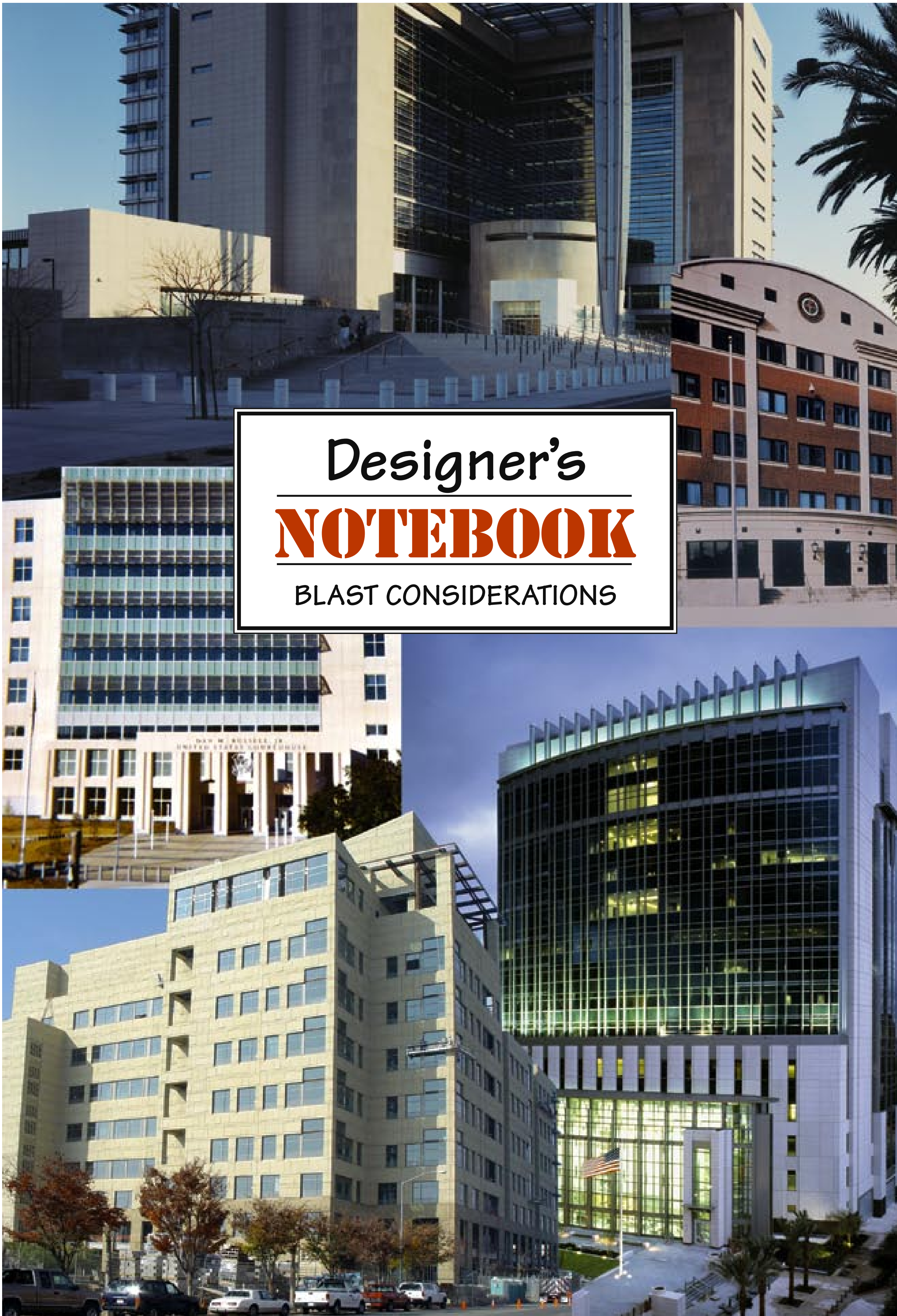

Designer's NOTEBOOK

BLAST CONSIDERATIONS

Design Considerations for Blast Resistance of Architectural Precast Concrete Façades

PCI's Architectural Precast Concrete Services Committee discusses items to consider in designing for 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.

The goal of protective design against the effects of blast is the protection of the building occupants and the reduction of casualties. Economically feasible design for antiterrorism/force protection (AT/FP) requires an integrated approach to facility siting, operation programming of interior spaces, employment of active and passive security measures employing both technological security provisions and human security provisions. This paper addresses the important element of design of the architectural façade as one element of the protective design chain.

Designing a structure that could face a threat from a terrorist bombing which could originate either external or internal to the structure requires finding the most effective way to meet the standards for enhanced safety that currently exist. This article only addresses external blasts. When considering protection for a building, owners and architects must work with structural engineers and blast consultants to determine the blast forces to protect against, considering the risk and vulnerability assessments and protection levels. Optimally, blast mitigation provisions for a new building should be addressed in the early stages of project design to minimize the impact on architecture and cost. Defensive design often affects aesthetics, accessibility, fire safety regulations, and budgetary constraints.

The building's exterior is its first real defense against the effects of a bomb. How the façade responds to this loading will significantly affect the behavior of the structure. Although this article is primarily concerned with the façade, some design concepts for the structure are discussed. The comprehensive protection of occupants within the structure is likely to cause window sizes to decrease in height and width, yet increase in thickness, and attachments to become more substantial. Considering the extent of surface area enclosing a building, even modest levels of protection will be expensive. As a result, the design philosophy might best be served by concentrating on the improvement of the post-damaged behavior of the façade. In order to protect the occupants to the highest degree, the aim should be for the building and its cladding components to remain standing or attached long enough to evacuate every person and to protect occupants from injury or death resulting from flying debris.

Several types of hazards can affect building systems (structural or architectural). These hazards can be subdivided into two general categories: man-made (blast) and natural (earthquakes, wind, etc). For a successful approach to any system design, it is essential to understand the nature of the hazard. Dynamic hazards can be described by their relative amplitudes and relative time (frequency) attributes. Fig. 1 shows a schematic representation of the amplitude-frequency relationships of several dynamic hazards.

It is important to emphasize the principal differences between static, dynamic and short-duration dynamic loads. Typically, static loads do not produce inertia effects in the structural response, are not time dependent, and are assumed to act on the structure for long periods of time (e.g. gravity loads). Dynamic loads, such as induced by earthquake or wind gusts, have strong time dependencies and their typical durations are measured in tenths of seconds. Short-duration dynamic loads, such as those induced by explosions or debris impact, are nonoscillatory pulse loads, and their duration is about 1,000 times shorter than the duration of typical earthquakes. Structural response under short-duration dynamic effects could be significantly different than the much slower loading cases, requiring the designer to provide suitable structural details. Therefore, the designer must explicitly address the effects related to such severe loading environments, besides the general principles used for structural design to resist conventional loads. As a starting point, the reader should review background material on structural considerations and design in the references in the Blast Analyses Standards section of this article.

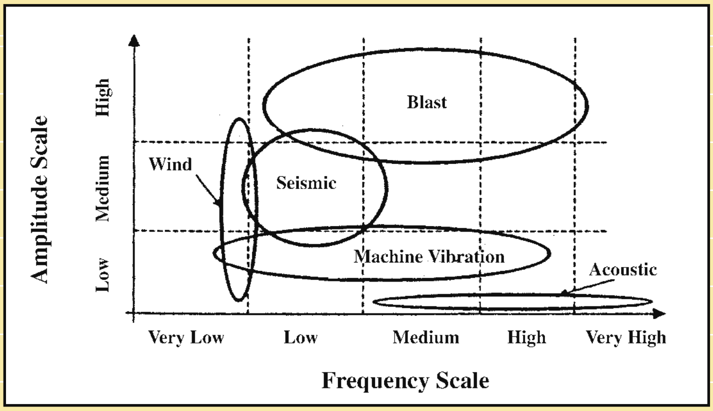

Fig. 1 – Qualitative amplitude-frequency distribution for different hazards. SOURCE: Ettouney, M., "Is Seismic Design Adequate for Blast?" Society of American Military Engineers National Symposium on Comprehensive Force Protection, Charleston, S.C., November 2001.

There are conflicting hazard demands on cladding relating to the weight or mass of a typical wall. For a seismic hazard, the forces on the wall are directly proportional to its mass. Forces that are produced from a blast hazard are inversely proportionate to the mass of the cladding. In some panel configurations, increasing the mass of the panel can provide improvements in the response of the panel to a defined level of blast loading. Wind-produced internal forces are independent of the wall mass. This produces a dilemma for the designer: higher mass would be beneficial in a blast condition, but be harmful in an earthquake condition. Obviously, an optimization or balanced design is needed in such a situation, with the understanding that both hazards require ductile behavior from the cladding and connections. However, the manner the cladding-structure interacts when subjected to each of the two hazards is completely different. During earthquakes, the movement of the structure will impose forces on the cladding. During a blast event, the cladding would impose reactions (through the connections) on the structure.

Blast Basics

An explosion is a very rapid release of stored energy characterized by an audible blast. Part of the energy is released as thermal radiation, and part is coupled into the air (air-blast) and soil (ground-shock) as radially expanding shock waves. Air-blast is the principal damage mechanism. Air-blast phenomena occur within milliseconds and the local effects of the blast are often over before the building structure can globally react to the effects of the blast. Also, initial peak pressure intensity (referred to as overpressure) may be several orders of magnitude higher than ambient atmospheric pressure. The overpressure radiates from the point of detonation but decays exponentially with distance from the source and time and eventually becomes negative (outward-rushing force) subjecting the building surfaces to suction forces as a vacuum is created by the shock wave, see Fig. 2. In many cases, the effect of the negative phase is ignored because it usually has little effect on the maximum response. The maximum impulse delivered to the structure is the area under the positive phase of the reflected pressure-time curve. Both the pressure and impulse (or duration time) are required to define the blast loading.

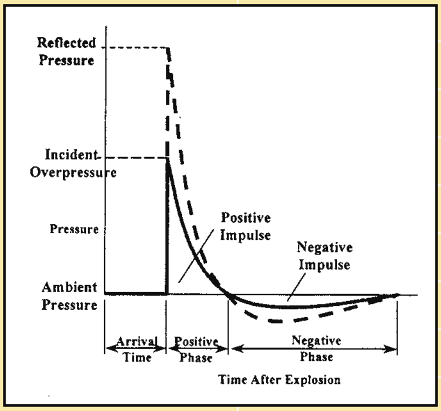

Fig. 2 – Qualitative pressure-time history. SOURCE: "Structures to Resist the Effects of Accidental Explosions," TM5-1300, November, 1990.

The shape of the building can affect the overall damage to the structure. For example, "U"- or "L-shaped" buildings may 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 for the exterior of the building. The reflected pressure on the surface of a circular building is less intense than on a flat building. The extent of damage depends on the yield or charge weight (measured in equivalent lbs. of TNT), the relative position of the explosive device, and the design details. The shock waves compress air molecules in its path, producing overpressure. When the shock waves encounter the building surfaces, they are reflected, amplifying the overpressure so that it is higher than the initial peak pressure. These blast load pressures can greatly exceed wind and seismic design loads. Therefore, it is typically costly for most buildings to be designed to withstand a large explosion in, or very near the building.

A secondary effect of the air-blast is dynamic pressure or drag loading, which is a very high velocity wind. It propels the debris generated by the air-blast, creating secondary projectiles. Also, the building is subject to the ground-shock, which produces ground motions sometimes similar to a short duration earthquake.

The response of a building to a large explosion occurs in distinct phases. Initially, as the blast wave contacts the nearest exterior wall of the building, windows are shattered, and the walls and columns deflect under the reflected pressure. If the blast intensity is sufficient, the wall eventually deforms inelastically and suffers permanent displacement or collapse. The internal pressure exerts a downward and upward pressure on the floor slabs, depending upon the expected performance of the façade in the blast. If the façade remains intact during a blast event this limits the propagation of the blast pressures within the building. The upward pressure is important because columns and slabs are not ordinarily designed for such loads. As the blast wave expands and diffracts around the building, it exerts an overpressure on the roof, side walls and, finally, on the walls of the far side, see Fig. 3. Although the pressure levels on the three sides facing away from the blast are smaller

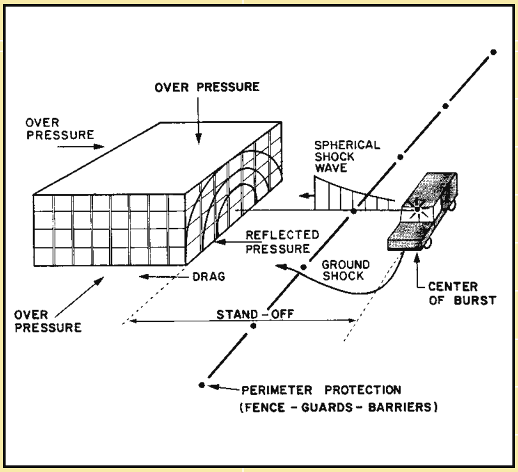

Fig. 3 – Blast loading on buildings. SOURCE: "Concrete and Blast Effects," ACI SP 175, American Concrete Institute, Farmington Hills, Mich., 1998.

than those on the front, they are significant. Since the location of the explosion cannot be anticipated, each building face must be designed for the worst case, i.e., an explosion normal to that face. Internal pressure may be reduced by decreasing the size and number of openings or by using blast resistant glazing and doors.

Blast characteristics are very different in open air versus confined spaces. Parking structures have varying degrees of openness or vent area and the blast response will be very structure specific. Confined and contained explosions produce very complex pressures within and exiting from the structure. Confined explosions include a reflected shock wave phase and a gas-loading phase. The reflected shock wave phase is similar to an open-air blast except that they are much more complex due to reverberation off various surfaces in the structure. The gas-loading phase is due to the confined space not being able to vent the gases from the explosion. The result is a much longer lasting and potentially more damaging pressure being applied to the structure.

Blast Analyses Standards

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

1) U.S. Departments of the Army, the Navy and the 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), Washington, DC, November, 1990. (This reference in combination with Con Wep software guides designer in the calculation of the pressure and related information necessary to perform an analysis for the structure.) Contact David Hyde, U.S. Army Engineer Research and Development Center, 3909 Halls Ferry Road, Vicksburg, Mississippi 39180 or via e-mail to hyded@ex1.wes.army.mil.
2) DAHSCWEMAN, "Technical Manual - Design and Analysis of Hardened Structures to Conventional Weapon Effects; PSADS (Protective Structures Automated Design System), Version 1.0" (incorporating Army TM 5-855-1, Air Force AFJMAN32-1055, Navy NAVFAC P-1080, and Defense Special Weapons Agency DAHSCWEMAN-97), Headquarters, U.S. Army Corps of Engineers (CEMP-ET), Washington, DC, September, 1998.
3) Unified Facilities Criteria, "Design and Analysis of Hardened Structures to Conventional Weapons Effects," U.S. Department of Defense, UFC 3-340-01, June 2002. **[For Official Use Only]** [Formerly Army TM 5-855-1].
4) Hyde, D., "ConWep - Application of TM 5-855-1," U.S. Army Engineer Waterways

Experiment Station, Vicksburg, MS, August, 1992. Con Wep is a collection of conventional weapon effects calculations from the equations and curves of TM 5-855-1.

5) U.S. Department of the Army, Security Engineering, TM 5-853 and Air Force AFMAN 32-1071, Volumes 1, 2, 3, and 4. Washington, D.C., Departments of the Army and Air Force. (1994).

6) Air Force Engineering and Services Center, "Protective Construction Design Manual," ESL-TR-87-57. Prepared for Engineering and Services Laboratory, Tyndall Air Force Base, FL., November 1989.

7) U.S. Department of Energy, "A Manual for the Prediction of Blast and Fragment Loadings on Structures," Revision 1, DOE/TIC 11268. Washington, DC, Headquarters U.S. Department of Energy, July, 1992.

8) Unified Facilities Criteria, DoD Minimum Antiterrorism Standards for Buildings, UFC 4-010-01. U.S. Department of Defense, July, 2002.

9) Interim Antiterrorism/Force Protection Construction Standards – Guidance on Structural Requirements (DRAFT), U.S. Department of Defense, March 5, 2001.

It is likely that to design against blast will require a comprehensive knowledge of explosive effects and fortification sciences, such as described in the 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. Departments of the Army, Navy, and Air Force 1990). The electronic version of the DAHSCWEMAN manual will greatly assist designers in applying blast design concepts.

Also the report "Structural Design for Physical Security: State of the Practice," prepared by the Structural Engineering Institute Task Committee, Edward J. Conrath, et al, American Society of Civil Engineers, (1999) addresses the design of structures to resist the effects of terrorist bombings. It provides guidance for structural engineers charged with designing for blast resistance of civil facilities.

Determination of Blast Loading

Currently there are no formal blast performance criteria for civilian buildings. The U.S. Department of Defense, Department of State, and General Services Administration have developed specific antiterrorism requirements for military, embassy, and federal buildings, respectively. However, for security reasons key portions of these criteria are only available to designers of specific projects to which they apply. Table 1 provides some recommendations for private-sector facilities. In all cases the designer's goal is to balance the nature and probability of each threat with the additional costs of protecting against it.

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 the building. Another factor is the level of security that can be placed around the building.

The design vehicle weapon size that is considered will usually be much smaller than the largest credible threat, measured say in the hundreds of pounds rather than the thousands of pounds of TNT equivalent. The decision is usually based on a trade off between the largest credible attack directed against the building and the design constraints of the project. Further, the design pressures and impulses may be less than the actual peak pressures and impulses may be less than the actual peak pressures and impulses acting on the building. This is the approach that the federal government has taken in their design criteria for federally owned domestic office buildings.

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 = W) and the distance from the blast = R. To calculate blast loads, the blast must be scaled. 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: $Z = \frac{R}{W^{1/3}}$

Table 1. Recommended Antiterrorism Design Criteria (Conrath et. al.)

Tactic	Parameter	Estimated Likelihood of Terrorist Attack				Measurement of Standoff Distance *R*
		Low	Medium	High	Very High	
Vehicle Bomb	Vehicle Size* (lbs GVW)	4,000	4,000	5,000	12,000	Controlled Perimeter, Vehicle Barrier, Or Unsecured Parking/Road
	Charge Size *W* (lbs TNT)	50	100	500	2,000	
Placed Bomb	Charge Size *W* (lbs TNT)	0	2	100	100	Unobstructed Space or Unsecured Parking/Road
Standoff Weapon	Charge Size *W* (lbs TNT)	2	2	50	50	Neighboring Structure
*For barrier design, with maximum velocity based on site configuration.						

SOURCE: Schmidt, Jon A., "Structural Design for External Terrorist Bomb Attacks," NCSEA, Structure magazine (www.structuremag.org), March, 2003.

With the scaled distance in the correct units, published curves can be used to find the total dynamic pressure and the positive phase duration.

Although the angle of incidence at which a blast wave strikes the building surface also influences these parameters, it is usually conservative to neglect this adjustment. Either way, in order to obtain the blast load, a number of different tools can be used. Tables of pre-determined values may be used (see GSA Security Reference Manual: Part 3 – Blast Design & Assessment Guidelines, July 31, 2001) or computer programs can perform these calculations and provide much greater accuracy. One such software product, AT Blast, is available for downloading free of charge from the U.S. General Services Administration (www.oca.gsa.gov). Designers of government projects may request Con Wep, another software product, through the agency that they have a contract with. Con Wep is a collection of conventional weapons effects calculations from the equations and curves of TM 5-855-1. Users should be thoroughly familiar with TM 5-855-1 before using this program as a design tool.

Although the actual blast load on an exposed element will vary over its tributary area, for design the maximum dynamic load is typically taken as the product of this area and either the maximum pressure or a spatially averaged value. This is analogous to the manner in which design wind loads for components and cladding are routinely calculated. Blast loads need not be factored since they already represent an ultimate design condition.

Blast Effects Predictions

After the blast load has been predicted, damage levels may be evaluated by explosive testing, engineering analysis, or both. Often, testing is too expensive an option for the design community and an engineering analysis is performed instead. To accurately represent the response of an explosive event, the analysis needs to be time dependent and account for non-linear behavior.

Non-linear dynamic analysis techniques are similar to those currently used in advanced seismic analysis. Analytical models range from equivalent single-degree-of-freedom (SDOF) models to finite element (FEM) representation. In either case, numerical computation requires adequate resolution in space and time to account for the high-intensity, short-duration loading and non-linear response. The main problems are the selection of the model, the appropriate failure modes, and finally, the interpretation of the results for structural design details. Whenever possible, results are checked against data from tests and experiments on similar structures and loadings. Available computer programs include:

- AT Planner (U.S. Army Engineer Research and Development Center)
- BEEM (Technical Support Working Group)
- BLASTFX (Federal Aviation Administration)

Components such as beams, slabs, or walls can often be modeled by a SDOF system and the governing equation of motion solved by using numerical methods. There are also charts developed by J.M. Biggs in "Introduction to Structural Dynamics," McGraw-Hill Publishing Company, 1964, and military handbooks for linearly decaying loads, which provide the peak response and circumvent the need to solve differential equations. These charts require only knowledge of the fundamental period of the element, its ultimate resistance force, the peak pressure applied to the element, and the equivalent linear decay time to evaluate the peak displacement response of the system. The design of the anchorage and supporting structural system can be evaluated by using the ultimate flexural capacity obtained from the dynamic analysis. Other charts are available which provide damage estimates for various types of construction based on peak pressure and peak impulse based on analysis or empirical data. Military design handbooks typically provide this type of design information.

For SDOF systems, material behavior can be modeled using idealized elastic, perfectly-plastic stress-deformation functions, based on actual structural support conditions and strain-rate-enhanced material properties. The model properties selected to provide the same peak displacement and fundamental period as the actual structural system in flexure. Furthermore, the mass and the resistance functions are multiplied by mass and load factors, which estimate the actual portion of the mass or load participating in the deflection of the member along its span.

For more complex elements, the blast consultant must resort to finite-element numerical time integration techniques. The time and cost of the analysis cannot be ignored when choosing design procedures. SDOF models are suitable for numerical analysis on PCs, but the most sophisticated FEM systems (with non-linear material models and options for explicit modeling of reinforcing bars) may have to be carried out on servers. Because the design analysis process is a sequence of iteration, the cost of analysis must be justified in terms of benefits to the project and increased confidence in the reliability of the results. In some cases, an SDOF approach will be used for the preliminary design and a more sophisticated approach, using finite elements, will be used for the final verification of the design.

A dynamic non-linear approach is more likely than a static approach to provide a section that meets the design constraints of the project. Elastic static calculations are likely to give overly conservative design solutions if the peak pressure is considered without the effect of load duration. By using dynamic calculations instead of static, it is possible to account for the very short duration of the loading. Because the peak pressure levels are so high, it is important to account for the short duration of the loading to properly model the structural response. In addition, the inertial effect included in dynamic computations greatly improves response. This is because by the time the mass is mobilized; the loading is greatly diminished, enhancing response. Furthermore, by accepting that damage occurs it is possible to account for the energy absorbed by ductile systems through plastic deformation. Finally, because the loading is so rapid, it is possible to enhance the material strength to account for strain-rate effects.

Both concrete and reinforcing steel subjected to the very short duration impulse type loading caused by a blast exhibit a higher strength than similar elements subjected to a static loading. The stiffness and strength of both steel reinforcement and concrete are likely to increase with the higher rate of loading under blast conditions. This obviously increases the strength of reinforced concrete members which translates into higher dynamic resistance. But the high rate of loading expected during blasts is also likely to significantly reduce the deformation capacity and the fracture energy of reinforced concrete. This translates into reduction of ductility of reinforced concrete in blast loading situations.

In dynamic non-linear analysis, response is evaluated by comparing the ductility (i.e., the peak displacement divided by the elastic limit displacement) and/or support rotation (the angle between the support and the point of peak deflection) to empirically established maximum values that have been established by the military through explosive testing. Not that these values are typically based on limited testing and are not well defined within the industry at this time. Maximum permissible values vary, depending on the material and the acceptable damage level.

If static design methods are used, it is recommended that an equivalent static pressure be used rather than the peak air-blast pressure. The peak air-blast pressure generally leads to over-designed sections that are not cost effective, add weight to the structure, and are difficult to construct.

Specifications for precast elements can be either in the form of a performance requirement, with the air-blast pressures and required performance provided, or as a prescriptive specification with equivalent static pressures provided. The equivalent static pressures are computed based on the peak dynamic response of the panel for the defined threat. The performance specifications give the precaster more flexibility to provide the systems with which they are most familiar. However, it requires that the precaster either have in-house dynamic analysis capability or have a relationship with a blast engineer who can work with them to customize the most cost-effective system.

On the other hand, as static equivalent pressures are based on the specific panel's response to the air-blast load, changing dimensions, reinforcement, or supported elements would require recalculation of the static equivalent load. However, when using the static equivalent loads, the designer may proceed normally with the lateral design process, using a load factor of one.

Note that equivalent static values are different from quasi-static values which assume a displacement ductility less than one. The equivalent static values are based on computations that are non-linear, with ductilities in excess of one.

Levels of damage computed by means of analysis may be described by the terms minor, moderate, or major, depending on the peak ductility, support rotation and collateral effects. A brief description of each damage level is given below.

Minor: Nonstructural failure of building elements such as windows, doors, curtain walls, and false ceilings. Injuries may be expected, and possible fatalities are possible but unlikely.

Moderate: Structural damage is confined to a localized area and is usually repairable. Structural failure is limited to secondary structural members such as beams, slabs, and non-loadbearing walls. However, if the building has been designed for loss of primary members, localized loss of columns may be accommodated. Injuries and some fatalities are expected.

Major: Loss of primary structural components such as columns or transfer girders precipitates loss of additional adjacent members that are adjacent to or above the lost member. In this case, extensive fatalities are expected. Building is usually not repairable.

Generally, moderate damage at the design threat level is a reasonable design goal for new construction.

Table 2 provides estimates of incident pressures at which damage may occur.

Table 2 Damage Approximations

Damage	Incident Overpressure (psi)
Typical window glass breakage	0.15 – 0.22
Minor damage to some buildings	0.5 – 1.1
Panels of sheet metal buckled	1.1 – 1.8
Failure of concrete block walls	1.8 – 2.9
Collapse of wood framed buildings	Over 5.0
Serious damage to steel framed buildings	4 – 7
Severe damage to reinforced concrete structures	6 – 9
Probable total destruction of most buildings	10 – 12

SOURCE: Explosive Shocks in Air, Kinney & Grahm, 1985; Facility Damage and Personnel Injury from Explosive Blast, Montgomery & Ward, 1993; and The Effects of Nuclear Weapons, 3rd Edition, Glasstone & Dolan, 1977

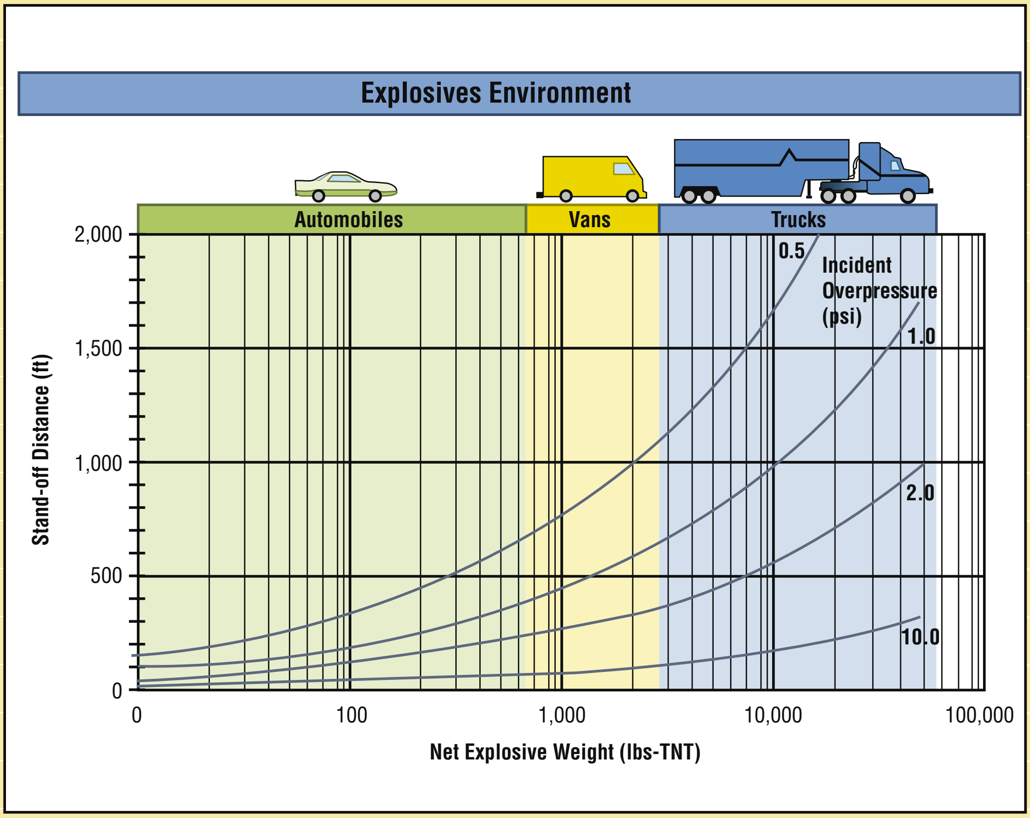

Fig. 4 – Incident overpressure measured in pounds per square inch, as a function of stand-off distance and net explosive weight (pounds-TNT).
Source: Federal Emergency Management Agency. Reference Manual to Mitigate Potential Terrorist Attacks. FEMA 426 (Washington, DC: Federal Emergency Management Agency, December 2003).

Fig. 4 provides a quick method for predicting the expected overpressure (expressed in psi) on a building for a specific explosive weight and stand-off distance. Enter the x-axis with the estimated explosive weight a terrorist might use and the y-axis with a known stand-off distance from a building. By correlating the resultant effects of overpressure with other data, the degree of damage that the various components of a building might receive can be estimated. The vehicle icons in Figs. 4 and 5 indicate the relative size of the vehicles that might be used to transport various quantities of explosives.

Fig. 5 shows an example of a range-to-effect chart that indicates the distance or stand-off to which a given size bomb will produce a given effect. This type of chart can be used to display the blast response of a building component or window at different levels of protection. It can also be used to consolidate all building response information to assess needed actions if the threat weapon-yield changes. For example, an amount of explosives are stolen and indications are that they may be used against a specific building. A building-specific range-to-effect chart will allow quick determination of the needed stand-off for the amount of explosives in question, after the explosive weight is converted to TNT equivalence.

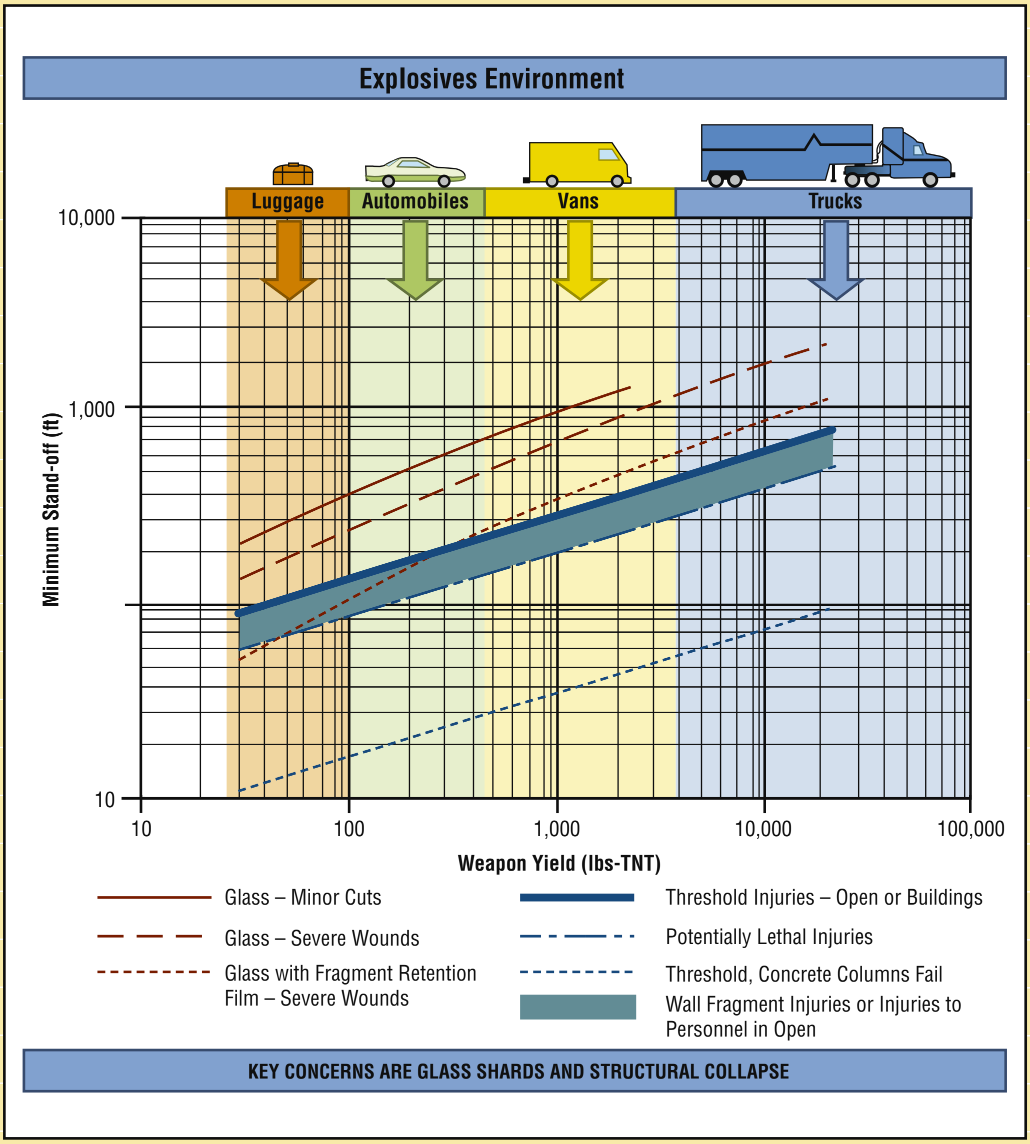

Fig. 5 – Explosives environments – blast range to effects.
Source: Federal Emergency Management Agency. Reference Manual to Mitigate Potential Terrorist Attacks. FEMA 426 (Washington, DC: Federal Emergency Management Agency, December 2003).