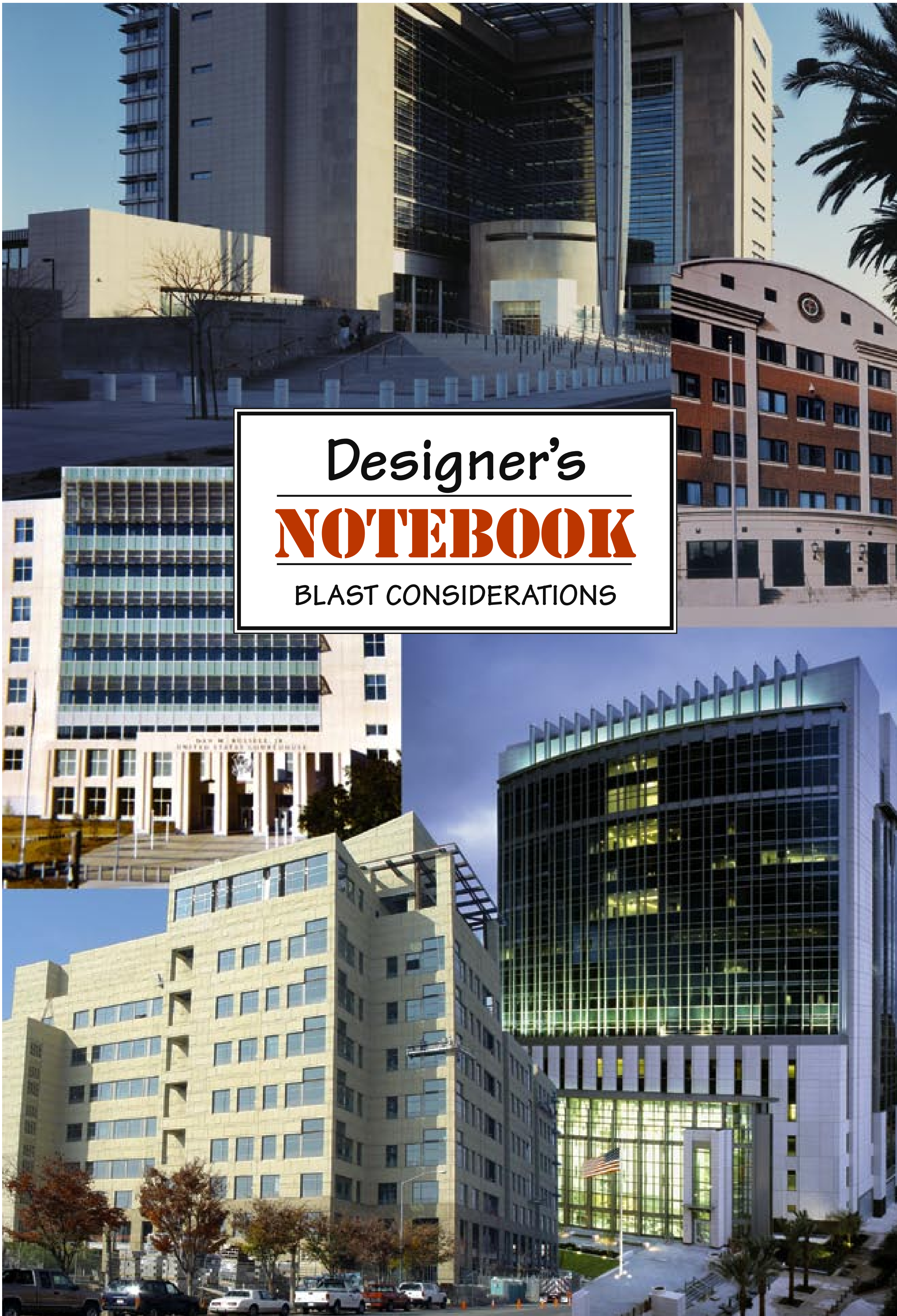

Designer's NOTEBOOK

BLAST CONSIDERATIONS

Standoff Distance

Protection for a commercial building, which comes in active and passive forms, will impact the damage sustained by the building and the rescue efforts of the emergency workers. The primary approach is to create a standoff distance that ensures a minimum guaranteed distance between the blast source and the target structure. The standoff distance is vital in the design of blast resistant structures since it is the key parameter that determines, for a given bomb size or charge weight, the blast overpressures that load the building cladding and its structural elements. The blast pressure is inversely proportional to the cube of the distance from the blast to the point in question. For example, if the standoff distance is doubled the peak blast pressure is decreased by a factor of eight, see Fig. 6. Furthermore, for a similar charge weight, the greater standoff distance results in a longer loading duration than the shorter standoff distance, and the blast wave is more uniformly distributed across the building face. Currently design standoff distances for blast protection vary from 33 to 148 feet depending on the function of the building. This standoff distance, or setback zone, is achieved by placing at the site perimeter anti-ram bollards, large planters, low level walls, fountains and other barriers that cannot be compromised by vehicular ramming. In urban areas, the setback choices are limited. In suburban or rural areas, large setbacks around a building can be used.

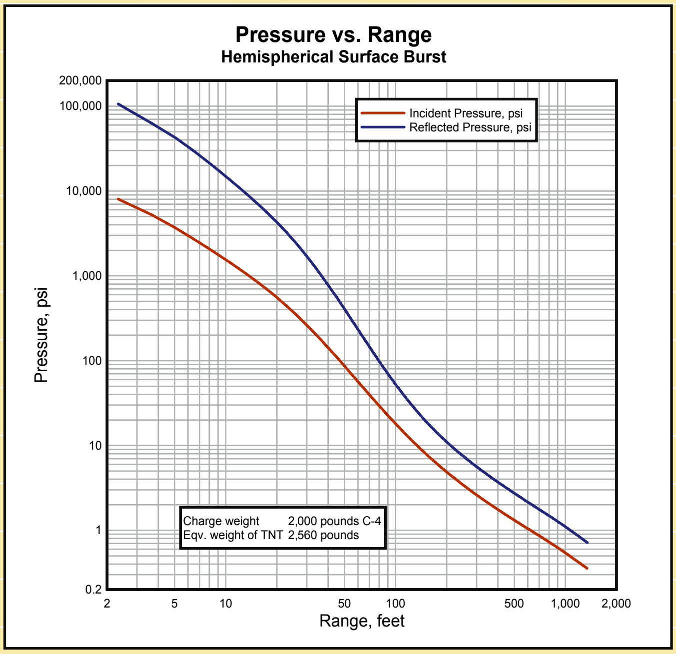

Fig. 6 – Pressure vs. Range-Hemispherical Surface Burst.*
Bridge and Tunnel Vulnerability Workshop, U.S. Army Engineer Research and Development Center, Vicksburg, MS, May 13-15, 2003

The maximum vehicle speeds attainable will be determined by the site conditions; therefore, the site conditions will determine the vehicle kinetic energy resulting from an impact that must be resisted by the standoff barriers. Both the bollard and its slab connection must be designed to resist the impact loading at the maximum speed attainable. Conversely, if design restrictions limit the capacity of the bollard or its slab connection, then site restrictions will be required to limit the maximum speed attainable by the potential bomb delivery vehicle.

While the setback zone is the most effective and efficient measure to lessen the effect of a terrorist vehicle bomb attack, it also can work against rescue teams since the barriers could deter access to the rescue and firefighting vehicles. In most urban settings, the typical setback distance from the street to the building façade is typically 10 to 25 feet, which does not pose any access problems for emergency vehicles. However, when designing prestigious buildings, including landmark office towers, hospitals and museums, the setback is often increased to 100 feet or more to create a grand public space. Details to allow emergency access should be included in the design of operational bollards or fences. If plaza or monumental stairs were used, some secondary access must be incorporated to similarly allow entry. Furthermore, public parking lots abutting the building must be secured or eliminated, and street parking should not be permitted adjacent to the building. Additional standoff distance can be gained by removing one lane of traffic and turning it into an extended sidewalk or plaza. However, the practical benefit of increasing the standoff depends on the charge weight. If the charge weight is small, this measure will significantly reduce the forces to a more manageable level. If the threat is a large charge weight, the blast forces may overwhelm the structure despite the addition of nine or ten feet to the standoff distance, and the measure may not significantly improve survivability of the occupants or the structure.

Figures 6 and 7 (next Page) illustrate the effect of increased standoff distances on the pressures that would be created on the structure.

Even where the minimum standoff distances are achieved, many aspects of building layout and other architectural design issues must be incorporated to improve overall protection of personnel inside buildings.

Design Concepts

Several important concepts should be kept in mind while designing buildings for blast resistance. These concepts include energy absorption, safety factors, limit states, load combinations, resistance functions, structural performance considerations, and most importantly, structural redundancy to prevent progressive collapse of the building. A design satisfying all required strength and performance criteria would be unsatisfactory without redundancy.

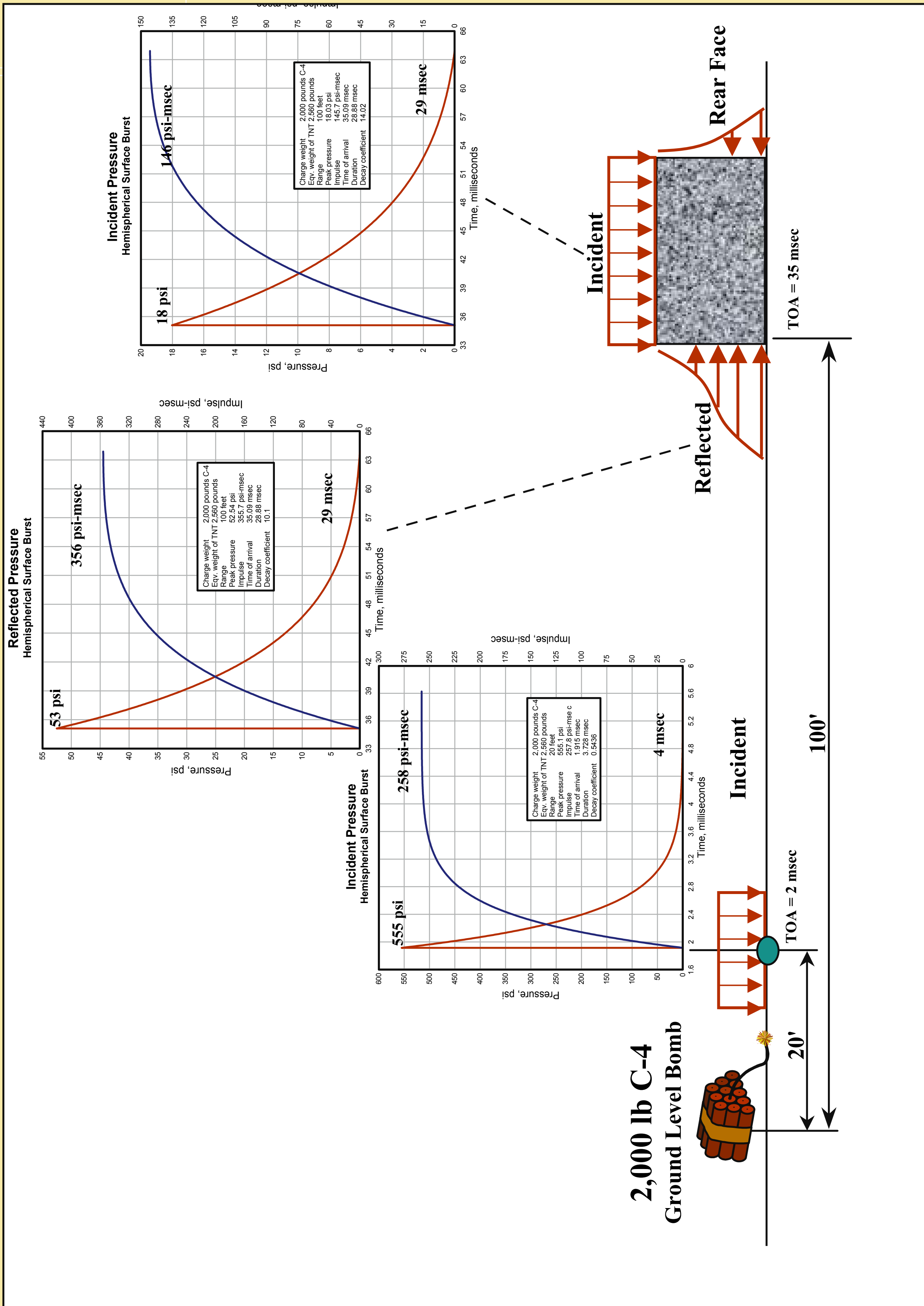

*Fig. 7 – Explosive Airblast Loadings from Vehicle Bombs.**

**Bridge and Tunnel Vulnerability Workshop, U.S. Army Engineer Research and Development Center, Vicksburg, MS, May 13-15, 2003.*

Structures with three or more stories are more likely to be subject to significant damage as a result of progressive collapse. The Engineer of Record needs to design the structure to sustain local damage with the structural system as a whole remaining stable and not being damaged to an extent disproportionate to the original localized damage. This is achieved through structural elements that provide stability to the entire structural system by transferring loads from any locally damaged region to adjacent regions capable of resisting those loads without collapse. Transfer girders and the columns supporting them are particularly vulnerable to blast loading. Unless specially designed, this form of construction poses a significant impediment to the safe redistribution of the load in the event the girder or the columns supporting it are damaged.

To limit the extent of collapse of adjacent components: (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 (i.e., a connection, column, beam or a portion of a loadbearing/shear wall system) without progressive collapse; (3) connections are detailed to provide continuity across joints equal to the full structural capacity of connected members (see Article 16.5-Structural Integrity in *ACI 318*); (4) floors are designed to withstand load reversals due to explosive effects; and (5) exterior walls employ one-way wall elements spanning vertically to minimize blast loads on columns.

Strength and ductility (energy-dissipating capacity) are necessary to achieve high energy absorption. High energy absorption is achieved through the use of appropriate structural materials and details. These details must accommodate relatively large deflections and rotation in order to provide redundancy in the load path. Elements with low ductility are undesirable for blast resistant design.

Margins of safety against structural failure are achieved through the use of allowable deformation criteria. Structures subjected to blast load are typically allowed to undergo plastic (permanent) deformation to absorb the explosion energy, whereas response to conventional loads is normally required to remain in the elastic range. The more deformation the structure or member is able to undergo, the more blast energy that can be absorbed. As member stresses exceed the yield limit, stress level is not appropriate for judging member response as is done for static elastic analysis. In dynamic design, the adequacy of the structure is judged on maximum deformations. Limits on displacements are selected based on test data or other empirical evidence as well as blast probability and potential consequences. A degree of conservatism is included to ensure adequate capacity because the applied loads are not "factored up" to provide a factor of safety.

As long as the calculated deformations do not exceed the allowable values, a margin of safety against failure exists. Since the actual weight of the explosive charge is unknown, the engineer cannot increase the design blast pressure loading to achieve a margin of safety. Blast resistant design requires that the loads from blasts be quantified by risk analysis and that the structural performance requirements be established for buildings subjected to these derived loads. Methods to determine the blast loading and structural performance limits are established in TM 5-1300 for buildings exposed to explosions from TNT or other high-yield explosives in military applications and munitions plants. Typical threats for civilian structures vary from suitcase and backpack bombs (20 to 50 lbs TNT equivalent) to van or small truck bombs (3,000 to 5,000 lbs TNT equivalent). Generally the smaller charge sizes are associated with vehicles that can be kept further from the building (60 to 100 ft) by appropriately designed vehicle barriers.

Design codes contain special provisions for high seismic conditions, which may be used to address the requirements to design against progressive collapse associated with design for blast resistance. However, these provisions are not sufficient for blast design. These provisions are intended to protect against nonductile failure modes, such as buckling or premature crushing of brittle materials, through use of special detailing and design requirements. The desirable features of earthquake-resistant design (ductility, redundancy, and load redistribution) are equally desirable in blast design. The provision for seismic detailing, which maintains the capacity of the section despite development of plastic hinges, is also desirable for resisting the effects of blast. However, the highly localized loading from a blast and the potential for different mechanisms/failure modes requires some additional considerations. The engineer should design the panels so that the full capacity of the section will be realized and that no premature failure will occur.

Building codes define the load factors and combinations of loads to be used for conventional loading conditions such as dead, live, wind and earthquake. However, no current building codes cover blast loading conditions. Blast loads are combined with only those loads that are expected to be present at the time of the explosion. Therefore, blast loads are not combined with earthquake or wind loads.

The Strength Design Method of *ACI 318* may be used to extend standard concrete strength and ductility requirements to the design of blast resistant structures. The resistance of concrete elements because of high strain rates is computed using dynamic material strengths, which are 10 to 30% greater than static load strengths. Strength reduction or resistance factors are not applied (i.e. $\phi = 1.0$) to load cases involving blast. The plastic response used in blast design is similar in concept to the moment redistribution provisions in *ACI 318*, Section 8.4 and the seismic criteria provided in *ACI 318*, Chapter 21. The seismic detailing provisions are applied to provide the necessary ductile response.

In addition to *ACI 318* requirements, the following items should be considered for blast resistant design.

a. The minimum reinforcing provisions of *ACI 318* apply, however the option to use one third more reinforcing than computed should not be taken. The moment capacity of under-reinforced concrete members is controlled by the uncracked strength of the member. To prevent a premature ductile failure, reinforcing in excess of the cracking moment should be provided. Two-way, symmetric reinforcement is reconnended to accommodate large deformations and rebound loads.

For panels, the minimum reinforcement ratio (percentage of reinforcing steel cross sectional area to the panel cross sectional area) of vertical reinforcing steel should be equal to or greater than Building Code ACI 318 minimums required for Seismic Design Categories D, E, or F. If the risk potential for a blast is high, the minimum reinforcement ratio required for blast-resistant design (TM 5-855-1; DAHSCWEMAN 1998) should be used as a basis for design. Generally, for concrete walls 8 in. or greater in thickness, the recommended minimum reinforcing should be 0.25% each face. For concrete walls less than 8 in. thick, 0.5% as a single row (on center line) of reinforcing should be the minimum specified.

b. Code provisions for maximum allowable reinforcing are included to prevent crushing of concrete prior to yielding of steel. Code provisions also allow compression reinforcing to offset maximum tension reinforcing requirements. Because blast resistant precast concrete panels typically have the same reinforcing on each face to resist rebound loads, maximum reinforcing provisions should not be a problem.

c. The substitution of higher grades of reinforcing should not be allowed. Grade 60 reinforcing bars (No. 11 and smaller) have sufficient ductility for dynamic loading. Bars with high yield strength may not have the necessary ductility for flexural resistance and shop bending, thus straight bars should be used when possible for these materials. Welding of reinforcement is generally discouraged for blast design applications; however, it may be required for anchorage. In these cases, ASTM A706 bars may be used.

d. Development lengths should not be reduced for excessive reinforcement. Because plastic hinges will cause over-designed reinforcing to yield, the full actual strength of reinforcing should be used in computing section capacities. The development of reinforcing should be computed accordingly.

e. Criteria intended to reduce cracking at service load levels need not be applied to load combinations including blast. Cracking, as well as permanent deformations resulting from a plastic range response, are an expected result of such an unusual type of load.

f. Some concrete elements are simultaneously subjected to out-of-plane bending loads in combinations with in-plane shear loads. For example, side walls must resist side overpressures acting into the plane of the side wall. Additionally, reactions from the roof diaphragm acting in the plane of the side shear wall must also be resisted.

Façade Considerations

A major structural consideration is the construction of the exterior façade. Second only to the impact the standoff distance has on the effects of the blast, the façade remains the occupant's last form of true protection. Not only does the building's skin protect the occupants from the weather, but it also has the potential to limit the blast pressure that can actually enter the workspace.