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Building Vulnerability Design Against Terrorist Attacks

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1. Introduction

Attacks against buildings using a stationary or moving vehicle laden with large amount of explosive have become the weapon of choice by some terrorist groups. Structural engineers today face a new challenge and require methods and guidance on how to design structures to resist various hostile acts.

Table 1 summarises some recent terrorist attacks on civilian buildings with bombs of variable magnitudes and their methods of delivery. The devastating attack against the Alfred P. Murrah Federal Building in Oklahoma City in April 1995, the collapse of both WTC Towers in New York in September 2001, the tragic events in Bali in October 2002, and the most recent bombing of the Australian Embassy in Jakarta in September 2004 have underscored the attractiveness and vulnerability of civilian buildings as terrorist targets. These attacks have also demonstrated that modern terrorism should not be regarded as something that could happen elsewhere. Any nation can no longer believe themselves immune to terrorist violence within their own borders. The fact is that the majority of government and civilian buildings continue to be vulnerable to terrorist attacks.

Date	**Site location**	**Method of delivery**	**Approx. Charge Weight (TNT equivalent)**
September, 2004	Australian Embassy, Jakarta, Indonesia	Moving van loaded with HE	150 kg
November, 2003	HSBC Bank, Istanbul, Turkey	Moving vehicle	150 kg
May, 2003	Housing Compounds, Riyadh, Saudi Arabia	Three cars loaded with HE	Not available
October, 2002	Sari Club Bombing, Bali, Indonesia	Car bomb in front of building	1 kg TNT + 100 kg fertilizer
December, 2002	Parliament House, Chechnya, Russian Federation	Two moving trucks loaded with HE	2000 kg
June, 1996	US Military Complex, The Khobar Towers, Saudi Arabia	Truck bomb	2000 kg
April, 1995	Murrah Building, Oklahoma City, USA	Stationary truck in front of building	1800 kg

Table 1. Selected recent terrorist attacks with high explosives

This paper aims to introduce concepts that can help structural engineers and building owners mitigate the threat of hazards associated with terrorist attacks on new and existing buildings. While the issue of blast-hardening of structures has been an active topic with the military services, the relevant design documents are restricted to official use only. A very limited body of design documentation exists currently to provide engineers with the technical data necessary to design civil structures for enhanced physical security. The professional skills required to provide blast resistant consulting services include structural dynamics, knowledge of the physical properties of explosive detonations and general knowledge of physical security practices.

Designing security into a building requires a complex series of trade-offs. Physical security measures need to be balanced with many other design requirements such as fire protection, energy efficiency, natural hazard mitigation, accessibility, and aesthetics. Because the probability of terrorist attack against a specific target building is very small, security measures should not interfere with daily operations of the building. On the other hand, because the effects of terrorist attack could be catastrophic, it is prudent to incorporate measures that may save lives and minimise business interruption in the unlikely event of an attack. Security design measures should be part of an overall multi-hazard approach to ensure that the building behaviour in the far more likely event of a fire, earthquake, or hurricane, is not worsened by the introduction of the security specific measures.

The primary objective of protecting office buildings against terrorist attack is to save lives with the focus on a damage-limiting or damage-mitigating approach rather than a blast-resistant approach. This can be achieved by incorporating some reasonable measures that will enhance the life safety of the persons inside the building and facilitate rescue efforts in the unlikely event of terrorist attack. Structurally this could be accomplished by preventing catastrophic collapse of the building to reduce the number of building occupants that become trapped under the structural debris. Maintaining structural integrity of the building can also help protect occupants from the flying debris and air-blast pressure of an explosion.

Better understanding what an explosion is and what it can do to a building are necessary for developing physical security measures which are effective in mitigating the effects of a terrorist attack. This paper reviews the general properties of a bomb blast, the concept of defence in depth for an urban planning layout, the blast barriers, and preventing progressive collapse of a structure. This paper will also discuss current state-of-the-art methods to enhance protection of the building by incorporating low-cost measures into new buildings at the early stages of design.

2. Explosion effects

An explosion is the rapid release of stored energy. This energy is released in part as thermal radiation; the rest manifesting as shock waves that are combinations of air blast and ground shock. The air blast is the main damage mechanism. Air blast has a primary effect, which is an ambient over-pressure or incident pressure, and a secondary effect, which is the dynamic pressure or drag load. The first effect is caused by the air blast that propagates at supersonic velocity, and compresses air molecules in its path. As the shock wave encounters a rigid object (e.g. a building wall), it is reflected thus amplifying the over-pressure by some significant factor between two and up to thirteen. The air blast enters the building through wall openings and failed doors and windows, affecting floor slabs, partitions, and content within the building. The shock waves undergo diffraction as they interact with various surfaces, thus increasing or decreasing in pressure. Eventually, the air blast subjects the entire building to over-pressure.

The pressures decay exponentially in time and with radial distance from the epicentre, measured typically in several milliseconds. Diffraction effects, caused by building features such as re-entrant corners may act to confine the air blast, prolonging its duration. Eventually, the shock wave becomes negative, creating suction forces. Following the vacuum, air rushes in, creating dynamic pressure or drag loading which manifests as a high velocity wind that propels debris generated by the blast. In case of an external explosion, a portion of the energy is also imparted to the ground, creating a crater and generating the ground shock that produces motions similar to high-intensity, short-duration earthquake. Figure 1 illustrates the parameters of a typical blast wave.

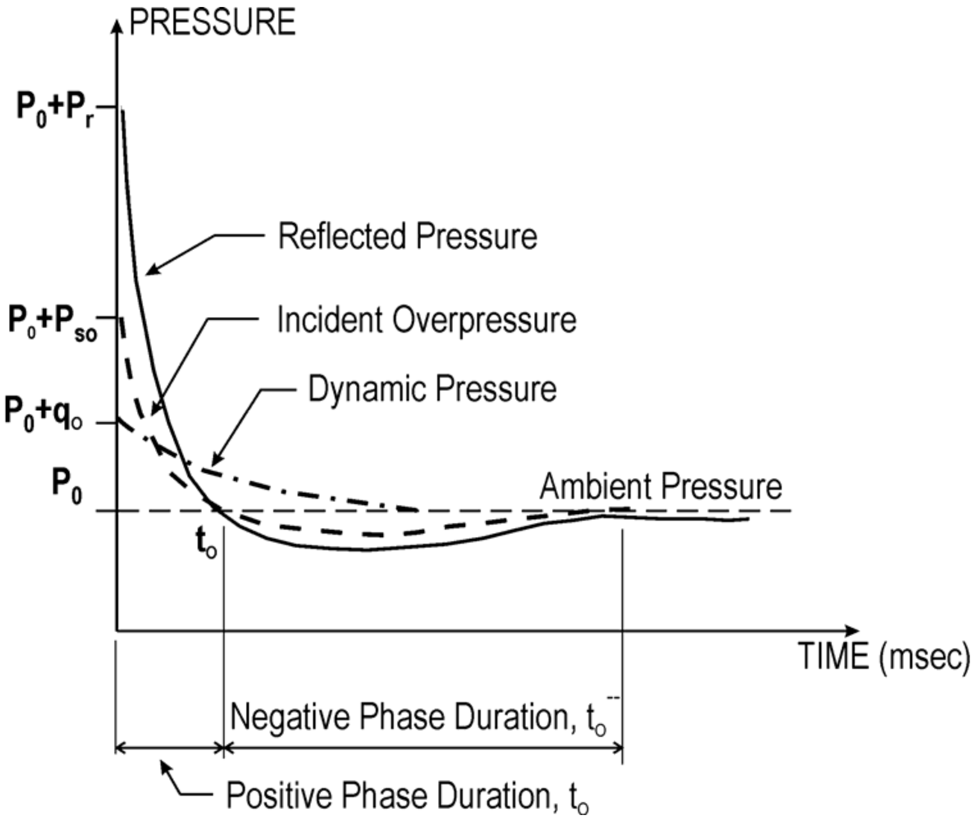

Figure 1 Air-blast pressure time history and blast wave parameters

The following effects are characterised from a blast wave (see Figure 1):

- Magnitude of the overpressure or the peak pressure during the over-pressure phase of the blast wave (P_{so} is the peak incident overpressure; and P_r is the peak reflected over-pressure).
- Impulse or duration of the over-pressure. Impulse is the area under the over-pressure time history curve. Positive phase duration, t_0, measures how long the over-pressure phase of the blast wave lasts.
- Shape of the over-pressure pulse. Military high explosives will typically have a very high shock value with near-zero rise-time, which then decays rapidly.

The peak blast pressure is a function of the weapon size and the cube of the distance called the standoff. For an explosive threat defined by its charge weight and standoff, the peak incident and reflected pressures and other blast wave parameters such as the incident and reflected impulse are evaluated using charts available in military technical manuals or using specialised computer programs such as CONWEP (Hyde, 1992).

2.1 Equivalent explosive weight

The charge weight of the explosive is typically measured in the net equivalent weight of TNT, as TNT is used as the standard explosive in assessing blast effects. The most common home-made type of explosive is fertiliser-fuel mixture or Ammonia Nitrate Fuel Oil (ANFO). ANFO’s average equivalent weight factor to TNT is 0.82, or 82 percent the blasting power by equivalent weight in TNT. Typical defensive design is for a vehicle laden with anywhere from 25kg to 2000kg of explosive. For reference the explosive weight of the standard hand grenade has about 0.3-0.4kg and the average sized ordnance deployed by aircraft during operation Desert Storm was about 500kg “bunker busters”.

2.2 Blast loading

The key aspect of structural design to resist blast effects and progressive collapse is determining the nature and magnitude of the blast loading. This involves assessing the amount and type of explosive, as well as its distance from the building. Another factor is the level of security that can be placed around and within the building. The blast threat may include a package bomb, a suitcase bomb, vehicle-borne bomb, or some other means of delivery. The type of explosive is an important factor because all explosives behave differently. Moreover, some types of explosives are easier to obtain than others.

The overall effect of an explosion may be quantified by its charge weight, *W*, measured in equivalent weight of TNT, and its distance from the building, or the standoff, *R*. The peak pressure is a function of distance *R* divided by the cube root of the charge weight *W*. This is commonly called and expressed as Scaled Distance = $R / W^{1/3}$. Another way of viewing scaled distance and pressure relationship is by Peak Pressure ~ W / R^3. This means that by doubling the standoff the incident pressure is reduced by a factor of eight for a given weapon. This gives an indication of how the damage to a building can be mitigated most effectively: keep large weapons as far from the building as we possibly can.

Figure 2 illustrates the above relationship between explosive weight and standoff distance with four incident pressure curves (5.0, 10.0, 20.0, 50.0 kPa). By entering the x-axis with the estimated weight of explosive and the y-axis with a known standoff distance, the resultant effects of overpressure could be determined. The vehicle symbols at the top of Figure 2 display the relative size of the vehicle that might be used to deliver various quantities of explosives.

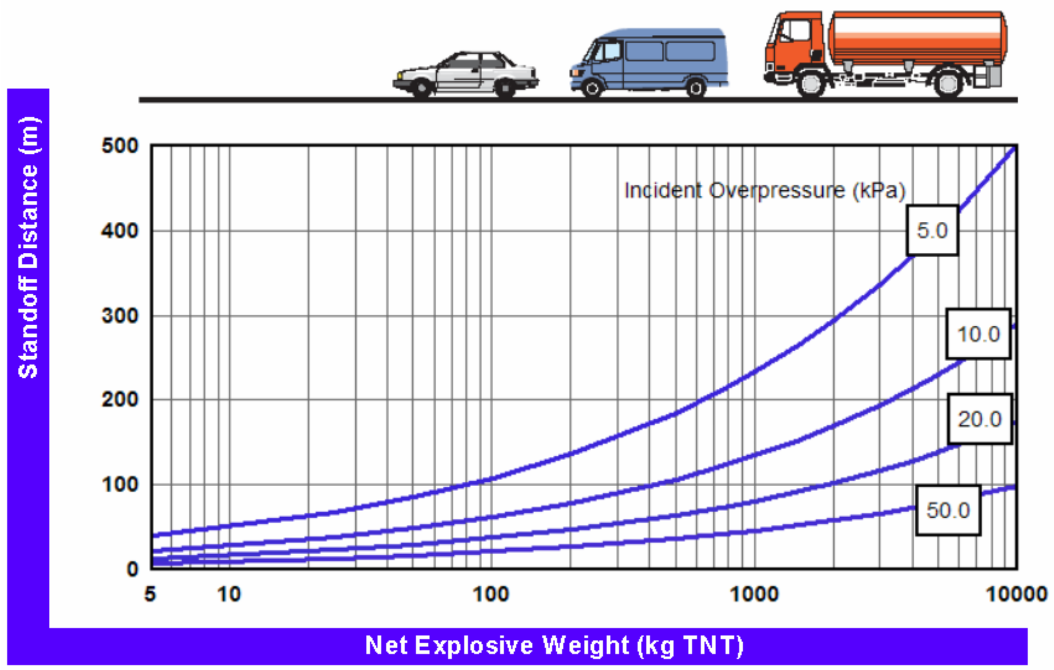

Figure 2 Incident pressure as a function of distance and explosive weight

2.2.1 Example: blast load on building facade

In this sample problem, an explosive device consists of 100 kg TNT and is located in a street 15 metres from a single office block. The blast load will be assessed in application to a double glazed unit 1.5m wide by 2m high with its centre 12m above the ground. It is required to determine peak reflected overpressure and reflected impulse for a point of interest on front elevation of office block (see Figure 3).

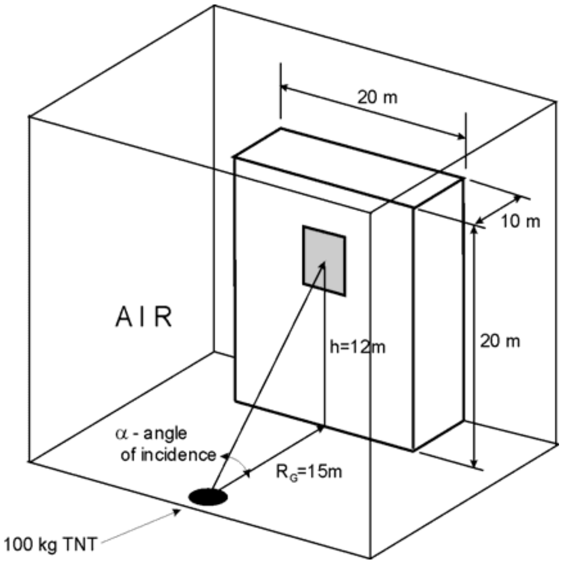

Figure 3 Geometry of an office block used for 3-D numerical simulation.

Step 1. Charge weight W = 100 kg of TNT (hemispherical charge), h = 12m, and R_G = 15m.
Step 2. For the point of interest:

$$R_h = \left(15^2 + 12^2\right)^{1/2} = 19.2 \text{ m}$$

$$Z_h = \frac{R_h}{W^{1/3}} = \frac{19.2}{100^{1/3}} = 4.1 \ \frac{\text{m}}{\text{kg}^{1/3}} > Z_{\min} = 1.2 \ \frac{\text{m}}{\text{kg}^{1/3}}$$

$$\alpha = \tan^{-1}\left[\frac{h}{R_G}\right] = \tan^{-1}\left[\frac{12}{15}\right] = 39\,\text{deg} < 45\,\text{deg}$$

Step 3. Determine reflected blast wave parameters for Z_h = 4.1 m/kg$^{1/3}$. From TM5-1300 (US Army, 1991):

P_r = 146 kPa
$i_r/W^{1/3}$= 154 kPa-msec/kg$^{1/3}$; i_r = 154x(100)$^{1/3}$ = 715 kPa-msec
$t_0/W^{1/3}$ = 4.05 msec/kg$^{1/3}$; t_0 = 4.05x(100)$^{1/3}$ = 18.7 msec

If the peak load on a glazing unit is required for design purposes, the panel load is calculated as:

Load = 146kPa x 1.5m x 2.0m = 438 kN
Impulse = 715 kPa-msec x (1.5m x 2.0m) = 2145 kN-msec

2.3 Predicting damage to a building

Airblast pressures are usually several orders of magnitude greater than the loads for which the building is designed. Fortunately, these only act for a fraction of a second on the building. It is because of the short duration of the loading that is possible to design structures to withstand blast loads. The extent and severity of damage and injuries in an explosive event cannot be predicted with high degree of certainty. Past events show that the overall level of damage can be influenced by the specific type of construction, the arrangement of buildings and their heights, the size of the structure, the presence of fragment loading, and other factors. Despite these uncertainties, it is possible to predict the expected extent of damage for a specific explosive event based on the size of the explosive device, distance from the explosion, and information about the construction type of the building. In addition, the extent of injuries can be correlated with the structural damage patterns. Certain types of construction are highly blast resistant while some others are not. Damage is prevalent for wood construction even at large standoff distances, which is due to the inherent fragility of wood components to explosions. Conversely, reinforced concrete frames offer a high level of blast resistance, even though some infill panels between structural columns may be destroyed. The size of the structure relative to the bomb size is a significant factor in the amount of damage inflicted. A small, strong masonry building may withstand damage better that a large, two-storey, lightly reinforced concrete building.

Damage to various building types can be calculated based on computer simulations and existing blast damage assessment tools such as P-I diagrams for various structural elements (FACEDAP, 1994). One example of blast damage prediction for a typical steel pre-engineered building is given in Table 2 (UG-2031-SHR, 1998).

Charge Weight (kg)	Distance for Specified Damage and Injury (m)				
	Minimal	**Minor**	**Moderate**	**Heavy**	**Severe**
25	**26**	**21**	**16**	**11**	**6**
100	**50**	**40**	**31**	**25**	**16**
225	**76**	**61**	**50**	**40**	**27**
450	**116**	**90**	**70**	**59**	**44**
1,800	**238**	**189**	**143**	**122**	**91**
18,000	**747**	**625**	**433**	**372**	**229**

Table 2. Pre-engineered Steel Building (one-storey, pre-engineered steel, 6 metres by 24 metres, steel frames at 6 metres, corrugated steel roof on purlins).

3. Methodology for protective design of buildings

The methods for protecting buildings against explosions have been in existence for several decades. The design guidelines have been produced, particularly for high-risk projects such as military facilities and embassies. In response to a potential threat of terrorist bombing attacks and following the events of September 11, 2001, the private sector has became increasingly interested to examine whether design methodologies and construction techniques developed for military purposes could be beneficially applied to civilian structures.

Many of the existing buildings have been designed and built with minimum consideration of protection against explosions. It is also unlikely that the building codes will fully incorporate blast resistant design requirements in the near future. Without change of policy and greater awareness among the engineering profession, new buildings will be designed and constructed in a similar fashion.

It is agreed that the most effective way to protect a building against blast loads is to stop the attack before it occurs. If the attack does occur, the measures must be employed to ensure that the threat from explosions has minimal effect. This may be achieved by the implementation of a series of redundant physical and operational security measures as well as through achieving protection during the design stage. Considerations should be given how to:

- Minimise the likelihood and magnitude of attack by making the building an unappealing target.
- Prevent catastrophic collapse of the building to save lives; the collapse is inevitable but must be local.
- Protect the people and assets from the primary and secondary effects of explosion (air-blast pressure, flying debris, etc).
- Provide shelter to the occupants of the building during an explosion and facilitate rescue and evacuation efforts.
- Enable rescue and repair efforts to be performed after an attack.

A flowchart showing the methodology for protecting buildings against explosions is shown in Figure 4. The flowchart presents the sequence of activities such that an effective approach for protecting people, property and the business can be achieved.

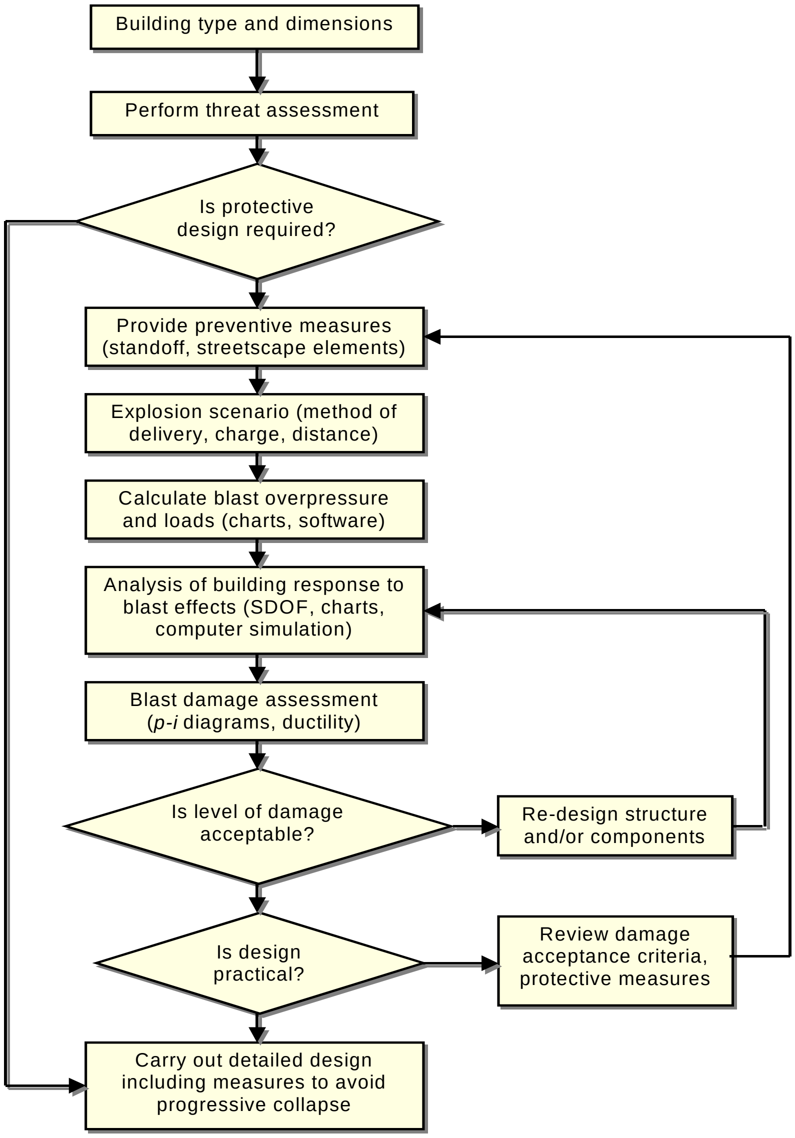

Figure 4 Flowchart of the methodology for protective design of buildings

3.1 Protective measures for buildings – defence in depth

Defence in depth is to provide several layers that attackers must breach before reaching the protected facility. The concept is similar to peeling away successive layers of an onion to reach the centre. The use of standoff distance as a defensive tool may be the most cost effective option, since shock wave pressure decreases by a factor of 8, each time the standoff distance is doubled. To create a protected space for the critical facilities, barriers will need to be erected to form a perimeter. Entry into the protected area will be through controlled entry points. The main focus will be to limit the vehicular traffic in and out of the protected area.

Orientation and building layout is also key in defence in depth. Two defensive issues should be addressed: (a) denying the attackers a straight or direct route to the critical structure; and (b) denying the attackers a clear line of sight to the critical structure. The first issue can be achieved by building routes that require vehicles to reduce their speed or prevent acceleration and therefore preventing use of their vehicle as ram. This can be accomplished with multiple turns or points where vehicles must stop.

3.1.1 Maximise standoff distance

Maximising the standoff distance keeps the threat as far away from critical buildings as possible. It is the easiest and least costly method for achieving the appropriate level of protection to a critical structure. Many times, vulnerable buildings are located in urban areas where site conditions are tight. When standoff distance is not available, the structure needs to be hardened to give the same level of protection that it would have with a greater standoff. The best way to increase the distance between a potential bomb and the critical building is to provide a continuous line of security along the perimeter of the facility to keep all vehicles as far away from critical assets as possible. The area within the standoff distance can be further partitioned (see Figure 5). The exclusive standoff zone provides a higher level of protection. Using the concept that vehicles are able to carry significantly more explosives than a person with a hand carry packages, the exclusive zone would be limited to pedestrian traffic only. The non-exclusive zone standoff zone would permit entry and parking of cars and trucks, after an initial search at an earlier entry control point.

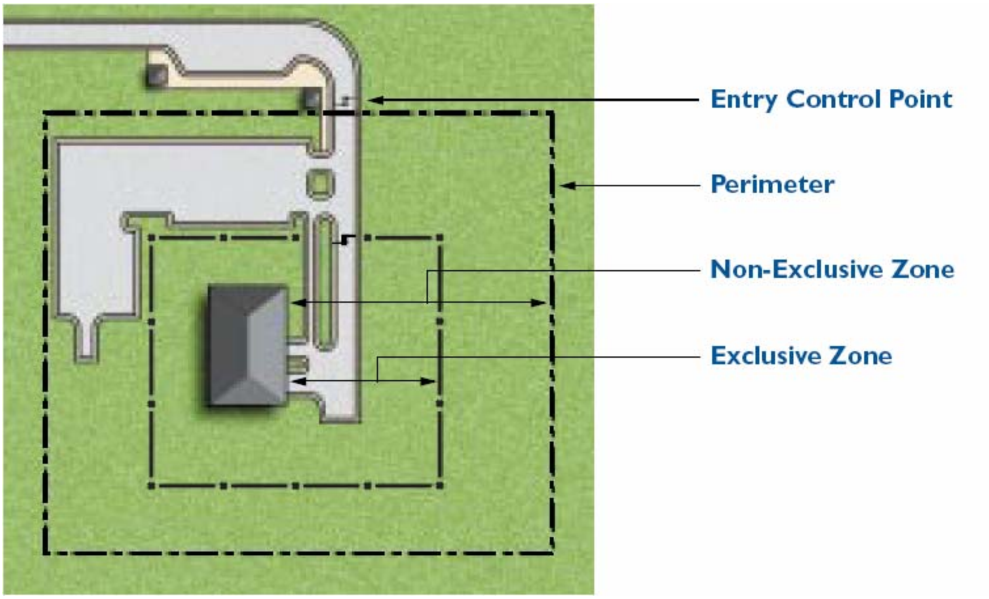

Figure 5 Exclusive and non-exclusive standoff zones (US Air Force, 1996)

The U.S. Department of Defence minimum standard for effective standoff distance for primary gathering buildings is 25 metres away from parking and roadways without a controlled perimeter, but is reduced to 10 metres for the same facilities inside a controlled perimeter (UFC-4-010-01, 2002). This is based on the assumption of a stationary vehicle bomb attack and the facilities are constructed of reinforced concrete or reinforced masonry. If the buildings were of light-weight construction such as a metal pre-engineered building, then the standoff distances would need to be increased.

3.1.2 Physical protective barriers

There are two categories of anti-ram barriers – passive (or fixed) vehicle barriers and active (or operable) vehicle barriers. These components enclose the standoff zone. Passive vehicle barriers are placed along the perimeter of the standoff zone where approach by land vehicle is possible. These barriers have no moving parts and are in a continuous "ready" state all the time. The majority of these are constructed in place.

Vehicle barriers are rated based on the kinetic energy resisted. The kinetic energy resistance measures the capacity of a barrier to stop a vehicle of a particular gross weight at a given velocity. The barrier rating is typically determined through crash testing of full-scale barriers but may also be determined through detailed structural analysis.

Figure 6(a) contains typical details for concrete planters. To be considered anchored, the planter must be embedded at least 0.5m into the foundation material. The traditional anti-ram solution is to use bollards (see Figure 6(b)). Bollards are concrete-filled steel pipes that are placed using about 0.5m spacing along the curb to prevent vehicle intrusion. In order for them to provide resistance to impact of a vehicle, the bollards need to be embedded into a concrete footing that is about 1.0-1.5m deep. The height of planters and bollards should be as high as a car or truck bumper. An alternative to a bollard is an anti-ram knee wall constructed of reinforced concrete with a buried foundation. The wall may be fashioned into a base for a fence or the wall for a planter. The foundation of the bollard and knee-wall system can present challenges. Unless the foundation can sustain the reaction forces, significant damage may occur.

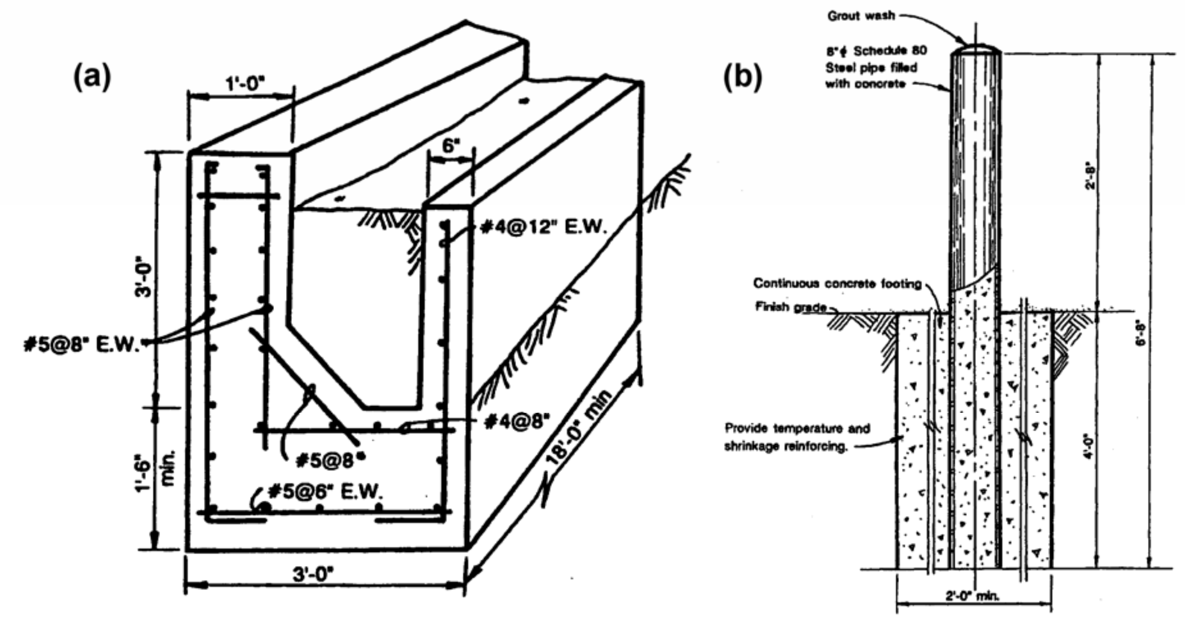

Figure 6 Passive barriers: (a) concrete planters construction; (b) bollards construction (US Army, 1994).

3.2 Preventing progressive collapse

Provisions in the applicable building codes do not give explicit requirements for the consideration of blast and progressive collapse resistance, except for general statements about structural redundancy, resilience and robustness. Because of the catastrophic consequences of progressive collapse, it is prudent to include measures of mitigating the effects of progressive collapse into the overall building design and give them the highest priority during the design process. Some issues related to structural protection measures to mitigate damage due to progressive collapse are summarised in a concise form below (US Dept of State, 1995):

- Buildings should be designed against progressive collapse using the indirect method, the alternate-load-path method, or the specific local-resistance method.
- Structural damage without collapse of the building is an acceptable and practical design parameter.
- Consider incorporating internal damping into the structural system to absorb the blast impact.
- Design floor systems for uplift in exterior bays that may pose a hazard to occupants.
- Symmetric reinforcement can increase the ultimate load capacity of the structure.
- Ductile details should be used for structural components to absorb the energy of a blast.
- Use two-way floor and roof systems.
- Avoid the use of masonry when blast is the threat. Masonry walls break up readily and become secondary fragments during blasts.
- Use dynamic non-linear analysis methods for design of critical structural components.

4. Conclusion

This paper has introduced several concepts that can be useful to structural engineers, building owners, and site planners in mitigating the threat of hazards resulting from terrorist attacks using an explosive-laden vehicle on new and existing buildings. The general properties of a bomb blast, the concept of defence in depth for an urban planning layout, the blast barriers, and preventing progressive collapse of a structure have been reviewed. The state-of-the-art methods to enhance protection of the building by incorporating low-cost measures at the early stages of building design have been addressed.

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