted shock waves producing the primary force associated with blasts. For explosions which occur at or near the ground surface, ground waves also occur and are treated similar to seismic waves. As shown in Fig. 1, materials exposed to blast loads experience very high rates of strain [5].

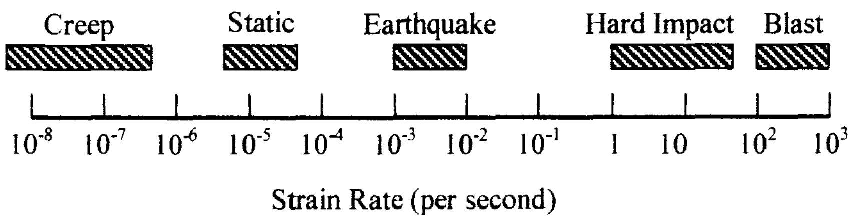

Fig. 1: A comparison of strain rates due to various types of stresses [5]

Various sources exist for explosions. These may occur inside or outside a structure, and may occur close to a structural element, or at a significant distance. These factors all change the way a blast affects the structure. In the most recent terrorist attack on the World Trade Center (WTC), jet fuel was the cause of the initial explosion. Generalizations about blast loading are therefore not only difficult to make, but may be misleading.

Blast sources are commonly categorized as low explosives (LE) and high explosives (HE). LE blasts are usually due to the accumulation of flammable gas/air mixtures. HE blasts are typically due to the detonation of chemical ammunitions. This category includes car bombs and military ammunition. As this type of blast is of more concern to the military, it is the type more focused in publications and will be treated in this paper.

4 Quantifying blast loads

The amount of energy released by an explosion is related to the type of the explosive device used. Because there are so many possible sources of explosions, it is helpful to have a standard measure by which various explosions might be compared. To this end, trinitrotoluene (TNT) has become the standard measure of a blast force. Tests have been performed to translate amounts of commonly used explosives into equivalent weights of TNT.

To translate test data of blasts for specific distances into information useful for other scenarios, a simple "cube root" scaling law is often employed. This sets a scaled distance Z as:

$$Z = (R/W)^{1/3} \qquad (1)$$

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where R is the distance of the test location from the center of gravity of the weapon in feet and W is the weight of the blast in pounds. In his analysis of blast damage due to Scud Missiles in Riyadh, Saudi Arabia, Amjad [6] uses cube root scaling in eqn (1) to equate the effects of an explosion of a given weight W at a given distance R to an equivalent weight W_2 at another given distance R_2 such that:

$$(R/W)^{1/3} = (R_2/W_2)^{1/3} \tag{2}$$

An additional important quantity is the impulse I. Engineers often use a linearly decaying curve with the same impulse content as the actual loading to simulate the actual pressure that decays exponentially with time. The duration of this equivalent loading, t_d, can be expressed as:

$$t_d = 2I/P \tag{3}$$

where P is the pressure which is roughly proportional to W, and inversely proportional to R, i.e.,

$$P = W/R^3 \tag{4}$$

Eqn (4) underlines the fact that for protection against external explosions, vehicles must be as far away from the building as possible.

5 Design approach for blast loads

While a definitive code on designing civilian structures to resist blast loads is yet to be written, there is military literature that is applicable. Since the early research on designing structures for atomic blasts after World War II, the branches of the military have put together design information for their employees and consultants in reports such as: "Principles and Practices for Design of Hardened Structures" [7], "Structures to Resist the Effects of Accidental Explosions," or TM 5-1300 [1] and "Protective Construction Design Manual" [8]. A typical design for blast loads begins with a preliminary design based on proportions required for service loads. From this, the fundamental period of the structure is determined. To calculate equivalent static loads on the structure, one needs to determine the peak pressure from the blast and multiply it by a dynamic load factor, which is a function of the period, load duration, and pressure impulse shape. This process is usually repeated two or more times until a design of consistent results is found.

For the static analysis procedures, the standard ACI strength design equations are employed, substituting the dynamic stresses for the static ones. As shown in Table 1, these are obtained by multiplying the static values by the dynamic increase factor (DIF). The most common approach for dynamic analysis of simple structures is to model the element or system being analyzed as a simplified single degree-of-freedom system.

The calculation of ultimate dynamic strength in flexural members is dependent upon the anticipated performance of the members. TM 5-1300 establishes three types of behavior: 1) the concrete cover is effective in resisting moment on both sides of the reinforcing (top and bottom) and it remains intact; 2) the concrete crushes but remains intact, and the steel has to handle the moments; and 3) the concrete cover disengages from both faces and the proper selection of ties becomes crucial in confining the steel. Also, it is suggested that structures

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depending on the strength of shear walls to transmit horizontal loads to the foundation is the best way to resist blast loads. Rigid frames are assumed to be not always dependable under such loads. Even though the slab and beams act together to resist loads, they are analyzed as separate objects in the dynamic analysis. Column design also follows the assumption of a shear wall system

Table 1: Dynamic increase factors in reinforced concrete [1]

TYPE OF STRESS	FAR DESIGN RANGE			CLOSE-IN DESIGN RANGE		
	Reinforcing Bars		Concrete	Reinforcing Bars		Concrete
	f_{dy}/f_y	f_{du}/f_u	f'_{dc}/f	f_{dy}/f_y	f_{du}/f_u	f'_{dc}/f
Bending	1.17	1.05	1.19	1.23	1.05	1.25
Diagonal Tension	1.00	—	1.00	...1.10	1.00	1.00
Direct Shear	1.10	1.00	1.10	1.10	1.00	1.10
Bond	1.17	1.05	1.00	1.23	1.05	1.00
Compression	1.10	---	1.12	1.13	---	1.16

being employed. Interior columns are considered to carry no lateral loads. On the perimeter of the building, shear walls are assumed to pick up the axial loads. Exterior columns, therefore, are assumed to act as vertical flexural elements, taking none of the axial load. This is considered a conservative simplification.

TM 5-1300 includes a few general recommendations for reinforced concrete design:

- Don't use below 4000 psi (28 MPa) concrete in order to handle the high magnitudes of blast loads.
- Limit aggregate size to a 1 in. (25.4 mm) diameter to minimize spalling effects. For laced elements, a slump larger than that normally allowed is recommended, i.e., 4-6 in. (102-152 mm).
- ASTM A 615, Grade 60 steel should be used.
- Slabs must be reinforced in perpendicular directions.
- Reinforcement should be continuous in any required direction. Since this is not possible for long spans, use the longest bar available and provide splices in the lowest stress areas.
- Bar size should range from #4-14 bars. #18 bars are too brittle to act properly under blast loads. Use less than #14 bars for splices.

6 Case studies

In the following section, a few of the more recent well-known explosions that

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damaged concrete buildings are briefly discussed.

6.1 Murrah Federal Building

On August 19, 1996, the Alfred P. Murrah Federal Building (Fig. 2) in downtown Oklahoma City became the site of the worst terrorist attack ever carried out on U.S. soil before the September 11, 2001 attack on the WTC. The explosion of a car bomb in front of the office building designed in 1974 brought down sections of each story in a progressive collapse that killed 168 people and injured over 500. While the collapse was initiated by the blast, the severity of the total damage is

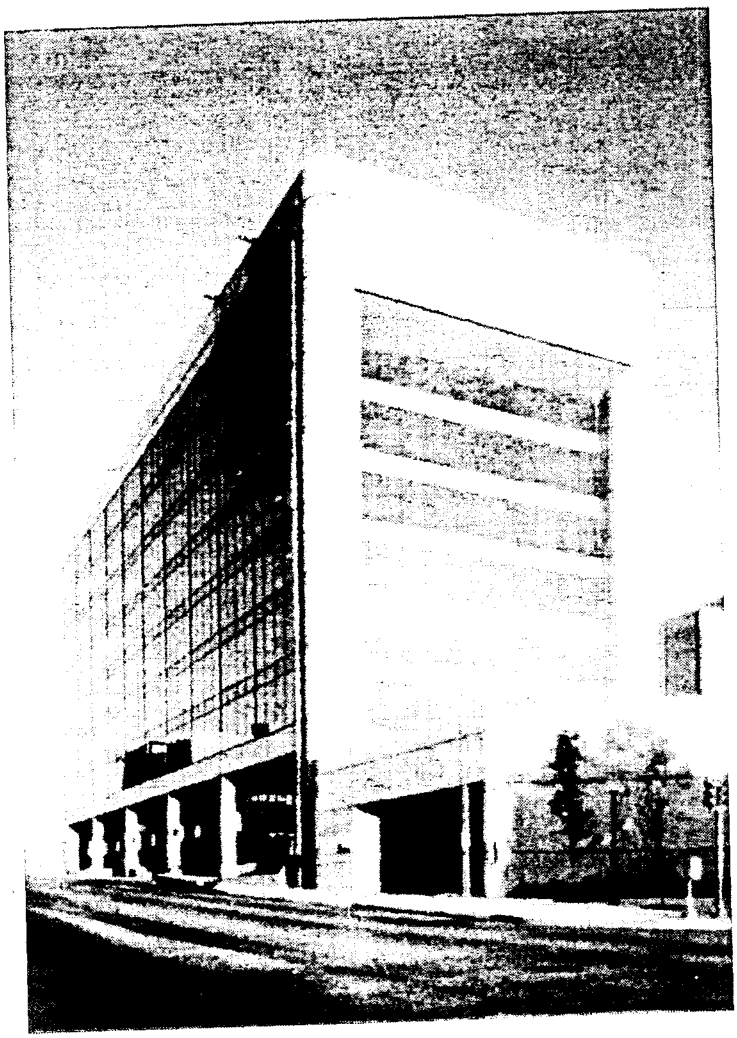

Fig. 2: A view of the Murrah Federal Building prior to explosion [2]

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believed to be due in part to the building's design [2]. The design of the building met all of the applicable building codes for office buildings at the time. Along the north exterior wall, a third-story transfer girder carried loads from the nine columns above and was supported by four columns below. Below the transfer beam, the facade stepped back to create a covered area for the entry. In all, roughly one-half of the building's occupiable space collapsed (Fig. 3).

Following the blast, the Federal Emergency Management Agency (FEMA) put together a team of investigating engineers who put together a report on their findings [2]. The findings emphasized the importance of redundancy in structures. Transfer girders should be avoided at lower floors. Also, they recommended designing to incorporate Special Moment Resistant Frame details.

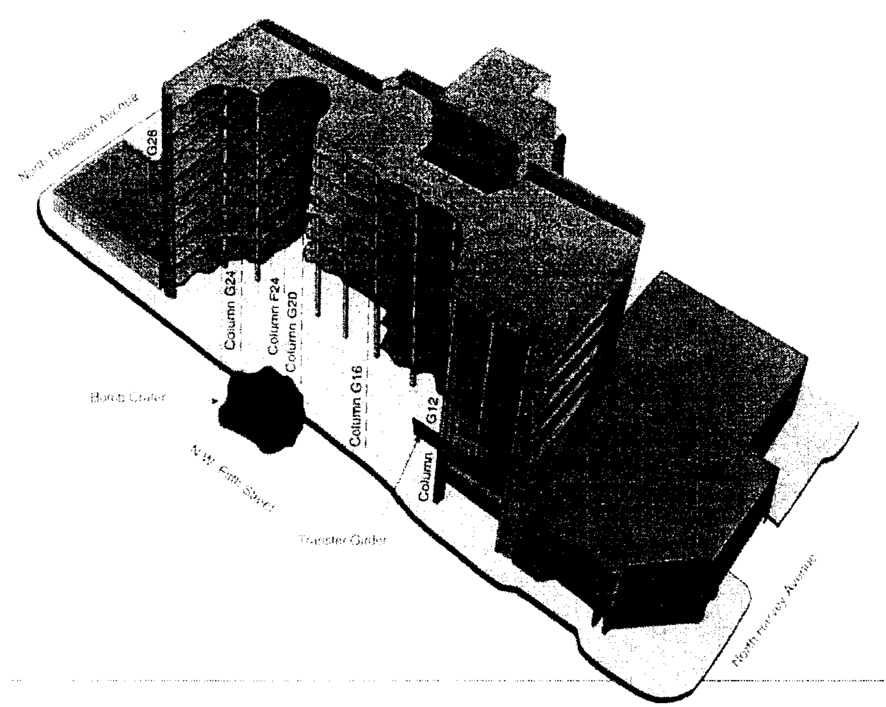

Fig. 3: Post-blast structure of the Murrah Federal Building [2]

It was hypothesized that if this had been incorporated into the design, approximately 50 to 80 percent of the losses could have been avoided. Even though certain elements would have failed, the additional steel would have held together some critical elements, at least long enough for the occupants to be safely evacuated from the building.

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6.2 Missile attack during the Gulf War

A paper by Amjad [6] examined the structural response of buildings in Riyadh, Saudi Arabia, to Scud missile attacks during the Gulf War. The structures affected were primarily two- to five-story reinforced concrete frames. By code, buildings in this region need only be designed for gravity and wind loads. Saudi Arabia is considered a non-earthquake region. In general, the author found the structural damage to be similar to that found following earthquakes.

Because of the rapid drop-off rate in blast loading, the amount of damage found in a structure was proportional to its distance from the source of the explosion. Using cube root scaling, for a charge load of about 185 lb. (83 kg) assumed for the missiles, it was found that an explosion occurring 984 feet (300 m) away, the structure would experience 0.08 psi (550 Pa) of peak incident pressure and 0.20 psi (1378 Pa) of peak reflected pressure. This is almost the same pressure that would be due to the wind loads for which the building was designed. At the other end of the spectrum, a blast at only 33 feet (10 m) away would produce 40 psi (276 kPa) peak incident pressure and 150 psi (1034 kPa) peak reflected pressure. This is a 750% increase in pressure above the design loads. This could easily result in the total collapse of a building's structure.

6.3 Air Force base in Dhahran

In another incident overseas, 19 American servicemen were killed by an explosion at the perimeter of an Air Force base in Dhahran, Saudi Arabia. Even though the car bomb went off outside base limits, it was strong enough to bring down the facade of the nearest reinforced concrete apartment building. Several other buildings suffered serious damage due to the blast. Had it not been for alert security personnel, the death toll would have been much higher. Many people were able to get to a safe location before the blast after they were forewarned by the guards who saw the truck and the drivers [9].

7 Current research

There is research currently being done to help engineers understand the complexities of the topic and to provide further insight into how the material reacts to these highly dynamic and impact-type loads. One recent article summarized the results of tests done on concrete slabs under high dynamic loads [10]. The authors of this article sought to analyze the effects of variations in free water content, porosity, and reinforcement on a structure's ability to resist blast loads. To obtain data, they used a long "shock tube" to transmit blast waves to sample slab sections. It was found that in reinforced concrete slab samples, the ultimate load capacities under dynamic loading were on the order of 22-27% higher than the ultimate static capacities.

Another consideration is the possible effects of spalling. Spalling is the result of high intensity blast pressures disengaging the concrete cover over flexural

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reinforcement, which subsequently weakens the structure. In a 1988 landmark, unclassified report "Spall Damage of Concrete Structures" by the U.S. Army Waterways Experiment Station, data from 374 spall tests were presented and were then used to develop improved empirical prediction curves for spalling that have been widely used to design concrete members to prevent spalling under blast loads. Research by Nash et al. [11] has tried to develop a numerical model for predicting spall damage for close-in explosions.

An engineering study on bomb vulnerability of flat slab construction based on full-scale blast tests was carried out by the Defense Threat Reduction Agency (DTRA) at White Sands, New Mexico [12]. DTRA also tested several types of window glass for blast resistance and internal wall debris "catch" systems that employ high-strength fabrics. Engineers from Weidlinger Associates in New York have studied blast vulnerability for about 50 years and have authored the U.S. State Department's "Engineering Guidelines for New Embassy Office Buildings" [12]. Hinman has reported design approaches for window protection under blast loads [13]. Window design is often in the domain of architects and subcontractors. For blast-resistant design of buildings, however, it becomes a part of structural design.

In the line of computer advancements, Lorron Corporation of Burlington, Massachusetts, has put together a software program, BOMBCAD, devoted to analyzing a building's structural system for susceptibility to bomb damage. The program is intended to help designers analyze the effectiveness of their designs to resist bomb damage. By entering the required information, the program can construct an analytical model of the structural response to a bomb detonation placed at any given location. It also shows graphically what happens by using three-dimensional CAD technologies [14].

Conclusion

This paper has reviewed the design concepts and process for blast-resistant design of concrete structures. For the design process of concrete members to resist blast loads, the formulas used are similar to those in the ACI code for strength design. In addition, limit-state analysis and design should be performed to ensure that connections perform as desired. One of the most important things to strive for is a ductile design and allowing for redundancy similar to earthquake-resistant design, a fact that should be recognized and explored by designers of new structures under blast loading.

It is possible to identify structural systems that could provide substantial increase in protection against blasts [15]. Compartmentalized construction, in which a large portion of the building has structural walls that are adequately reinforced to provide structural integrity in a damaged building, can reduce progressive collapse. Other systems offering toughness and ductility are Special Moment Frames and Dual Systems that are used in areas of high seismic activity. Close spacing of columns at the lower levels is also helpful. Transfer girders at these levels should be avoided. Blast-resistant glass should always be used for windows. Also, the stand-off distance of the building should be maximized. For

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retrofitting existing buildings, many of the seismic upgrading techniques are applicable although additional considerations are required for blast loads, that are fast, localized, and occur at a higher frequency. The columns may be wrapped with carbon fiber reinforced sheets.

With escalating socio-political unrest in the United States and worldwide, blast-resistant design should be considered for buildings of strategic interest or political sensitivity. More specific code provisions offering specific guidelines to designers of civilian buildings will be very useful. As a current topic of general concern and interest in the engineering community following the WTC collapse, further information is sure to be on its way concerning the design of buildings to resist blast loads.

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References

[1] Joint Departments of the Army, the Navy, and the Air Force, *Structures to Resist the Effects of Accidental Explosions*, TM 5-1300/NAVFAC P-397/AFR 88-22, November, 1990.

[2] Federal Emergency Management Agency (FEMA-277), *The Oklahoma City Bombing: Improving Building Performance Through Multi-Hazard Mitigation*, American Society of Civil Engineers, August, 1996.

[3] Embassies move to combat terrorist attacks, *ENR News*, McGraw-Hill, January 3, 1985.

[4] Nadis, S., Bomb stoppers, *Popular Science*, January 1996, V248, pp. 58-59.

[5] Bischoff, P. H. and Perry, S. H., Compressive behaviour of concrete at high strain rates, *Materials and Structures*, Vol. 24, 1991, pp. 425-450.

[6] Amjad, M. A., Performance of building structures affected by scud missile attacks in Riyadh, *Magazine of Concrete Research*, Vol. 45, No. 165, December 1993, pp. 241-246.

[7] Newmark, N. M. and the Department of Civil Engineering, University of Illinois, Urbana, *Air Force Design Manual: Principles and Practices for Design of Hardened Structures*, TDR 62-138, Air Force Special Weapons Center, Kirkland Air Force Base, New Mexico, December 1962.

[8] Drake, J. L., Twisdale, L. A., et al., *Protective Construction Design Manual*, TR-87-57, Air Force Engineering & Services Center, Tyndall Air Force Base, Florida, November 1989.

Paper from: *Structures Under Shock and Impact VII*, N Jones, CA Brebbia and AM Rajendran (Editors).
ISBN 1-85312-911-9

[9] Dickey, C., Target America, *Newsweek*, July 8, 1996, v. 128, pp. 22-26.

[10] Toutlemonde, F., Rossi, P., et al., Dynamic behaviour of concrete: tests of slabs with a shock tube, *Materials and Structures*, June 1995, v. 28, pp. 293-298.

[11] Nash, P. T., Vallabhan, C.V.G., and Knight, T. C., Spall damage to concrete walls from close-in cased and uncased explosions in air, *ACI Structural Journal*, Nov.-Dec. 1995, pp. 680-688.

[12] Engineers study bomb vulnerability of flat-slab construction, *Civil Engineering*, American Society of Civil Engineers, p. 22, August, 1998.

[13] Hinman, E. E., Blast-mitigating window design, *Structural Engineer*, pp. 42-47, November, 2000.

[14] Massa, R., personal communication with Eric Friedman, November 18, 1996.

[15] Corley, W. G., Can structural engineering reduce loss from malevolent bombings?, *Structure*, National Council of Structural Engineers Association, Chicago, Illinois, pp. 12-17, Fall, 1997.