PROTECTING BUILDINGS AGAINST VEHICLE BOMB ATTACKS

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ABSTRACT: Two significant terrorist vehicle bomb attacks took place in the United States over a relatively short span of time: the World Trade Center, New York City, was attacked in February 1992 and the Alfred P. Murrah Federal Building, Oklahoma City, in April 1995. This paper briefly compares the two vehicle bombs in terms of their probable energy content, based on available information. Damage/casualty mechanisms that are manifested by the interaction of a vehicle bomb with a building are described. Building structural systems capable of resisting progressive collapse when subjected to vehicle bomb attacks are briefly identified. Nonstructural building components and building systems capable of interacting with a blast loading without inducing significant secondary damage and casualties are identified. Several types of building perimeter protection concepts capable of preventing access or close proximity of a vehicle bomb to the subject building are described. Related references are provided.

INTRODUCTION

The April 19, 1995 bombing of the Murrah Federal Building in Oklahoma City intensified the already high level of concern about terrorist attacks on large buildings in the United States. Considerably more powerful than the bomb used on the World Trade Center two years earlier, the explosive device that was detonated in Oklahoma City virtually destroyed the Murrah Building and killed many of the people in it. Both explosions produced significant damage and casualties.

The following paragraphs describe damage mechanisms that are manifested by solid phase explosions and provide suggestions on steps to reduce damage and casualties in buildings subjected to such attacks.

Air Blast and Terrorist Bombs [("Structures" 1969; Crawford et al. 1974)]

Explosives are substances capable of exerting sudden pressure on their surroundings as a result of a rapid conversion of the substance into hot gases. Since, at the instant of their formation, the gases occupy only the volume of the explosive, they are at extremely high pressure. Their pressure, which is raised by the generation of heat in the course of the explosion, overbalances the restraining pressure of the surrounding matter. Rapid expansion characterized by a shock wave follows, and this constitutes the explosion.

Explosions generate shock waves. A shock wave is characterized by a sudden increase in pressure at the front of the wave, with a gradual decrease in pressure behind it. A shock wave in air is referred to as an "air blast" because it resembles and is accompanied by a very strong wind. A typical variation of air-blast pressure with time is shown in Fig. 1.

Typical terrorist bombs tend to be homemade types rather than military types, and are generally as good as the maker's experience, creativity, knowledge of chemistry, and access to "how-to" information. The ingredients for large bombs tend to be economical and easy to get. They include mixtures of readily available fertilizers, liquid fuels, and solid fuels combined in a form to achieve the optimum oxygen balance and homogeneity. These mixes tend to fall into the explosive category of what is called "blasting agents," which is a Department of Transportation (DOT) classification indicating an explosive that cannot be initiated by a blasting cap. Therefore, a large solid explosive booster, such as a stick of dynamite or its equivalent, is often necessary to initiate such an explosive. Such a booster is much harder to get than the main bomb ingredients, and is usually obtained from black-market sources or through theft.

The size of a terrorist bomb can be anything that can fit within any utility container and is limited only by its delivery transport difficulties. A large terrorist bomb transported via car or truck is termed a "car or vehicle bomb."

The weight of the bomb, which is proportional to its energy content, is dependent on the material density, usually in the range of 1.0 g/mL. Therefore, a large vehicle bomb can easily weigh several thousand pounds, given the constraints of available space within a vehicle.

Simplified Comparison of Two Vehicle Bomb Attacks

World Trade Center

A van reportedly containing approximately 816.5 kg (1,800 lb) of fertilizer-based explosive was parked on an exit ramp just south of Column 324, one of the main columns supporting the 110-story structure. It is a steel column that measures roughly 1.22 m by 1.22 m (4 ft by 4 ft) in cross section. The column lost its fireproofing and its lateral restraint (i.e., the bracing provided by two concrete floors that were blown out around it), but was not otherwise damaged by the explosion. The fact that it did not buckle due to the significant increase in its effective length speaks well for the redundancy in a building that, in all likelihood, was not designed for a blast loading.

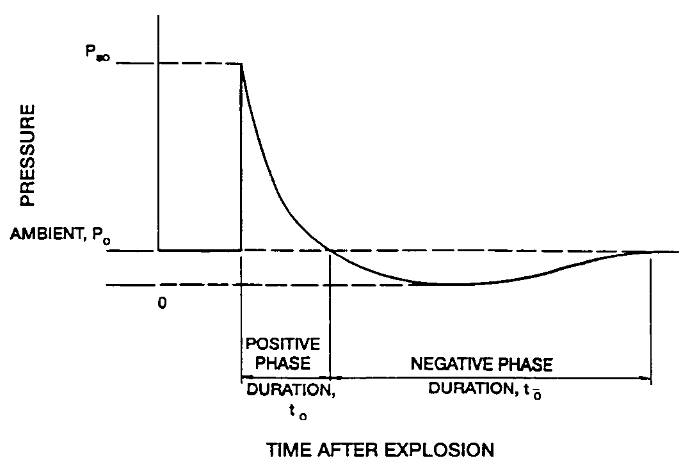

FIG. 1. Qualitative Pressure—Time History

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There was no major structural building collapse. Although several injuries and fatalities occurred due to blast-energized fragments and blast pressures, most injuries were respiratory because of smoke travel through ruptured vertical shafts driven by the stack effect of the high building. Building communication and electrical power were disrupted, hampering egress efforts.

Murrah Federal Building

A truck reportedly containing some 1,814 kg (4,000 lb) of fertilizer-based explosive was parked next to the nine-story reinforced-concrete office building. The side of the building facing the blast had corner columns and four interior columns between the corner columns. These columns supported a transfer girder at the first story, which in turn supported additional interior columns. The blast knocked out the transfer girder and severed three of the four 0.51 m (20 in.) by 0.091 m (36 in.) interior columns. All the floors supported by these columns collapsed in a progressive fashion, resulting in about a third of the building being pancaked onto the ground.

Here major structural collapse occurred, and a multitude of injuries/fatalities were caused by blast pressure, energized debris, and structural collapse. Stairwells remained intact for the most part and allowed evacuation efforts. Smoke was a problem outside the building during the initial Fire Department response from secondary automobile fires. However, interior smoke travel and accumulation was not a major problem since the building was naturally vented on every floor.

Comparing the Bombs

Both bombs used a fertilizer-based or, in technical terms, ammonium nitrate fuel oil (ANFO) explosive, which has a TNT equivalence of approximately 70%. With aluminum powder added, the energy can be increased by as much as 50%. Thus, the TNT equivalent of ANFO/aluminum can be as high as 105%.

The Oklahoma City bomb reportedly had aluminum powder in it. We are not aware whether the World Trade Center bomb had aluminum powder in it. If it is assumed that the World Trade Center vehicle bomb consisted of properly mixed ordinary ANFO, then the TNT equivalent was 816.5 (0.7) = 571.6 kg (1,260 lb). The TNT equivalent of the Oklahoma City bomb was 1,814 (1.05) = 1,905 kg (4,200 lb) (if optimally mixed). If the assumptions made here are correct, the energy content of the World Trade Center bomb might be only 30% of that used in Oklahoma City.

Air Blast/Building Interaction ("Structure" 1969; Crawford et al. 1974)

Blast propagates with supersonic speed and is reflected when it encounters an object such as a building. The reflected

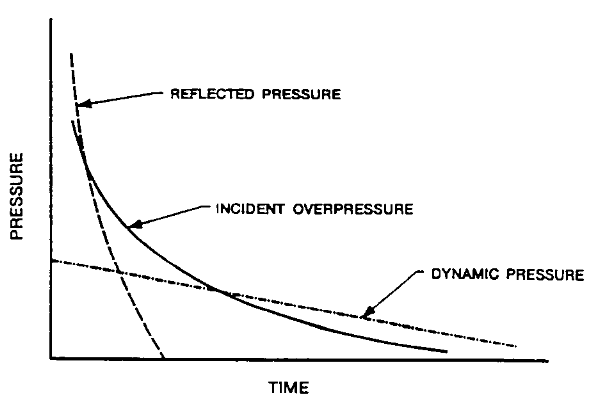

FIG. 2. Blast Wave Characteristics Related to Structural Loadings

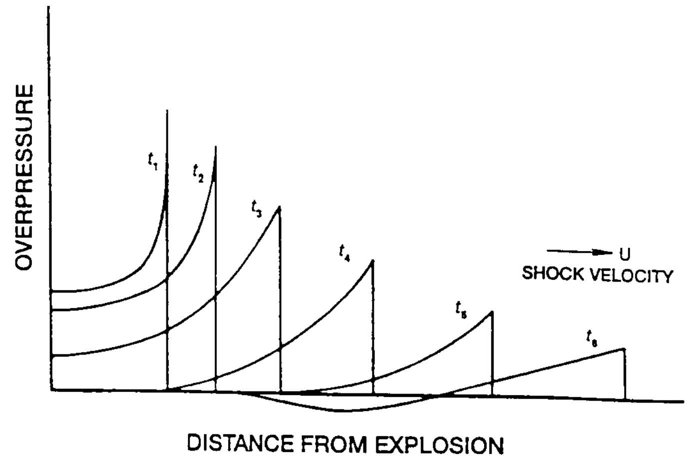

FIG. 3. Variation of Overpressure with Distance

pressure is at least twice that of the incident shock wave and is proportional to the strength of the incident shock, which is proportional to the weight (yield) of the explosive (see Fig. 2).

If the exterior building walls are capable of resisting the blast load, the shock front penetrates through window and door openings, subjecting the floors, ceilings, walls, contents, and people to sudden pressures and fragments from shattered windows, doors, etc. Building components not capable of resisting the blast wave will fracture and be further fragmented and moved by the dynamic pressure that immediately follows the shock front. Building contents and people will be displaced and tumbled in the direction of blast wave propagation. In this manner the blast will propagate through the building.

The blast pressure decays exponentially and eventually becomes negative as shown in Fig. 1. This then subjects the building to pressures acting in the direction opposite (suction pressures) to that of the original shock front. In this manner, the process starts all over again in the opposite direction but at a decreased load magnitude. Air blast parameters such as the positive and negative phase durations (Fig. 1) are measured in milliseconds.

Peak blast loads may be several orders of magnitude larger than the largest loads for which conventional buildings are designed. For example, for a charge of 816.5 kg (1,800 lb) of TNT, the peak pressure of the shock front at a distance of 1.52 m (5 ft) from the point of detonation is approximately 16,902 kPa (353,000 psf). That, from a 1,814 kg (4,000 lb) charge, is approximately 23,270 kPa (486,000 psf). Compare this to the stagnation pressure of 1.24 kPa (26 psf) produced by a 161 km/h (100 mph) wind. The peak pressure drops off rapidly with distance (see Fig. 3). For a 816.5 kg (1,800 lb) charge of TNT, a peak pressure of 1.24 kPa (26 psf) at the shock front is produced at about 457 m (1,500 ft) from the point of detonation. The corresponding distance for a 1,814 kg (4,000 lb) charge is approximately 610 m (2,000 ft).

Blast-Resistant Design

Design of structures to resist the effects of blast is a well-established discipline practiced mostly by the military ("Structures" 1969; Crawford et al. 1974). Blast-resistant structures have been designed, tested, and built to protect personnel and equipment against the effects of conventional and nuclear weapons.

The majority of blast-resistant structures are located below grade to eliminate the need to design for reflected pressures, which may be significant, to take advantage of the soil cover and soil restraint that provides additional protection and resistance, to force the attacker to be more accurate in weapon delivery, etc.

Civilian Structures and Vehicle Bombs

Designing conventional, abovegrade structures to significantly resist the effects of blast is generally impractical for the following reasons.

1. The risk cannot be defined. We do not know with any degree of certainty which building may be attacked, nor do we know when an attack will occur.
2. The threat cannot be quantified. We generally do not know the type of weapon, its size, or mode of delivery.
3. Blast pressures are several orders of magnitude greater than ordinary gravity and wind loads; the impact on cost, function, and appearance is not acceptable.

Nonetheless, significant improvements in susceptibility to a car bomb attack can be accomplished through favorable structural systems, effective passive protection measures, and a contingency or security plan.

Structural System

Structures that do not experience large-scale collapse as a result of localized blast are desirable. Such structures will have fewer casualties than those that experience essentially immediate and total progressive collapse. To accomplish this, the framing system needs to be sufficiently redundant to effectively redistribute loads when a portion of the structure is knocked out by the blast. Examples of redundant structural systems include steel and concrete moment-resistant frames.

The structural design should consider vertical loadings both from above and below. Floor systems and other members will need to be tied down to resist upward blast loads. Blast loads will cause stress reversal, and this effect should also be considered in the design of members, connections, and foundations.

Although structural steel-framed buildings may be particularly amenable to stress reversal, reinforced-concrete frames can be detailed to function well in a blast load environment. In fact, a massive, reinforced-concrete building with a great deal of ductility and damping is likely to perform as well as a ductile steel-framed building.

Nonstructural Systems

Nonstructural systems include fenestration, interior partitions, stairs, building equipment, etc. When improperly selected, supported, or protected, these items may contribute to personnel injuries during a blast.

For example, glass fragments from broken windows, when accelerated by the blast, are capable of causing serious injuries. This effect can be minimized by using laminated glass or special plastic coatings. This will reduce the number of airborne fragments. Full-length window blinds or curtains, weighted or connected at the floor, are likely to catch most of the broken window fragments and thus minimize injuries. The number of windows on potentially vulnerable sides of new buildings should be minimized.

Heavy building facades adequately connected to the structural frame are less likely to be dislodged by the blast, to fall and to produce injuries, secondary damage, and/or inhibit rescue operations.

Steel plates connected to the inside of reinforced-concrete walls will prevent spalling when the wall is exposed to blast on the outside. Chunks of concrete dislodged by blast forces have been shown to move at high speeds and to be capable of causing injuries.

Light and frangible interior partitions (such as normal drywall and metal stud walls) are likely to break up in many light pieces when exposed to a blast loading. In this manner, light partitions are less likely to cause injuries to building occupants in a blast environment than heavier and less frangible partitions, such as plastered walls or those covered with tile, stone, or mirrors.

Building Systems

Building service equipment and furnishings, when tied down, are not as likely to be moved and tumbled by the blast as loose and gravity-supported equipment. Loose equipment is very likely to cause injuries when interacting with people in a blast environment. It can also produce secondary damage.

After a blast, fires may be fueled by spilled flammable substances and leaking natural gas. When stored in blastproof and tied-down containers, flammable substances are less likely to lead to injuries. Automatic shutoff valves are capable of preventing large-scale natural gas leaks.

Secondary fires and the bomb reaction itself may produce a great quantity of smoke. Breaching of vertical channels in the building (e.g., stairwells, elevator shafts, pipe chases) provide natural channels for smoke driven by the stack effect. The strength of the stack effect is a function of the height of the building and the indoor-outdoor temperature differential. This was evident in the World Trade Center bombing and resulted in a number of respiratory injuries and egress problems. Fire sprinkler systems will be ineffective on secondary fires if any of the main piping is ruptured from the blast. Strengthening of vertical channels, special smoke control and alarm systems, and seismic-type sprinkler pipe construction may be considered in efforts to mitigate the effects of secondary fires.

Other building services such as electrical, telephone, and fire alarm/emergency voice communication may be disrupted. Disruptions may be minimized by the protected routing of main lines and use of redundant lines. Adequate coverage of egress areas with emergency lighting will help with escape where lighting power is disrupted.

Equipment such as rope ladders will facilitate escape when stairs are damaged or blocked by building debris. Emergency egress equipment should be stored in protected central areas on the upper floors.

Backup services for electric power, communications, and water should be provided to ensure continued operation of critical functions in case of an emergency.

A positive pressurization inside the building should be made possible, if needed, to eliminate infiltration of contaminated air from outside.

Perimeter Protection (Walsh and Healy 1987; National 1986, 1988)

A building with a strong perimeter fence is better protected against a car bomb attack than one where a car may be parked directly next to the building. A strong perimeter fence located at a sufficient distance from the building is very likely to render a car bomb ineffective because the bomb would need to be larger than usual to be effective.

Following are the perimeter security guidelines:

1. The perimeter should be at the maximum feasible distance such that any anticipated explosion will not cause major damage to the building. The effectiveness of an explosive device is a function of its TNT equivalency and the distance of the detonation from the target.
2. The site perimeter should be designed to confine hostile activities to the outside of the perimeter fence.
3. Perimeter features should be such as to completely deny or delay sufficiently any unauthorized site access.
4. The perimeter fence should protect the building and its

occupants from standoff or drive-by attacks including explosive devices.

5. The perimeter fence should be well lit and fully observable from the building.
6. If possible, the perimeter should make use of a combination of barrier techniques, e.g., walls, berms and planting, bollards, static barriers, fences, embankments, tire traps, ditches, etc. Such an approach offers a degree of redundancy; if one component fails, the entry may not necessarily be compromised.

When the building to be protected is located in an urban area, local streets may be closed off to prevent parking close to the building. Bollards may be spaced along the perimeter to prevent vehicles from entering the safety zones.

Perimeter protection may also be enhanced by controlling the movement of traffic around the building, the vehicular access and egress, and the street parking around the building. Circulation or movement of traffic around the building may be controlled by some of the following:

- Setting a speed limit on all adjacent streets and using speed bumps, pavement cuts, etc.
- Restricting the area around the building to passenger cars only.
- Controlling the direction of circulation of traffic on adjacent streets.
- Controlling attempts to leave the roadway by means of high curbs, median strips, bollards, etc.

Vehicular access to and egress from the building may be made safe by access denial or by containment of the threat to the entry area, which is strengthened to resist blast loads.

Wherever possible, parking should not be permitted along streets adjacent to the building to reduce the possibility of a preset vehicle bomb.

Building Parking Garages

As was demonstrated by the World Trade Center experience, a public parking garage located within a building is a likely place to locate a car bomb. One way to eliminate the potential problem is to restrict the garage to building occupants and to inspect every car that enters. Another way to deal with the problem is to eliminate parking in the building.

The parking area may be transformed into a safe working area for building occupants, for storage of critical documents and communications equipment, etc. As indicated earlier, underground spaces are easier to protect against blast effects than are upper story spaces. While both options are more feasible than shutting off entire streets, they raise serious practical difficulties in urban areas that depend heavily on occupants driving into the city.

New Concepts in Structural Blast Resistance

It is certain that in the near future devices intended to protect buildings from vehicle bombs will surface. Some of these will be the same ones that were produced in the past. Some may be useful; many will not be. There have been some clever and useful concepts such as crushable materials that absorb blast energy and composite wall panels that prevent spalling. Interesting methods to mitigate blasts in airplane baggage holds have been developed. Although potentially useful, such concepts require careful analysis before being used in a building. They can also be quite expensive. The U.S. Patent Office is a good source for such concepts.

Contingency Plan (Walsh and Healy 1987)

Every building that houses a significant number of occupants needs a contingency or security plan. Such plans are developed to provide for the safety of building occupants in the event of an emergency such as fire. Building occupants are made aware of contingency plans by means of periodic safety seminars and evacuation exercises. Contingency plans that specifically address hazards from car bomb attacks should be developed and implemented.

SUMMARY AND CONCLUSIONS

Car bombs parked close to inhabited buildings can produce significant damage and casualties. In the general case, it is not practical to design conventional buildings against the effects of a close-in blast. To retrofit existing buildings against blast is generally even more impractical. The reason is that, in the general case, we are unable to define the risk or quantify the threat. Moreover, blast loads produced by a car bomb are several orders of magnitude greater than those produced by ordinary gravity and wind loads. This results in additional design and construction costs, which are prohibitive.

Nonetheless, a building may be made significantly less susceptible to a car bomb attack when using a highly redundant and ductile structural system, effective passive protection measures, and a contingency plan that contains specific provisions against car bomb attacks.

Additional protection can be obtained for the building and its occupants by controlling or eliminating parking within the building. This protection can be further enhanced by means of a sufficiently large and protected safety zone around the building.

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