Approach for Designing Civilian Structures Against Terrorist Attack

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Abstract: Hardening structures against weapons effects has been, until recently, of concern almost exclusively of the military. However, with the increase of terrorist activities directed against civilian targets, there is a growing interest in applying these principles to the design of non-military structures. A design approach is presented for civilian structures subject to an external explosion. The issues addressed are threat assessment, countermeasures, weapons effects, analytical techniques, and optimization techniques used.

Introduction

In military terminology, terrorism is considered low-grade warfare. As such, many of the principles used to design military targets are applicable to the protective design of civilian targets subject to terrorist attack. However, the objectives of design are different for civilian targets. For military facilities the primary objective is to maintain function after attack. 'Function' refers to essential activities such as launching a missile or maintaining communications or intelligence. For civilian facilities the primary objective is to save lives while preserving the non-military character of the facility; maintaining function becomes a secondary issue.

Because of this difference, protective design principles need to be reevaluated. In this paper the fundamental principles of military facility design are used to develop a rational approach to the design of new civilian structures. These ideas are also applicable to the retrofit of existing structures.

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Threat and Countermeasures

There are many possible threats to be considered in the design of civilian structures (Fig. 1). Some threats are excluded, such as aerial attack or nuclear attack because they are impractical to design for. Other threats are not

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considered here because they do not cause structural damage, such as chemical/biological contaminants.

The most serious threat against a civilian structure in the recent past has been the "car-bomb", i.e., a large external explosion. If the facility is able to resist this threat, it should be able to withstand (with minor modifications) many of the other threats shown in Fig. 1.

The designer needs to be concerned with four broad groups of countermeasures: "deterrence," "keep-out," "deception," and "hardening." These terms are listed in order of decreasing effectiveness. "Deterrence" refers to the perceived protection level of the facility. If effective, the facility will not be selected as a target because it presents more obstacles than the intruder is willing to overcome. If deterrence is not effective, then the next tier of protection is "keep-out." This refers to devices such as fences, walls, etc., which prevent the intruder from reaching the target or at least delay him until outside help arrives. If the "keep-out" measures are overcome, then the attacker is confronted by "deception." This diverts his attention from the most vulnerable or valuable part of the facility towards a more visible, less important part. If all these countermeasures are overcome, then as a last resort, the building is "hardened" to protect the occupants and contents against the effects of the explosion.

The objective of the physical security design is to maximize the protection level within the design constraints of the project. This paper focuses on the role of the engineer, however, it is important to be aware that a successful design can be achieved only if the architect, engineer, and security specialist cooperate. Also, for a cost effective design, security issues should be addressed throughout the design process -- not as an afterthought during the final design phase.

Countermeasures may be divided into active or operational, which require human intervention, and passive or physical, which do not require human intervention. Security specialists are needed to define active countermeasures which include:

- Intelligence
- Guards
- Sensors
- Search
- Surveillance
- Active Defense
- Access Control
- Rescue

Passive countermeasures (Fig. 2), which facilitate the operational measures, are the responsibility of architects and engineers. Architects are responsible for incorporating planning and functional security measures, engineers for the design the structural components to resist blast effects. A generic site plan, showing a variety of physical security measures discussed, is given in Fig. 3.

Weapons Effects

An explosion is a very rapid release of stored energy characterzed by an audible blast. Part of the energy is released as thermal radiation, and part is coupled into the air (air-blast) and soil (ground-shock) as radially expanding shock waves. Air-blast is the principal damage mechanism. The shock wave propagates by compressing the air molecules in its path, producing the ambient over-pressure or incident pressure. It propagates with supersonic velocity, and when it encounters the building (see Fig. 4), it is reflected, amplifying the over-pressure by a factor of as much as twelve. The air-blast penetrates through window and door openings, subjecting floor slabs, partitions, and contents to pressure. Diffraction of the wave occurs as the shock propagates around corners, creating amplifications and reductions in pres sure in these regions. Finally, the entire building is engulfed by the shock wave, subjecting all building surfaces to the over-pressure. The pressure decays exponentially in time and space and eventually becomes negative (negative loading phase), subjecting the building surfaces to suction forces.

A secondary effect of the air-blast is dynamic pressure or drag loading, which is a very high velocity wind. It propels the debris generated by the air-blast, creating secondary projectiles. Also, the building is subject to the ground-shock, which produces ground motions somewhat similar to a high intensity, short duration earthquake.

All air-blast phenomena take place in very short time intervals, measured in milliseconds. Also, initial peak pressure intensity may be several orders of magnitude higher than the typical live loads. The magnitude of the pressure, P, is roughly proportional to the amount of explosive used, W, and inversely proportional to the cube of the distance from the center of gravity of the charge, R:

$$P \propto \frac{W}{R^3} \tag{1}$$

e.g., if the range is doubled, the peak intensity is decreased by a factor of eight. In relation (1), the amount of explosive, W, is called the yield or charge weight, measured in equivalent lbs. of TNT. Typical car bomb yield ranges from 200 to

12000 lbs. As a comparison, it is worth noting that the usual aerial bombs used to attack military targets have yields ranging from 500 to 2000 lbs. (see Fig. 5).

In addition to over-pressure and reflected pressure there are some other important blast parameters -- such as the time of arrival of the shock wave, shock velocity, duration, and impulse. There are tables for determining these parameters for a given yield and range [1]. These tables are not directly applicable to buildings which have complicated architectural features and cause significant wave diffractions.

Ground-shock loads may be determined using Ref. 3. Internal pressure may be determined using the charts provided by Luwa [5]. An analytical description of the internal loading phenomena is given in Ref. 2.

The response of a building to a large explosion occurs in distinct phases (Fig. 6). Initially, as the blast wave contacts the nearest exterior wall of the building, windows are shattered, and the walls and columns deflect under the reflected pressure (Fig. 6a). As the blast wave expands and diffracts around the building, it exerts an over-pressure on the roof, side walls and, finally, on the walls of the far side. Although the pressure levels on the three sides facing away from the blast are smaller than those on the front, they are significant. It must be remembered that because the location of the explosion cannot be anticipated, each building face must be designed for the worst case, i.e., an explosion normal to that face.

The internal pressure which penetrates through openings, exerts a downward and upward pressure on the floor slabs (Fig. 6b). The upward pressure is important because columns and slabs are not ordinarily designed for such loads. This pressure may also cause injury to lungs and blood vessels. Occupants may also be injured by glass fragments and other debris. Internal pressure may be reduced by decreasing the size and number of openings or by using blast resistant glazings and doors.

Finally, the frame responds to the loads induced by an explosion (Fig. 6c) as the inertia of the building becomes mobilized. The side sway experienced by the building is similar to what might be expected due to a short duration, high intensity earthquake.

Structural Design Issues

It is usually impractical to design a civilian structure to resist large explosions so that it remains intact. A realistic objective is to protect the occupants, contents, and essential functions. After an explosion we require only that the structure is still standing in order to permit rescue of occupants, removal of contents, and maintenance of emergency functions. We accept that the structure may be heavily damaged and in need of substantial repairs.

The structural design must assume that the plans are in agreement with requirements of the active and passive countermeasures. Major structural components have the characteristics described below.

Exterior Walls: These are usually constructed of reinforced concrete with two-way reinforcing on both faces and ties at bar intersections. Breaching due to ballistic attack or contact charges must also be considered. Special reinforcing and anchors are provided around blast resistant window and door frames. Masonry walls may be inadequate.

Exterior Columns: These are designed to resist the reflected pressure including the load transmitted by the wall. The reinforcing must provide for: elastic rebound, tension induced by the upward loading on slabs, and stability.

Roof Framing: The primary loading on the roof is the downward over-pressure. Secondary loads include the suction upward during the negative loading phase and the upward pressure due to the blast which penetrates through openings.

Floor Framing: The floors are subject to the blast which penetrates through the openings. Blast pressure may act from above or below. In plane forces due to the airblast loads are also considered.

Lateral Frames: The frame responds to the total blast acting on the building and also to the ground-shock. Often the exterior concrete walls alone are sufficient to transmit the load to the foundation. Progressive collapse criteria must also be satisfied. These criteria ensure that there is redundancy in the design so that if a critical supporting element fails, it will not cause the total or partial collapse of the structure.

In the design of these elements, the blast loads are combined with the effect of dead load by using a load factor of unity. The strengths of the concrete and steel are increased by 10%-20% for strain rate effects. Also, the 1-year concrete strength is used instead of the 28-day strength. The design takes advantage of the energy absorption due to inelastic deformations.

Because of the sensitivity of air-blast to the geometry of the target, unusual building shapes become very time consuming to analyze. Diffraction modeling on large computers is costly, justified only for military structures.

Dynamic Analysis Techniques

Non-linear dynamic analysis techniques are similar to those currently used in advanced seismic analysis. Analytical models range from equivalent single-degree-of-freedom (SDOF) models to finite element (FEM) representation. In either case, numerical computation requires adequate resolution in space and time to account for the high intensity, short-duration loading, and non-linear response. The main problems are the selection of the model, the appropriate failure modes, and finally, the interpretation of the results for structural design details. Whenever possible, results are checked against data from tests and experiments on similar structures and loadings.

Components, such as beams, slabs, or walls can often be modeled by a SDOF system. The response can be found by using the charts provided by Biggs [1] and military handbooks [3,6]. For more complex elements, the engineer must resort to numerical time integration techniques. The time and cost of the analysis cannot be ignored in choosing analytical procedures. SDOF models are suitable for numerical analysis on PC's and micro-computers but the most sophisticated FEM systems (with non-linear material models and options for explicit modeling of reinforcing bars) may have to be carried out on mainframes (Fig. 7). Because the design analysis process is a sequence of iteration, the cost of analysis must be justified in terms of cost benefits to the project and increased confidence in the reliability of the results. In some cases, an SDOF approach will be used for the preliminary design and a more sophisticated approach using finite elements will be used for the final design.

Optimization Studies

The cost of protection has two components -- fixed and variable. Fixed costs are those for security hardware, space requirements, hardware maintenance and security personnel. These costs do not depend on the level of an attack, e.g., it costs the same to keep a truck away from a building whether the truck contains 500 or 5000 lbs. of TNT. Blast protection, on the other hand, is a variable cost. It depends on the threat level which is a function of the explosive charge weight and the stand-off distance. We have no control over the amount of explosives used, but we are able to keep it at a stand-off distance by providing a secured perimeter.

The optimal stand-off distance is determined by defining the cost of protection as the sum of the cost of protection (construction cost) and the cost of stand-off (land cost). In the example shown in the top graph on Fig. 8, these two costs are considered as a function of stand-off for a given explosive charge weight, *W*. The cost of protection is assumed proportional to the peak pressure level, as expressed by relation (1). The cost of land is given by the square of the stand-off (R^2). The optimal stand-off is the one for which the sum of these costs is minimum.

If additional land is not available the required floor area of the building is distributed among several floors. As the number of floors is increased, the footprint decreases, providing an increased stand-off distance. Taking into account the increasing cost of the structure (due to the added floors) and the corresponding decrease in protection cost (due to added stand-off), we find the optimal number of floors for which the cost of protection is minimum.

The above methods are used for the maximum credible explosive charge. If the cost of protection for this charge weight is not within the budgetary constraints, then the charge weight must be modified. A study is conducted to determine the largest yield and corresponding level of protection which can be designed within the given budget.

If the primary objective of protection is to save contents or maintain function, we are able to provide a design solution which minimizes the cost of attack. The cost of attack consists of the cost of protection, the cost of loss, and the cost of repairs. This optimization is illustrated in the bottom curve of Fig. 8. We calculate the minimum cost of protection, as previously shown, for a range of threat levels. These minimum costs are compared with the corresponding cost of an attack for an unprotected structure. The optimal threat level is the one for which the sum of these costs is minimum.

Conclusion

The design of structures to survive the effects of an explosion requires knowledge of several disciplines (see Fig. 9). The threat and associated weapons effects need to be evaluated based on site specific vulnerability of the facility. Risk analysis is required to evaluate a reasonable level of protection and the appropriate design criteria within the budgetary and other constraints of the project. Design-analysis requires an understanding of the dynamic character of the loads and the anticipated response mechanisms, verified by test data. The end product is a balanced design achieved through an interdisciplinary approach combining the skills of the architect, engineer, and security specialist involved throughout the design process. The cost of implementing these design principles can be cost effective particularly for new buildings where it is estimated that the added cost is on the same order of magnitude as implementing seismic code requirements in the San Francisco Bay area.

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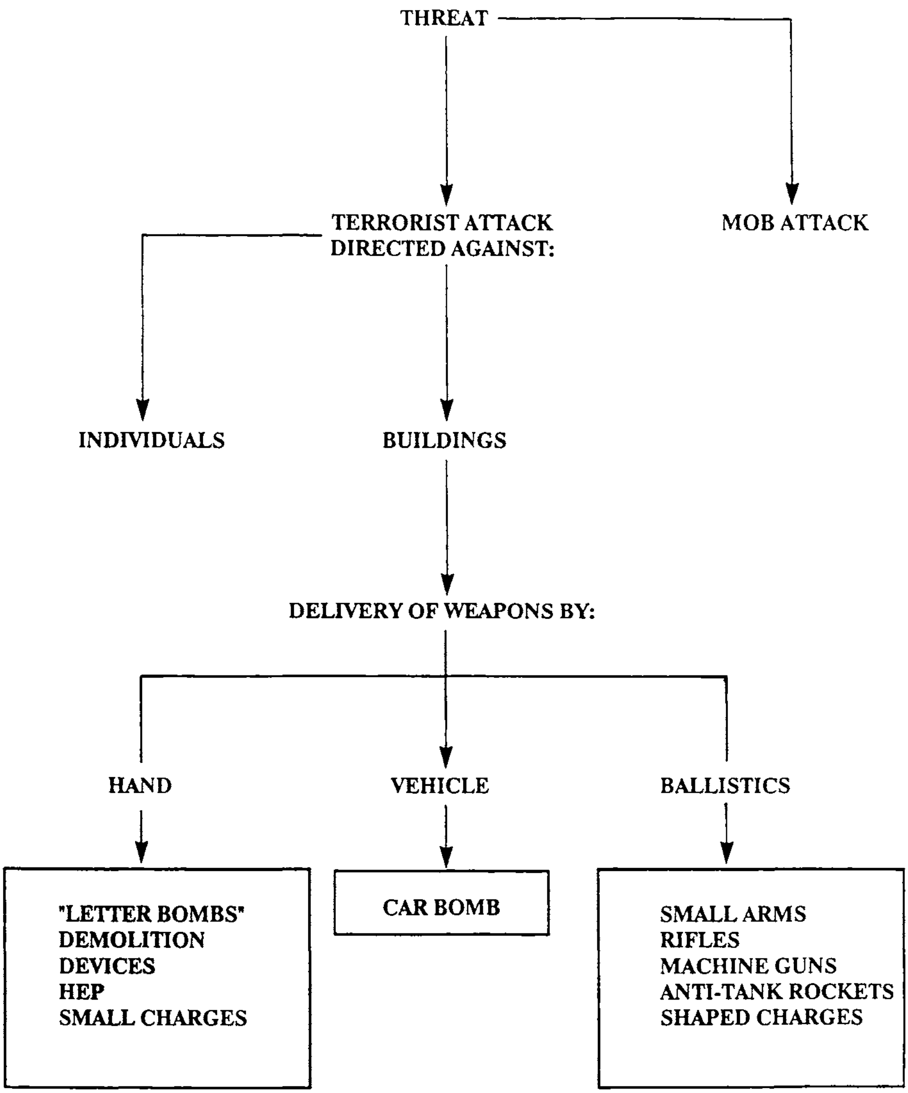

Fig. 1—Threat definition

PASSIVE COUNTERMEASURES

PERIMETER PROTECTION	Intrusion Detection Alarms Fence/Wall Bollards/Planters Street Countermeasures
ACCESS CONTROL	Vehicle Barriers/Traps Chicanes Guard House
FUNCTIONAL PLANNING	Crisis Management: Search & Rescue Evacuation & Assembly Access Control Driveway Geometry
PHYSICAL PLANNING	Fragment Mitigation Geometry Glazings Window Frames Emergency Equipment
HARDENING	Walls Columns Floors Frame Roof

Fig. 2—Passive countermeasures