Defensive Design

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How can you design buildings for blast resistance? How do you design structures to prevent progressive collapse? Here are some answers for typical, prescriptive and performance-based building designs.

Provisions in the applicable building code are oriented almost exclusively toward life safety, with little consideration of property protection. Similarly, there are no explicit requirements for the consideration of blast and progressive-collapse resistance, except for general statements about resiliency, redundancy and robustness. This article gives guidance for typical buildings, and special cases of prescriptive and performance-based design for blast and progressive-collapse resistance.

Considerations for defensive design usually fall into one of three general categories:

Typical building designs: The majority of buildings receive no special treatment other than judicious attention to redundant configurations and robust connection designs so that the structural (and non-structural) components are tied together effectively. The typical details used in steel buildings inherently provide for redundancy and robustness, with the capability for load redistribution through alternative load paths. This fact has been demonstrated repeatedly when steel buildings have been subjected to abnormal loadings.

Prescriptive building designs: Some buildings receive special treatment through the application of prescriptive criteria for design that go beyond those in the basic building code. While there are a variety of prescribed criteria, such as the removal of a building column, there is usually no attempt to characterize the exact effects of the blast. Instead, the goal could be to reduce the probability of progressive collapse in areas not directly affected by the blast.

Performance-based building designs: Performance-based criteria are used for a small number of buildings, normally ones that are government-related, high-risk or high-profile. Performance criteria vary, but generally require that the building withstand the effects of the blast, protect the occupants of the building, and/or maintain a defined level of operability. The nature and characteristics of the threats are identified realistically and modeled in the design. Note that the performance criteria affect more than the structural frame, and often require non-structural elements, like blast-resistant windows, special site layouts, and site-perimeter protection.

Many designs combine prescriptive and performance-based approaches. Some guidance is available:

- The General Services Administration (GSA) published its "Progressive Collapse Analysis and Design Guidelines for New Federal Office Buildings and Major Modernization Projects," available for free download at www.oca.gsa.gov.

Designing for Defense – Step by Step

1. Create a complete security plan: consider non-structural solutions and avoid arbitrary structural choices without consideration of the actual security threat.
2. Determine the nature and magnitude of a potential blast loading:
    - the means of transport for explosives
    - the amount/type of explosive that can be delivered
    - the distance from the building an explosive could be placed

   Consider structural and non-structural solutions to potential threats.
3. Determine the level of structural design: typical (no special treatment); prescriptive (going beyond the basic building code with prescriptive criteria); and performance-based (for high-profile or high-risk buildings, design for the blast's dynamic loading).
4. For typical buildings: give attention to redundant configurations and robust connection designs
5. For prescriptive building designs: apply prescriptive criteria, such as perimeter moment frames, the use of a strong story or floor, or other innovative solutions.
6. For performance-based designs: Determine blast loading by calculating the total dynamic pressure and positive phase duration. Determine blast effects–consider member and connection ductility, overstrength, beneficial strain-rate effects, and the benefits of composite construction. Design for individual structural elements by applying the dynamic load to members of the structural system.

- The Department of Defense (DoD) published its "DoD Minimum Antiterrorism Standards for Buildings," available for free download at www.tisp.org/files/pdf/dodstandards.pdf.

More specialized and advanced guidance exists, particularly in terms of high-end defensive design such as for U.S. Department of State embassy buildings. Security clearance is required to obtain these documents.

BLAST THREAT ANALYSIS

When considering the need for blast-design criteria, a complete building security plan must be developed and the appropriate design criteria identified. The most critical aspects of a security plan could be non-structural in nature. Chemical and/or biological threats, alarm-system tampering, power disruption, arson, potable water-supply protection, protection of sensitive information, and computer network infiltration are all potential areas of need.

From a structural perspective, the use of prescribed "solutions" or arbitrary choices without consideration of the actual security threat(s) and effect(s) might do nothing but add cost or result in a building that fails to meet the needs of the owner or its occupants. The arbitrary use of concrete encasement, or the prescriptive reliance upon seismic detailing in applications where normal construction would suffice, wastes money. Who would choose to live or work in a windowless bunker?

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 – or location within – the building. Another factor is the level of security that can be placed around and withing the building.

- The means of transport for the explosives can be the limiting factor as to the amount of explosive that can be delivered. Does the threat include a package bomb, vehicle-borne bomb, both, or another means of delivery? Is there a security presence or feature that limits the distance or size at which the explosive can be delivered?
- The type of explosive is important because all explosives behave differently. Some types of explosives are easier to obtain than others.
- The distance from the building at which an explosive could be placed is perhaps the most critical factor. A large stand-off distance from the blast is essential to blast resistance. Can a defensible perimeter be used to ensure a certain stand-off distance?

Equally important is to determine what level of design is required: typical, prescriptive or performance based.

STRATEGIES FOR TYPICAL BUILDINGS

The majority of buildings receive no special design treatment, but the following ideas can be beneficial:

- Configure the building's lateral systems to provide multiple load paths from the roof to the foundations. Multiple lateral framing systems distributed throughout the building are generally better than fewer isolated systems.
- Provide horizontal floor and roof diaphragms to tie the gravity and lateral framing systems together.
- Minimize framing irregularities in both horizontal and vertical framing when possible. Horizontal and vertical offsets with copes and/or eccentricities can reduce the available strength at member ends – or require extensive reinforcement to maintain that strength.
- Use multiples of the same shape, rather than changing girder and column sizes. The additional strength in girders and columns that are heavier for convenience could cost less or be free. The use of a smaller number of different shapes in the building means a labor savings in fabrication and erection, and often more than offsets the cost of the additional steel weight, which is only around 20 cents per pound.
- Remember that serviceability limit states indirectly add significant structural redundancy to steel framing. Usually, beams and girders are sized for deflection or floor-vibration criteria, and girders and columns are commonly sized for drift control. As a result, these elements have significant reserve strength.
- Use typical shear, moment and/or bracing connections judiciously. Reserve strength is gained at low cost if connection details are clean. It costs little to fill the web of a girder with bolts using a single-plate or double-angle connection.
- Recognize other sources of redundancy and robustness inherent in steel buildings, including: the common overstrength in the steel materials and connecting elements, membrane action in the floor and roof diaphragms, and the strength and stiffness contributions of nonstructural components.

With little – sometimes no – modification, steel framing provides redundancy and robustness.

STRATEGIES FOR PRESCRIPTIVE BUILDING DESIGNS

Some buildings receive special treatment through the application of prescriptive criteria. An example is design for the removal of a building column, where several strategies can be employed:

The use of a perimeter moment frame. This can result in a system that is significantly robust. As an extreme example, the perimeter moment frame in the tube structure of each of the World Trade Center towers spanned a hole about 140' wide before succumbing to the combined effects of structural damage and fire, each likely at their lifetime maximum values. More likely, the prescribed criteria will be the removal of a single column.

In some cases, the framing will have enough redundancy to accept column removal without modification. If not, the column spacing can be reduced or the framing hardened by increasing size or switching to composite construction.

The use of a strong story or floor. This solution can be a truss system with diagonals or a Vierendeel truss system, incorporated into a single story or multiple stories in the building. Additionally, a recent study by Simpson Gumpertz and Heger Consulting Engineers demonstrated that a single, strong floor with heavier framing and moment connections throughout could carry or hang at least 10 floors.

The World Trade Center towers demonstrate this solution. The damaged core columns in each tower to some extent hung from the hat trusses, which created strong-story framing at the top of each tower. The link between the core gravity columns and the perimeter tube framing carried more than 10 stories in one tower and more than 25 stories in the other. Nonetheless, exercise caution when considering hat-truss framing to create a strong story. Unless specifically designed for progressive-collapse resistance, hat trusses normally reduce the level of reserve strength and redundancy because of the efficiency they allow in the structural system.

Other innovative solutions. One particularly innovative solution has been used by Magnusson Klemencic Associates in the Seattle Courthouse. The building has a steel-framed composite core and gravity steel framing around it. The perimeter has steel cables banding it to prevent progressive collapse should a column be lost. The result is one of the most open and inviting blast-hardened buildings built to date.

There are other potential prescriptive criteria, but structural solutions usually flow from criteria like those described above. Most often, there is no attempt to rigorously assess the actual blast effects and the emphasis is on arresting the effects of the blast.

STRATEGIES FOR PERFORMANCE-BASED BUILDING DESIGNS

Performance-based criteria are used for a comparatively small number of buildings, where the nature and characteristics of the threat are realistically identified and modeled in the design. When the threat, building characteristics, and performance criteria are known, the solution is a matter of design for the dynamic loading of the blast, including mitigation of damage and the associated progressive collapse potential. There are several references available. One is the U.S. Army Technical Manual TM5-1300 *Structures to Resist the Effects of Accidental Explosions*. Though written in the 1960s, it is still used today. Normally, software also is required to model the dynamic effects of the blast and the structure's response.

Determination of Blast Loading. The total dynamic pressure (in psi) and the positive phase duration (in milliseconds) are found using TNT equivalents (the equivalent weight of the explosive in TNT), the distance from the blast, and other information in TM5-1300. To calculate blast loads, the blast must be scaled. Hopkinson (1915) and Cranz (1926) formulated the most common form of blast scaling, postulating that similar blast waves are produced at identical scaled distances when two explosive charges of similar geometry and of the same explosive, but of different sizes, are detonated in the same atmosphere. The scaled distance parameter Z (ft per lb TNT equivalent) is:

$$Z = \frac{R}{W^{1/3}}$$

where R is equal to the distance from the center of the blast (ft) and W is the weight in lb TNT equivalent. With the scaled distance in the correct units, graphs in TM5-1300 can be used to find the total dynamic pressure and the positive phase duration.

Blast Effects on Structural Steel and Composite Structures. Steel's response to the characteristics of a blast affects the loading for several reasons:

- *Member Ductility:* Structural steel has a linear stress-strain relationship up to the yield stress but then can undergo extreme elongation without an increase in stress; about 10 to 15 times the amount needed to reach yield. Stress then increases in the "strain hardening" range until a total elongation of about 20 percent to 30 percent. This response has benefits beyond routine design-level forces for resisting the effects of a blast. The ductility ratio m, defined as the maximum deflection over the elastic deflection, commonly is used to account for this effect.
- *Connection Ductility:* Steel connections can be extremely ductile. As in seismic design practice, connections can be configured so that yielding-limit states will control over fracture-limit states. However, there is still significant ductility in many limit states that involve fracture. Block shear rupture, for example, is a fracture-limit state accompanied by significant deformation prior to the actual failure.

  Additionally, some limit states have "failures" that, in blast applications, can be considered benign or even beneficial. For example, there is little structural consequence to connection-slip or bearing deformations at bolt holes due to blast effects. Moreover, these phenomena consume energy when they occur, progressively reducing the blast effect through the structure.
- *Overstrength:* Structural steel usually is stronger than the specified minimum strength. For example, ASTM A992 has a specified minimum yield strength $F_y = 50$ ksi. From Table I-6-1 in the 2002 AISC Seismic Provisions, it has an expected yield strength F_{ye} of 55 ksi. This supports the practice endorsed by the Department of Defense Explosives Safety Board, which allows the use of an average yield-strength increase factor (generally a 10-percent increase in the yield strength) for blast design.
- *Beneficial Strain-Rate Effects:* Structural steel benefits from an increase in apparent strength when the rate of loading is rapid. The yield point increases substantially by a factor that is called the dynamic-increase factor for yield stress. The ultimate tensile stress also increases, but not as greatly as the yield stress. The total elongation at failure typically remains unchanged or decreases slightly because of the increased strain rate. The modulus of elasticity is unaffected by the strain rate.
- *Beneficial Effects of Composite Construction:* The use of composite construction can have benefits for blast-design applications due to the mass effect of composite systems with steel elements (490 lb/ft^3) and concrete elements (150 lb/ft^3). The inelastic action in a composite system generally will limit deflections and local deformations, and partially mitigate rebound effects through the damping effect of concrete cracking.

Designing the Individual Structural Elements for Blast Loads. Once the total dynamic pressure and the positive phase duration are known, apply the dynamic load to members of the structural system. One approach is recommended in TM5-1300.

- *Perimeter Column Design:* At the building perimeter, the columns will be loaded by the blast through the façade. A critical design decision is the selection of an appropriate tributary area for the column, which must be based upon the expected performance of the façade in the blast. Will the façade and its connection to the structure be such that the full blast load will be delivered to the framing, or will the façade components be shattered in the blast before the load can be delivered through it?

The tributary area is then used with the maximum total dynamic pressure and the dynamic load factor to find an equivalent static load on the column. Either a rigorous beam-column design approach or the simplified approach suggested in TM5-1300 can be used:

- Support conditions for the column are taken as if the column were a simple-span beam.
- The moment perpendicular to the plane of the façade is taken as $wl^2/8$ based upon the blast loading.
- The moment in the plane of the façade is a function of the magnitude of the strong-axis moment and the angle of incidence of the blast to the column.
- The axial load applied concurrently with the blast load is based upon the full dead load and one-quarter of the live load.

Based upon these loadings, TM5-1300 recommends checking limit states like flange-local buckling, web-local buckling, shear yield, and interaction between flexural and axial forces.

- *Perimeter Girder Design:* The consequences of a girder failure normally are not as high as the consequences of a column failure. If you are designing the girder to the same performance level as the columns, use the forgoing approach to column design for the girder design, without the axial load. Otherwise, use a less restrictive approach, permitting inelastic deformations. It is important to consider the differing support conditions between the top and bottom flanges of the girder. Often this can be mitigated by orienting the infill beams to provide restraint to the girder bottom flange along the span. Also, the girder end connections often will be best configured as moment connections.
- *Slab Design:* The blast pressure could subject the slab to significant uplift, depending upon the expected performance of the façade in the blast. As with girder design, the consequences of a local slab failure normally are not as high as the consequences of a column failure, so it could be sufficient to utilize the typical reinforcing steel in the upper portion of the slab. If a higher performance objective is established, the blast pressure can be applied to the slab and the reinforcement selected appropriate for the loading.

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REFERENCES

Cranz, C., “Lehrbuch der Ballistik, Springer-Verlag,” Berlin, 1926.

Department of Defense, DoD Minimum Antiterrorism Standards for Buildings, available for free download at www.tisp.org/files/pdf/dod-standards.pdf.

General Services Administration, Progressive Collapse Analysis and Design Guidelines for New Federal Office Buildings and Major Modernization Projects, available for free download at www.oca.gsa.gov.

Hopkinson, B., “British Ordnance Board Minutes,” 13565, 1915.

U.S. Army Technical Manual TM5-1300 Structures to Resist the Effects of Accidental Explosions. ★