4.1 PREDICTING DAMAGE LEVELS

The extent and severity of damage and injuries in an explosive event cannot be predicted with perfect certainty. Past events show that the specifics of the failure sequence for an individual building due to air-blast effects and debris impact significantly affect the overall level of damage.

For instance, two adjacent columns of a building may be roughly the same distance from the explosion, but only one fails because it is struck by a fragment in a particular way that initiates collapse. The other, by chance, is not struck and remains in place. Similarly, glass failures may occur outside of the predicted areas due to air-blast diffraction effects caused by the arrangement of buildings and their heights in the vicinity of the explosion. The details of the physical setting surrounding a particular occupant may greatly influence the level of injury incurred. The position of the person, seated or standing, facing towards or away from the event as it happens, may result in injuries ranging from minor to severe.

Despite these uncertainties, it is possible to calculate the expected extent of damage and injuries to be expected in an explosive event, based on the size of the explosion, distance from the event, and assumptions about the construction of the building. Additionally, there is strong evidence to support a relationship between injury patterns and structural damage patterns.

4.2 DAMAGE MECHANISMS

Damage due to the air-blast shock wave may be divided into direct air-blast effects and progressive collapse.

Direct air-blast effects are damage caused by the high-intensity pressures of the air blast close to the explosion. These may induce localized failure of exterior walls, windows, roof systems, floor systems, and columns.

Progressive collapse refers to the spread of an initial local failure from element to element, eventually resulting in a disproportionate extent of collapse relative to the zone of initial damage. Localized damage due to direct air-blast effects may or may not progress, depending on the design and construction of the building. To produce a progressive collapse, the weapon must be in close proximity to a critical load-bearing element. Progressive collapse can propagate vertically upward or downward (e.g., Ronan Point[1]) from the source of the explosion, and it can propagate laterally from bay to bay as well.

The pressures that an explosion exerts on building surfaces may be several orders of magnitude greater than the loads for which the building is designed. The shock wave also acts in directions that the building may not have been designed for, such as upward pressure on the floor system. In terms of sequence of response, the air blast first impinges the exterior envelope of the building. The pressure wave pushes on the exterior walls and may cause wall failure and window breakage. As the shock wave continues to expand, it enters the structure, pushing both upward on the ceilings and downward on the floors (see Figure 4-1).

Floor failure is common in large-scale vehicle-delivered explosive attacks, because floor slabs typically have a large surface area for the pressure to act on and a comparably small thickness. Floor failure is particularly common for close-in and internal explosions. The loss of a floor system increases the unbraced height of the supporting columns, which may lead to structural instability.

For hand-carried weapons that are brought into the building and placed on the floor away from a primary vertical load-bearing element, the response will be more localized with damage and injuries extending a bay or two in each direction (see Figure 4-2). Although the weapon is smaller, the air-blast effects are amplified due to multiple reflections from interior surfaces. Typical damage types that may be expected include:

- localized failure of the floor system immediately below the weapon;
- damage and possible localized failure for the floor system above the weapon;
- damage and possible localized failure of nearby concrete and masonry walls;
- failure of nonstructural elements such as partition walls, false ceilings, ductwork, window treatments; and

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1. "Ronan Point" is the name of a high-rise pre-cast housing complex in Britain that suffered progressive collapse in 1968 due to a gas explosion in a kitchen in a corner bay of the building. The explosion caused the collapse of all corner bays below it and was a seminal event for progressive collapse, precipitating funding for research and development in the United States, Britain and Europe. As a result, Britain developed a set of implicit design requirements to resist progressive collapse in buildings and, in the 1970s, the National Institute of Standards and Technology (NIST) produced some state-of-the-practice reports on this topic.

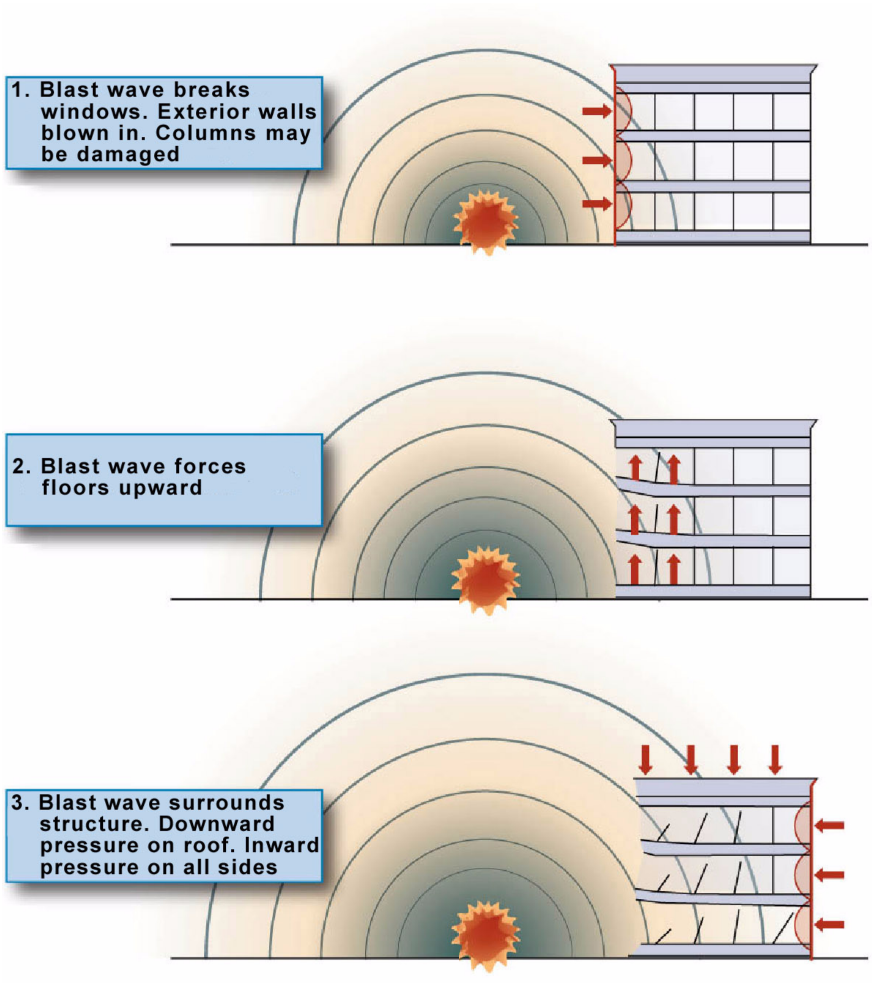

Figure 4-1 Schematic showing sequence of building damage due to a vehicle weapon

- flying debris generated by furniture, computer equipment, and other contents.

More extensive damage, possibly leading to progressive collapse, may occur if the weapon is strategically placed directly against a primary load-bearing element such as a column.

In comparison to other hazards such as earthquake or wind, an explosive attack has several distinguishing features, listed below.

- *The intensity of the localized pressures acting on building components can be several orders of magnitude greater than these other hazards.* It is not uncommon for the peak pressure on the building from a vehicle weapon parked along the curb to be in excess of 100 psi. Major damage and failure of building components is expected even for relatively small weapons, in close proximity to the building.

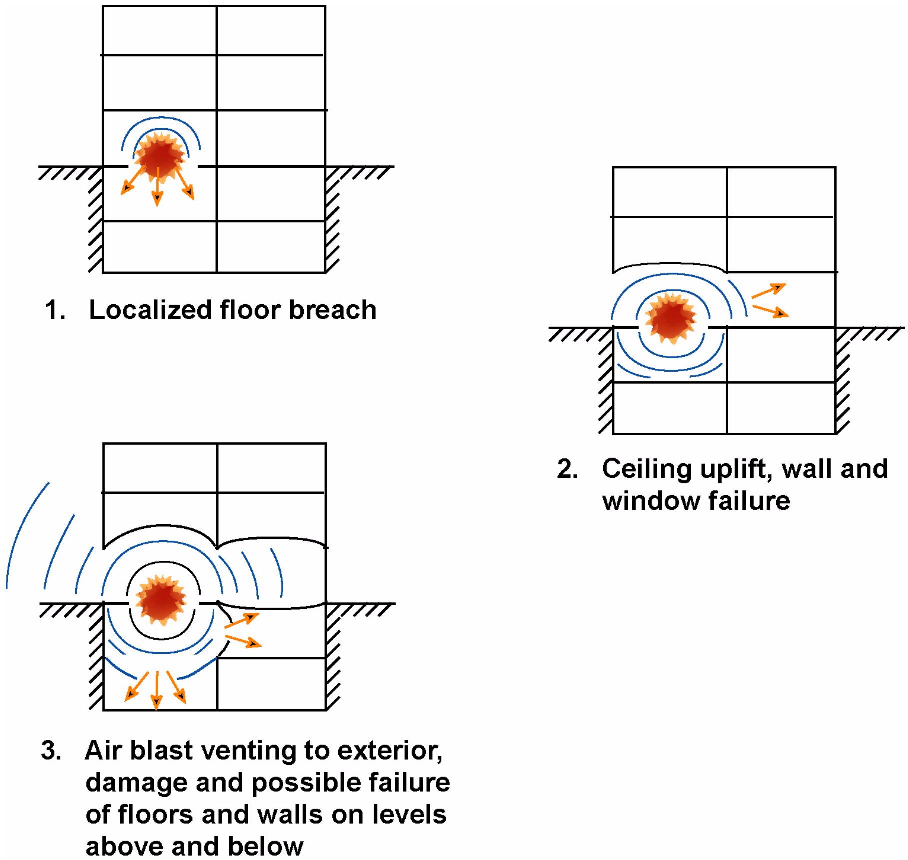

Figure 4-2 Schematics showing sequence of building damage due to a package weapon

- *Explosive pressures decay extremely rapidly with distance from the source.* Pressures acting on the building, particularly on the side facing the explosion, may vary significantly, causing a wide range of damage types. As a result, air blast tends to cause more localized damage than other hazards that have a more global effect.
- *The duration of the event is very short, measured in thousandths of a second, (milliseconds).* In terms of timing, the building is engulfed by the shockwave and direct air-blast damage occurs within tens to hundreds of milliseconds from the time of detonation due to the supersonic velocity of the shock wave and the nearly instantaneous response of the structural elements. By comparison, earthquake events last for seconds and wind loads may act on the building for minutes or longer.

4.3 CORRELATION BETWEEN DAMAGE AND INJURIES

Three types of building damage can lead to injuries and possible fatalities. The most severe building response is collapse. In past incidents, collapse has caused the most extensive fatalities. For the Oklahoma City bombing in 1995 (see Figure 4-3), nearly 90 percent of the building occupants who lost their lives were in the collapsed portion of the Alfred P. Murrah Federal Office Building. Many of the survivors in the collapsed region were on the lower floors and had been trapped in void spaces under concrete slabs.

Figure 4-3 Exterior view of Alfred P. Murrah Federal Building collapse

Although the targeted building is at greatest risk of collapse, other nearby buildings may also collapse. For instance, in the Oklahoma City bombing, a total of nine buildings collapsed. Most of these were unreinforced masonry structures that fortunately were largely unoccupied at the time of the attack. In the bombing of the U.S. embassy in Nairobi, Kenya in 1998, the collapse of the Uffundi building, a concrete building adjacent to the embassy, caused hundreds of fatalities.

For buildings that remain standing, the next most severe type of injury-producing damage is flying debris generated by exterior cladding. Depending on the severity of the incident, fatalities may occur as a result of flying structural debris. Some examples of exterior wall failure causing injuries are listed below.

- In the Oklahoma City bombing, several persons lost their lives after being struck by structural debris generated by infill walls of a concrete frame building in the Water Resources building across the street from the Murrah building.
- In the Khobar Towers bombing in 1996 (see Figure 4-4), most of the 19 U.S. servicemen who loss their lives were impacted by high-velocity projectiles created by the failed exterior cladding on the wall that faced the weapon. The building was an all-precast, reinforced concrete structure with robust connections between the slabs and walls. The numerous lines of vertical support along with the ample lateral stability provided by the "egg crate" configuration of the structural system prevented collapse.

Figure 4-4 Exterior view of Khobar Towers exterior wall failure

- In the bombing of the U.S. embassy in Dar es Salaam, Tanzania in 1998, the exterior unreinforced masonry infill wall of the concrete-framed embassy building blew inward. The massiveness of the construction generated relatively low-velocity projectiles that injured and partially buried occupants, but did not cause fatalities.

Even if the building remains standing and no structural damage occurs, extensive injuries can occur due to nonstructural damage (see

Figure 4-5). Typically, for large-scale incidents, these types of injuries occur to persons who are in buildings that are within several blocks of the incident. Although these injuries are often not life-threatening, many people can be affected, which has an impact on the ability of local medical resources to adequately respond. An example of nonstructural damage causing injuries is the extensive glass lacerations that occurred in the Oklahoma City Bombing within the Regency Towers apartment building, which was approximately 500 feet from the Murrah Building. In this incident, glass laceration injuries extended as far as 10 blocks from the bombing. Another example is the bombing of the U.S. embassy in Nairobi, Kenya. The explosion occurred near one of the major intersections of the city, which was heavily populated at the time of the bombing, causing extensive glass lacerations to passersby. The ambassador, who was attending a meeting at an office building across from the embassy, sustained an eye injury as a result of extensive window failure in the building.

A summary of the relationship between the type of damage and the resulting injuries is given in Table 4-1.

Figure 4-5 Photograph showing non-structural damage in building impacted by blast

Table 4-1: Damage and Injuries due to Explosion Effects

Distance from Explosion	Most Severe Building Damage Expected	Associated Injuries
Close-in	General Collapse	Fatality due impact and crushing
Moderate	Exterior wall failure, exterior bay floor slab damage	Skull fracture, concussion
Far	Window breakage, falling light fixtures, flying debris	Lacerations from flying glass, abrasions from being thrown against objects or objects striking occupants

4.4 FURTHER READING

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