An Engineer's guide to: Concrete Buildings and Progressive Collapse Resistance

Progressive collapse is defined as a situation where local failure of a primary structural component(s) leads to the collapse of adjoining members, which in turn leads to additional collapse. Hence, the extent of total damage is disproportionate to the original cause. Another way of describing progressive collapse is a chain reaction or propagation of failures following damage to a relatively small portion of a structure.

Regardless of the definition, blast loading or other unforeseen events can cause progressive collapse due to damage of some key element(s) which can either make the structure unstable or trigger the failure of the main portions of the gravity structural system. Blast generally results in a high-amplitude impulse loading which lasts for a very short period of time and produces high pressure loading. The loading in many situations is local in the sense that only those elements closest to the blast may be directly impacted. Elements far from the blast site may experience little or no direct impact due to sharp attenuation (dissipation) of blast energy with distance. The forces experienced by structural components depend on the size, geometry and proximity of the explosion. Because all of these parameters can vary, it is not easy to accurately predict the force level that a particular structure could experience as a result of an unexpected blast. See the Appendix for information on blast loads.

Large amounts of explosives at short distances from the structure can cause excessive pressure forces, which cannot be accommodat-

DoD 2002

A progressive collapse is a chain reaction of failure of building members to an extent disproportionate to the original localized damage. Such damage may result in upper floors of a building collapsing onto lower floors.

GSA 2003

Progressive collapse is a situation where local failure of a primary structural component leads to the collapse of adjoining members which, in turn, leads to additional collapse. Hence the total damage is disproportionate to the original cause.

ASCE 7-02

Progressive collapse is defined as the spread of an initial local failure from element to element, eventually resulting in the collapse of an entire structure or disproportionately large part of it.

ed in the design of an ordinary structure. Thus it becomes imperative to put in place other measures such as perimeter control and standoff distances to reduce the possibility of a blast at close proximity to the structure.

The response of reinforced concrete under blast loading is different from its response to typical static and dynamic loads because of the very short duration and extreme pressure loading caused by blast. The stiffness and strength of reinforced concrete is likely to increase with the higher rate of loading experienced under blast conditions. This, in turn, increases the strength of reinforced concrete members and translates into higher resistance. On the other hand, the high rate of loading expected during blasts may also reduce the deformation capacity and the fracture energy of reinforced concrete significantly. This translates to a reduction of ductility of reinforced concrete in blast loading situations, a property generally mandated by most codes and standards to preserve the integrity of a structure.

To achieve targeted integrity during blast, the redundancy of the gravity load carrying structural system takes center stage in tackling the issue of progressive collapse. This is not explicitly addressed in mainstream building codes. However, ASCE 7-02 and ACI 318 imply a desired alternate load path in the event one or more beams and/or columns of a building fail as a result of a blast. The structure should be able to remain stable by redistributing the gravity loads to other members and subsequently to the foundation through an alternate load path, while keeping building damage somewhat proportional to the initial failure.

The inherent mass and stiffness characteristics of reinforced concrete offer distinct advantages over other building materials such as steel and timber under blast loading. Reinforced concrete structures are better able to resist the overall shock due to local disintegration caused by the blast. There is more information on blast resistance of reinforced concrete than for any other material. Reinforced concrete structures have been studied and researched in much detail by governmental, public and military agencies for decades. These aspects give reinforced concrete advantage over other materials for blast type of loading. Most of U.S. embassies, governmental buildings, and public facilities have been entrusted to reinforced concrete.

With the tragic events of September 11, 2001, preceded by the bombing of the Alfred P. Murrah Federal Building in Oklahoma City, it became evident that certain buildings will need to be designed to address the threat of explosions. Most structural engineers would not expect the World Trade Center Towers to survive the extraordinary events on September 11 that included fire on several floors combined with the loss of fire suppression water. It is, however, likely that certain owners and insurers of buildings will be interested in seeing more provisions in the building codes for design against the threat of terrorism. The available provisions currently in the codes, standards, and procedures used for design of tall buildings are under close scrutiny. It is imperative that new buildings which may be subject to terrorist attack be designed to provide anti-terrorism and force protection features that protect and ensure the safety of its occupants.

GSA Criteria

Following the Alfred P. Murrah Federal Building bombing in 1995, an executive order was issued by the federal government to establish construction standards for federal buildings subject to terrorist attack. The Interagency Security Committee (ISC) was organized to respond to the executive order and developed the "Security Design Criteria for New Federal Office Buildings and Major Modernization Projects.". The General Services Administration (GSA) published "Progressive Collapse Analysis and Design Guidelines for New Federal Office Buildings and Major Modernization Project" in 2000 and revised it in June 2003 to meet the progressive collapse requirements of the ISC design criteria.

The GSA publication provides a threat independent method to reduce the potential for progressive collapse. The application of the guideline is not an explicit design and its use is limited to buildings without unusual structural configurations. The method discussed in the GSA publication is normally used for buildings 10 stories above grade and less, but can be applied to taller buildings.

The purpose of the GSA guideline is to prevent progressive collapse in new buildings and to provide a method for assessment of the potential for progressive collapse in existing buildings.

To analyze for progressive collapse potential, different scenarios are assumed. Each scenario assumes the instantaneous removal of a column in the first story, followed by structural analysis for a prescribed set of load combinations and material strength factors. The GSA procedure is as follows:

1. Columns to be removed are selected near the middle of the short side of the building, near the middle of the long side of the building, and at the building corners. For buildings that have underground parking areas or uncontrolled ground floor area, an interior column loss also has to be evaluated.
2. Building dead load factors are amplified to account for the dynamic effects resulting from the blast. The small probability for the presence of full live load during this extreme event is accounted for by decreasing the live load factor.
3. Material strengths are increased to account for the effect of the increased rate of loading caused by the instantaneous support removal.
4. The potential for progressive collapse is evaluated based on a demand-capacity-ratio (DCR). DCR is defined as the ratio of the force (bending moment, axial force, shear force) in the structural member after the instantaneous removal of a column for each scenario to the member capacity. A structural member is considered to have failed if its DCR exceeds 2.0 for

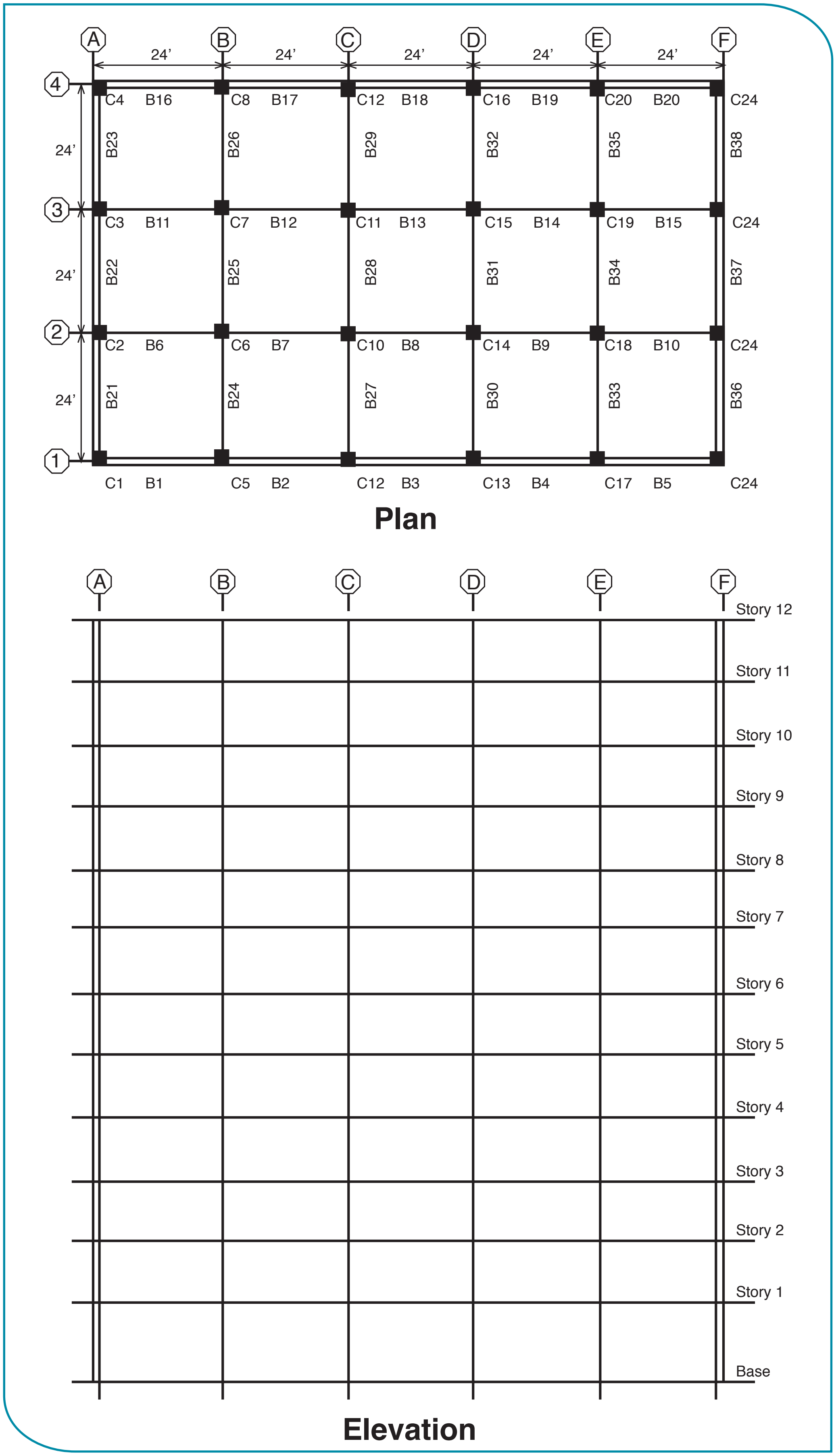


Figure 1. Building in PCA Study

typical structural configurations and 1.5 for atypical structural configurations. A typical structural configuration is defined as facilities that have a relatively simple layout. If the DCR value is more than allowed, strengthening of the member is required.

5. According to the GSA guidelines, the maximum allowable extent of collapse resulting from the instantaneous loss of a column should be confined to the smaller of the following two areas: 1) the structural bays directly associated with the instantaneously removed column or 2) 1,800 square feet at the floor level directly above the instantaneously removed exterior column or 3) 3,600 square feet for an interior column. If the damaged area exceeds the maximum allowed above, strengthening of structural members is required.

The *DCRs* structural components shall be determined as:

$$DCR = \frac{Q_{UD}}{Q_{CE}}$$

Where

Q_{UD} = Acting force determined in component or connection/joint (moment, axial force, shear, and possible combined forces)

Q_{CE} = Expected ultimate, unfactored capacity of the component and/or connection/joint (moment, axial force, shear and possible combined forces)

***DCR* ≤ 2.0 for typical structural configurations**

***DCR* ≤ 1.5 for atypical structural configurations**

PCA Study

In 2003, the Portland Cement Association (PCA) initiated a study of the use of the GSA method for analysis and design against progressive collapse utilizing a 12-story cast-in-place concrete frame building, **Figure 1**.

In this study, the example building was designed and analyzed in accordance with the gravity and lateral force provisions of the 2000 *International Building Code* (2000 IBC). The building design and analysis was repeated for three different seismic force levels corresponding to seismic design category (SDC) A, C and D. For each category the flexural and shear reinforcement was determined to satisfy the seismic force demand. Each SDC also requires a different level of detailing of frame-reinforcing steel commensurate with the anticipated ductility and performance demand. As a result, an ordinary moment frame is used in SDC A, an intermediate moment frame is used for SDC C, and a special moment frame is used for SDC D.

For static analysis purposes the following vertical load shall be applied downward to the structure under investigation:

Load = 2(DL + 0.25LL)

where,

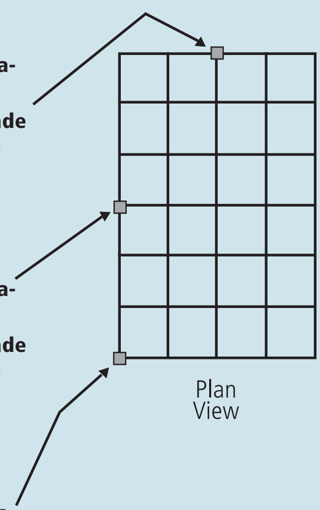
DL = dead load

LL = live load

1 **Analyze for the instantaneous loss of a column for one floor above grade (1st story) located near the middle of the short side of the building.**

2 **Analyze for the instantaneous loss of a column for one floor above grade (1st story) located near the middle of the long side of the building.**

3 **Analyze for the instantaneous loss of a column for one floor above grade (1st story) located at the corner of the building.**



Each of the three building examples were subjected to the GSA progressive collapse criteria to assess potential for progressive collapse. **Figures 2a and b** show the bending moment diagrams (BMD) for column row 1 before and after the column removal. The figures illustrate clearly the substantial impact column removal has on the magnitude of the moment applied to the structure which remains in place. Generally the beams supported by the removed column experience bending moment reversal and an increase in the magnitude of the shear forces. Zones in the beam designed to resist negative bending moment (internal tension forces at the top) will be subjected to positive bending moment after column removal (internal tension forces at the bottom). Figure 3 shows the DCR values for moments in beams adjacent to the removed column for the seismic categories. Only beams where DCR > 2 need to be strengthened to prevent progressive collapse.

The study findings can be summarized as follows:

1. Building columns in each of the three seismic categories do not require additional reinforcement to prevent progressive collapse.

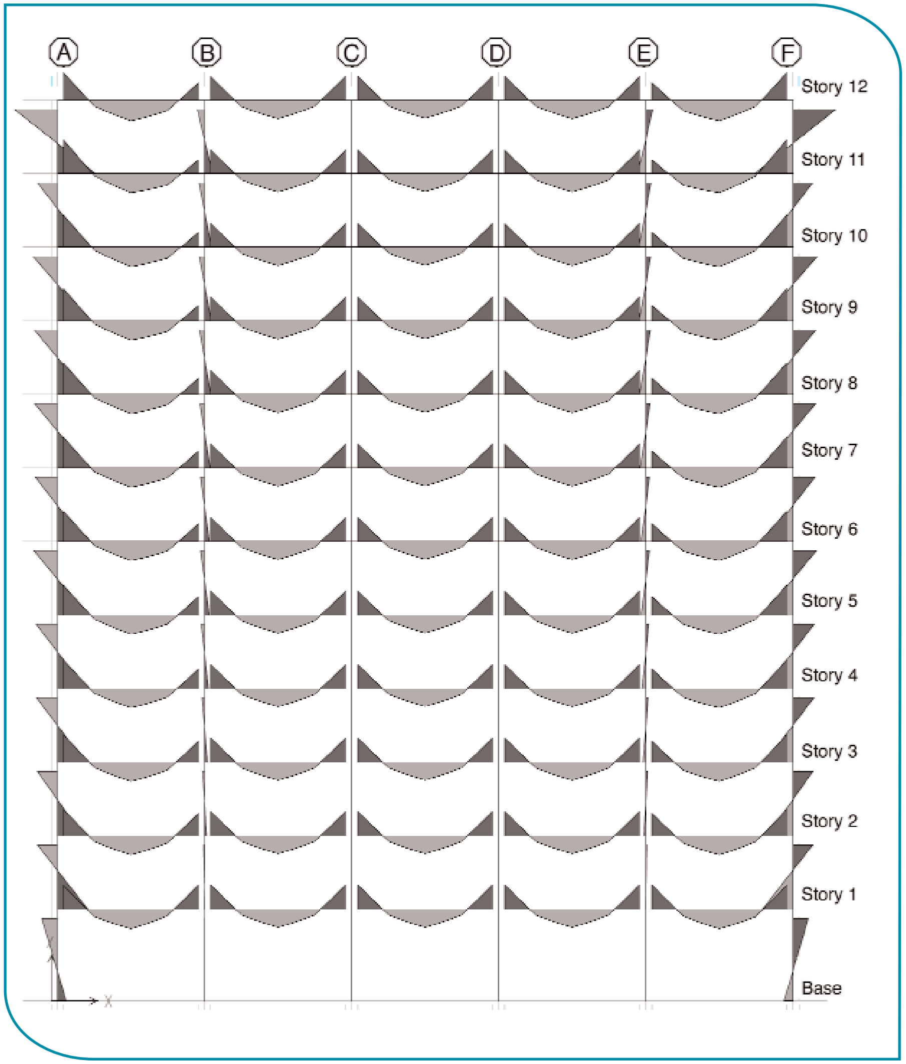


Figure 2a. Bending moments before column loss

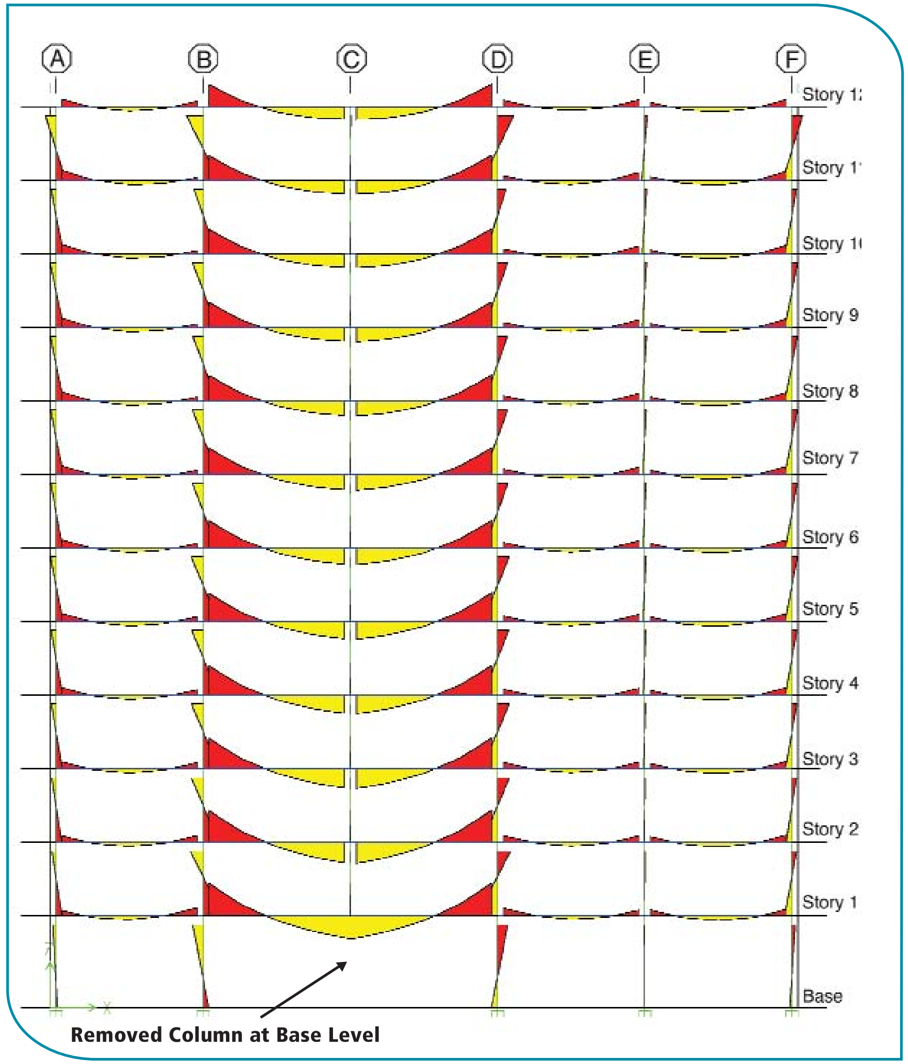


Figure 2b. Building moments after column loss

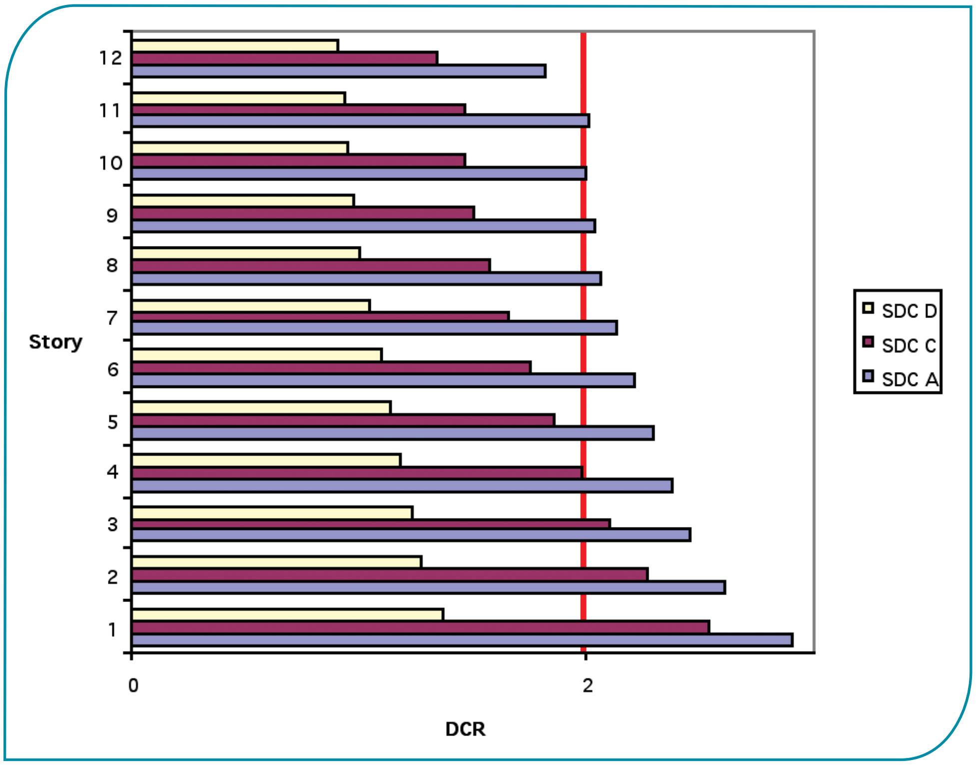


Figure 3. Flexural DCR for beams in the vicinity of the removed column (exterior column near the middle of the long side)

2. Beams proportioned and reinforced according to the strength requirements for seismic category, SDC D, have sufficient strength to resist progressive collapse.
3. Perimeter beams designed to satisfy the strength requirements for SDC C only need additional flexural reinforcement in the beams in the lower four stories.
4. Perimeter beams designed for SDC A only need additional flexural reinforcement in stories one through eleven in order to prevent progressive collapse.
5. The cost of the additional reinforcement required to satisfy the GSA criteria is relatively small.

Resources

1. *Progressive Collapse Analysis and Design Guidelines for New Federal Office Buildings and Major Modernization Projects*, U.S. General Services Administration, November-June 2003.
2. *International Building Code*, International Code Council, Falls Church, Virginia, 2000.
3. *America Society of Civil Engineers Minimum Design Loads for Buildings and Other Structures*, ASCE 7-02, America Society of Civil Engineers, New York, New York, 2003.
4. *Structural Design for Physical Security State of the Practice*, America Society of Civil Engineers, 1999.
5. *U.S. General Services Administration Progressive Collapse Design Guidelines Applied to Concrete Moment-Resisting Frame Buildings*, David N. Bilow, Mahmoud Kamara, 2004 ASCE Structures Congress, Nashville, Tennessee, May 18-22, 2004.
6. *Building Code Requirements for Structural Concrete ACI 318-02 and Commentary-ACI 318R-02*, American Concrete Institute, Farmington Hills, Michigan, 2002.
7. *Notes on ACI 318-02 Building Code Requirements for Structural Concrete* (EB702), Portland Cement Association, Skokie, Illinois, 2002.

APPENDIX

Blast Load

An explosion results in a rapid release of energy in the form of light, heat, sound, and a shock wave. The shock wave consists of highly compressed air that reflects off the ground surface and travels outward from the source at supersonic velocities. As the shock wave expands, the magnitude of the incident pressures decreases. When the shock wave encounters a surface it reflects, the pressure is amplified. Due to the supersonic velocity of the shock wave at impact, the waves can reflect with an amplification factor of up to thirteen. The magnitude of the reflection factor is a function of the proximity of the explosion and the angle of incidence of the shock wave on the surface. The resulting pressures decay rapidly with time and the shock wave becomes negative, followed by a partial vacuum, which creates suction behind the shock wave. In an external explosion, a portion of the energy is also imparted to the ground, creating a crater and generating a ground shock wave analogous to a high-intensity, short-duration earthquake.

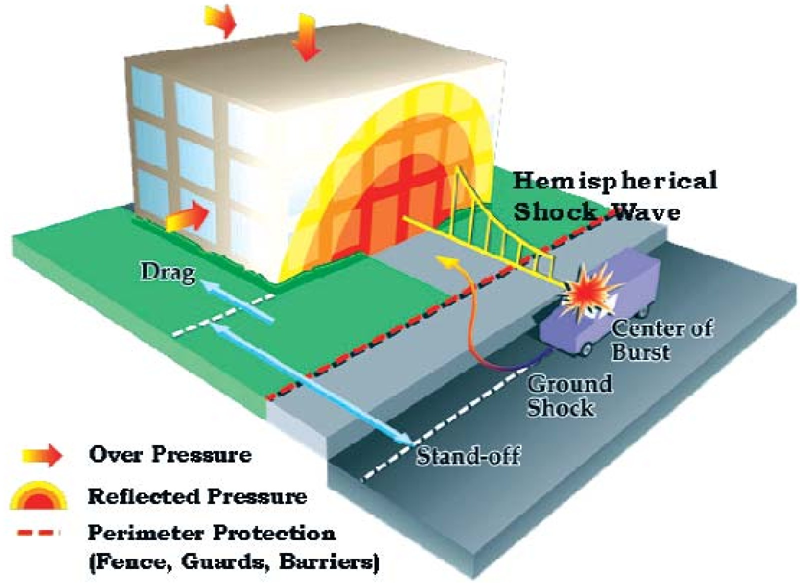


Figure A-1 Parameters and definitions of external vehicle explosion - FEMA 427

Blast load generally is impulse-type high-amplitude loading that lasts for a very short period of time measured by milliseconds. The loading in many situations is local and only those elements closest to the blast may be directly impacted. Elements farther removed from the blast site may experience little or no direct impact due to sharp attenuation of blast energy with distance. The forces experienced by members of the structure depend upon the size and proximity of the explosion.

Higher explosive weights at short distances from the structure can cause excessively large forces which cannot be reasonably accommodated in design of the structure. Thus, it becomes imperative to put in place other measures, such as perimeter fences and standoff dis-

The blast effects of an explosion is in the form of a shock wave composed of a high pressure shock front which expands outward from the center of detonation with the intensity of the pressure decaying with distance and as a function of time.

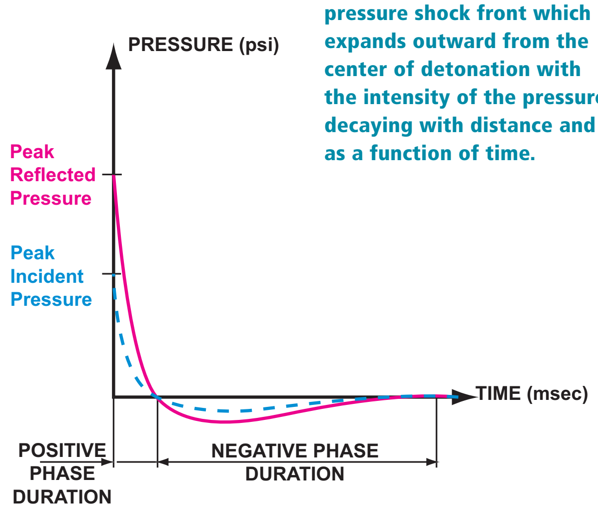


Figure A-2 Air-blast pressure time history - FEMA 427

The peak pressure is a function of the weapon size or yield, and the cube of the distance. For an explosive threat defined by its charge weight and standoff, the peak incident and reflected pressures of the shock wave and other useful parameters, such as the incident and reflected impulse, shock velocity, and time of arrival, are evaluated using charts available in military handbooks.

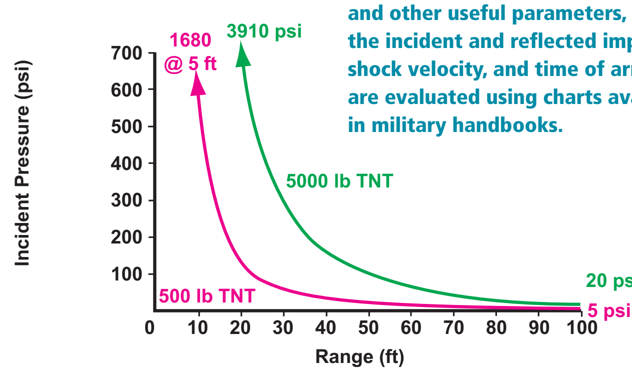


Figure A-3 Pressure decay with distance - FEMA 427

tances, to reduce the possibility of blast at close proximity to the structure.

Damage due to the air-blast shock wave may be divided into direct effects caused by the high-intensity pressures and progressive collapse. The damage caused by the pressure may cause localized failure of exterior walls, windows, roof systems, floor systems, and columns. Progressive collapse as defined previously refers to the spread of an initial local failure from element to element, resulting in a disproportionate collapse.

The magnitude of the pressure that affects building surfaces due to an explosion may be several times greater than the loads for which the building is designed. Also it is likely that the building may not have been designed for other shock wave effects such as upward pressure on the floor system.

As the shock wave travels, the air blast first collides with the exterior surface 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.

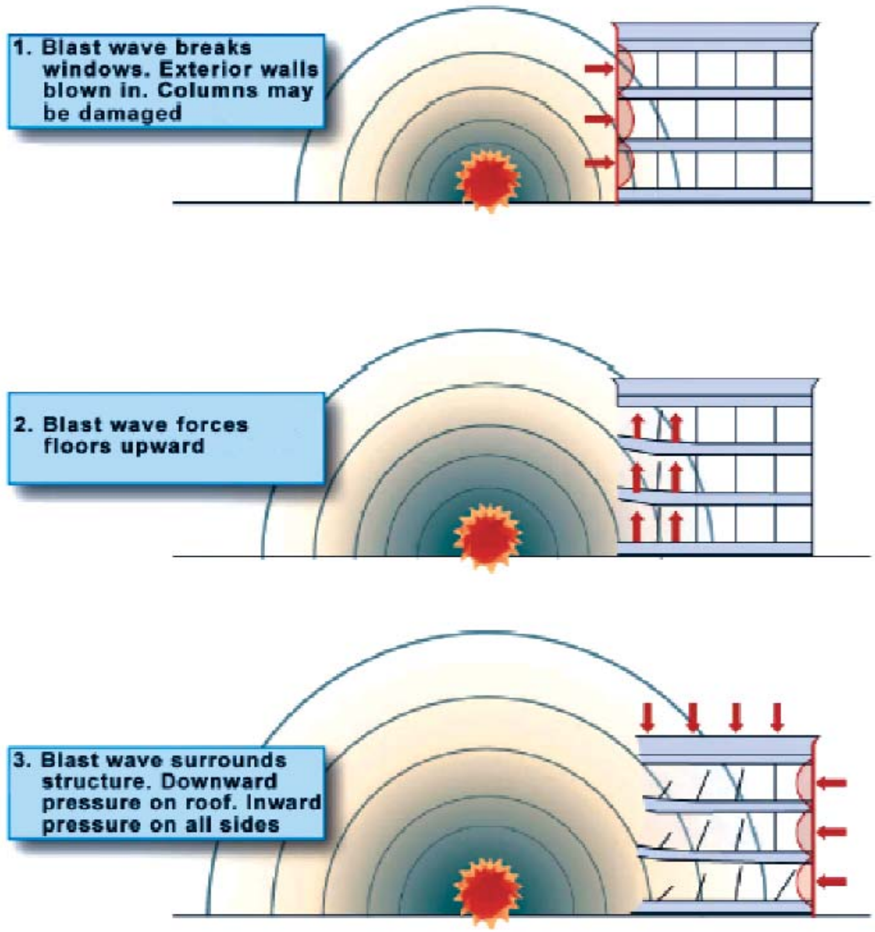


Figure A-4 Sequence of building damage due to external explosion - FEMA 427

References

1. *Primer for Design of Commercial Buildings to Mitigate Terrorist Attacks*, Federal Emergency Management Agency, FEMA 427, December 2003.
2. U.S. Department of the Army Technical Manual, TM5-1300, *Design of Structures to Resist the Effects of Accidental Explosions*, Washington, DC, 1990.
3. U.S. Department of the Army Technical Manual, TM5-885-1, *Fundamentals of Protective Design for Conventional Weapons*, Washington, DC, 1967.
4. *Blast Effects on Buildings*, G. C. Mays and P. D. Smith, Editors, Thomas Telford, 1995.

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