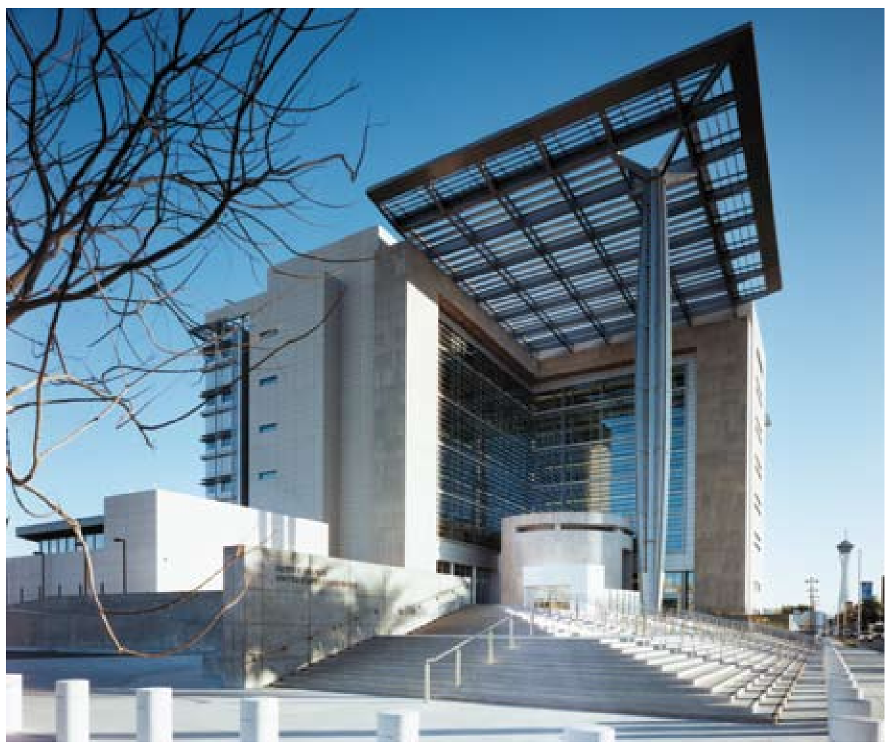
EXTERNAL BLAST RESISTANCE

In today's environment of enhanced risk, some facilities require protective design and the management of risk. There are many design options available to reduce the risk to any building. Economically feasible design for antiterrorism/force protection (AT/FP) requires an integrated approach encompassing many aspects of the development, including siting, operation programming of interior spaces, and the use of active and passive security measures using provisions of both technology and human involvement.

The objective of blast-resistant design is to provide an acceptable level of safety to building occupants in the event of an explosion. Considerable damage is usually acceptable as long as components remain attached to the building and the building does not experience a progressive collapse.

Planning must include all involved members of the design team (owners, architects, structural engineers, and blast consultants). They must agree upon the blast forces to be withstood as well as the risk and vulnerability assessment to the occupants and the protection levels that can be achieved within budget.



Lloyd D. George Federal Courthouse, Las Vegas, Nev.; Architect: Langdon Wilson; Photo: Langdon Wilson.

The first major federal courthouse built after the 1995 blast in Oklahoma City contains features intended to avoid a catastrophic collapse in the event of a terrorist attack. The precast concrete panels were designed to be more ductile than conventional panels so they could absorb as much of a bomb blast as possible without destroying the connections that tie them to the main structure. Note: Bollards used to increase the standoff distance.

Probability Considerations

An awareness of a blast threat from the beginning of design helps to make decisions early about what the priorities should be for the facility. Including protective measures as part of the discussion regarding trade-offs early in the process helps to clarify the issues.

The willingness to pay the additional cost for protection against blast hazards is a function of the "probability of regrets" in the event that a sizable incident occurs. In some situations, with some buildings, the small probability of an incident may not be compelling enough to institute the design enhancements.

This logic will likely lead to a selection process in which buildings stratify into two groups: those that incorporate no measures at all or only minimal provisions and those that incorporate high levels of protection. It also leads to the conclusion that it may not be appropriate to consider any but the most minimal measures for most buildings.

Key Considerations

Unlike seismic and wind loads, blast loads have an extremely short duration (i.e., milliseconds). Often, the large mass associated with the overall building response provides enough inertia so the building's framing does not need to be strengthened to resist blast loads. The lateral force-resisting system on smaller one- and two-story buildings generally needs to be designed to resist blast loads. Conventional foundation systems are almost always adequate to resist the short-duration reaction loads from building response to blast loads.

Quantifying blast events into overpressures and time durations is a science of its own. Blast engineers should be consulted when explosion scenarios are to be considered in the building's design.

A key consideration will be designing the building's façade, which is the structure's first defense against an exterior explosion. How the façade responds to this loading will significantly affect the structure's behavior. The need for comprehensive protection of occupants within the structure will likely cause window sizes to decrease in height and width and increase in thickness. Attachments likewise will become more substantial.

Architectural precast concrete can be designed to mitigate the effects of an explosion and thereby satisfy requirements of the General Services Administration (GSA) and the Department of Defense (DOD). Protecting the entire façade, however, will impose a great cost regardless of the material used. To provide the best protection for occupants, designers should plan for the building and its cladding to remain standing or attached long enough to protect occupants from injury or death resulting from flying debris and to evacuate everyone safely.

The shape of the building can affect the overall damage. A U- or an L-shaped building can trap the shock wave, which may increase blast pressure locally because of the complex reflections created. Large or gradual re-entrant corners have less effect than small or sharp re-entrant corners. In general, convex rather than concave shapes are preferred. The reflected pressure on the surface of a circular building is less intense than on a flat building.

Currently, no specific standards or guidelines exist for blast design from either the American Concrete Institute (ACI) or the PCI.

All building components requiring blast resistance should meet the criteria required for GSA or DOD facilities. They should be designed using established methods and approaches for determining dynamic loads and dynamic structural response. Design and analysis approaches should be consistent with the following manuals:

- U.S. Departments of the Army, Navy and Air Force, “Structures to Resist the Effects of Accidental Explosions,” Revision 1 (Department of the Army Technical Manual TM 5-1300, Department of the Navy Publication NAVFAC P-397, Department of the Air Force Manual AFM 88-22).
- DAHSCWEMAN, “Technical Manual – Design and Analysis of Hardened Structures to Conventional Weapon Effects; PSADS (Protective Structures Automated Design System), Version 1.0.” (It incorporates Army TM 5-855-1, Air Force AF JMAN32-1055, Navy NAVFAC P-1080, and Defense Special Weapons Agency DAHSCWEMAN-97).
- Unified Facilities Criteria, “Design and Analysis of Hardened Structures to Conventional Weapons Effects,” U.S. Department of Defense, UFC 3-340-01, June 2002.
- Hyde, D. “ConWep – Application of TM5-855-1,” U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., August 1992.
- U.S. Department of the Army, Security Engineering, TM 5-853 and Air Force AFMAN 32-1071, Volumes 1-4, Washington, DC, Departments of the Army and Air Force, 1994.
- Air Force Engineering & Services Center, “Protective Construction Design Manual,” ESL-TR-87-57, Prepared for Engineering & Services Laboratory, Tyndall Air Force Base, Fla., November 1989.
- U.S. Department of Energy, “A Manual for the Prediction of Blast & Fragment Loadings on Structures,” Revision 1, DOE/TIC 11268, Washington, DC, Headquarters U.S. Department of Energy, July 1992.
- Unified Facilities Criteria, DOD Minimum Antiterrorism Standards for Buildings, UFC 4-010-01, U.S. Department of Defense, July 2002.
- Interim Antiterrorism/Force Protection Construction Standards – Guidance on Structural Requirements (Draft), U.S. Department of Defense, March 5, 2001.

Designing for blast resistance requires a comprehensive knowledge of explosive effects and fortification sciences, as described in DAHSCWEMAN (1998), in Technical Manual (TM) 5-855-1 (U.S. Department of the Army 1998), and in the Tri-Service Manual (TM-5-1300, U.S. Department of the Army, Navy, and Air Force 1990). The electronic version of the DAHSCWEMAN manual will greatly assist in applying blast-design concepts.

The report “Design for Physical Security—State of the Practice Report,” prepared by the Structural Engineering Institute Task Committee, American Society of Civil Engineers (1999), addresses the design of structures to resist the effects of terrorist bombings and provides guidance for engineers.

Creating Standoff Distance

Basic protection is produced by creating a minimum guaranteed distance between the blast source and the target structure. The setback zone restricts vehicular access by using dense components such as perimeter anti-ram bollards, large planters, low-level walls, or fountains. Creating this standoff distance helps minimize the design requirements for protecting the building cladding and structural elements.

The blast pressure is inversely proportional to the cube of the distance from the blast to the point in question. Current design standoff distances for blast protection vary from 33 ft to 148 ft, depending on the building's function.

Nimitz-MacArchur Pacific Command Center, Oahu, Hawaii; Architect: Wimberly Allison Tong & Goo Design; Photo: Gary Hofheimer Photography.

The four lowest stories of the building will be most impacted by a street-level blast and must follow accepted blast criteria. Those criteria are described in "Security Design Criteria for New Federal Office Buildings and Major Renovation Projects," issued May 28, 2001, by the Interagency Security Committee (ISC).

When designing with architectural precast concrete panels, designers should combine these criteria with the applicable blast-analysis standards. This combination ensures that the architectural precast concrete cladding system will be sufficiently sized, reinforced, detailed, and installed to resist the required blast-loading criteria.

The panels should also be tested in accordance with "Standard Test Method for Glazing and Window Systems Subject to Dynamic Overpressure Loadings (GSA-TS01-2003), released by the General Services Administration.

In addition to safely transferring the blast pressures into the supporting structure, the panels must be checked for their capacity to transfer the additional loading caused by the specified window framing and the blast-resistant glass units.

Preventing Progressive Collapse

Several significant factors must be considered when designing buildings for blast resistance. These concepts include energy absorption, safety factors, limit states, load combinations, resistance functions, structural-performance, and structural redundancy to prevent progressive collapse of the building. This final one is most important, as a design satisfying all required strength and performance criteria would be unsatisfactory without redundancy.

To limit the extent of collapse of adjacent components requires five steps:

1. Highly redundant structural systems are designed.
2. The structure is analyzed to ensure it can withstand removal of one primary exterior vertical or horizontal load-carrying element, such as a column, beam, or portion of a loadbearing or shear-wall system without complete collapse of the entire structure.
3. Connections are detailed to provide continuity across joints equal to the full structural capacity of connected members.

4. Floors are designed to withstand load reversals due to explosive effects.
5. Exterior walls use one-way wall components spanning vertically to minimize blast loads on columns.

Strength and ductility (energy-dissipating capacity) are necessary to achieve high energy absorption. The structural materials and details must accommodate relatively large deflections and rotation to provide redundancy in the load path. Components with low ductility are undesirable for blast-resistant design.

Margins of safety against structural failure are achieved by using allowable deformation criteria. Structures subjected to blast loads are typically allowed to undergo permanent plastic deformation to absorb the explosion energy, whereas response to conventional loads is normally required to remain in the elastic range. The component's response is determined by how much deformation it is able to undergo before failure.

The more deformation the structure or member can provide, the more blast energy it can absorb. As long as the calculated deformations do not exceed the allowable values, a margin of safety against failure exists.

Rigidity versus Ductility

A balance must be found between panel stiffness and the forces that the panel connections must resist. The proper balance must be evaluated by the structural engineer. Typically, the panels should have increased section thickness or ribs and have additional reinforcement, which should be placed on both faces of the panel to resist load reversals. However, the amount of flexural reinforcing should be limited so that tensile reinforcing yields before concrete crushing can occur. Shear steel can help increase shear resistance, confine the flexural reinforcing, and prevent buckling of bars in compression. The mode of failure should be that of the panel itself in flexure and not failure of the connections or a shear failure of the panel.

The 6-in.-thick x 22-ft-tall panels were reinforced with ribs spaced 6 ft apart.

A minimum panel thickness of 5 in., exclusive of reveals, should be designed. The panels also should include two-way reinforcing bars spaced not greater than the panel's thickness to increase ductility and reduce the chance of flying concrete fragments. The thinnest panel thickness acceptable for conventional loads should be used. The objective is to reduce the loads transmitted into the connection, which must resist the panel's ultimate flexural resistance.

The following features typically are incorporated into precast concrete panel systems to accommodate blast loading:

- Panel sizes should be increased to two stories tall or one bay wide, at least, to increase their ductility. Panels can then absorb a larger portion of the blast energy and transfer less through connections to the main structure.
- Panels should be connected to floor diaphragms rather than to columns, to prevent applying lateral loads to the columns.

- Panels may be designed with integrally cast and reinforced vertical pilasters or ribs on the back to provide additional support and act as beams that span floor-to-floor to take loads. This rib system makes the panels more ductile and better able to withstand an external blast, but it also forces the window fenestration into a punched-opening symmetry.

Loadbearing precast panels must be designed to span failed areas through arching action, strengthened gravity connections, secondary support systems, or other ways of providing an alternative load path.

Connection Concepts

Precast concrete wall-panel connections for blast-loading conditions can be designed as strengthened versions of conventional connections, with a likely significant increase in connection hardware. They also may be designed as connection details that emulate cast-in-place concrete to provide building continuity.

For a panel to absorb blast energy and provide ductility while being structurally efficient, it must develop its full plastic-flexural capacity, which assumes the development of a collapse mechanism. The failure mode should result in yielding of the steel, not the connection splitting, spalling, or pulling out of the concrete. This means that structural steel connection material must be designed for 5% to 10% more than tensile and yield strength. The connection's shear capacity also should be at least 20% higher than the member's flexural capacity.

Steel-to-steel connections should be designed so the weld is never the weak link in the connection. Where possible, connection details should provide redundant load paths, since connections designed for blast may be stressed to near their ultimate capacity, and the possibility of single-connection failures has to be considered. The number of components in the load path and the consequences of a failure of any one of them will also be a factor.

The key concept in the development of these details is to trace the load or reaction through the connection. This is more critical in blast design than in conventionally loaded structures. Connections to the structure should have as direct a load path as practical, using as few connecting pieces as possible.

It is also important that connections for blast-loaded members have sufficient rotational capacity. A connection may have sufficient strength to resist the applied load, but when significant deformation of the member occurs, this capacity may be reduced due to rotation of the connection. Both bolted and welded connections can perform well in a blast environment if they can develop strength at least equal to that of the connected components.