Structural Design for External Terrorist Bomb Attacks

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Events of the last ten years have greatly heightened the awareness of building owners and designers of the threat of terrorist attacks using explosives. The United States government has funded extensive research into blast analysis and protective design methods and has produced a number of guidelines for its own facilities. The private sector is increasingly considering similar measures, especially for so-called "icon buildings" that are perceived to be prime targets, as well as nearby structures that are vulnerable to collateral damage. This article summarizes the methods available to define an external terrorist bomb threat and estimate structural design loads and element responses using simple dynamic system models and principles.

Threat Definition

The details of an actual external terrorist bomb attack are by definition unpredictable. Therefore, the first design criteria that must be established for a structure that is intended to survive one are various combinations of standoff distance (R) and explosive charge size (W). R measures how close to the building a bomb could explode and is therefore a function of the physical characteristics of the surrounding site. W is expressed in weight or mass of TNT in order to correlate with tests; the equivalent W of any other explosive material is based on experimentally determined factors or the ratio of its heat of detonation to that of TNT. The effects of any blast are then normalized by the scaled distance parameter $Z = R / W^{1/3}$.

Potential threats and examples of corresponding standoff distances include:

- Moving vehicle bomb - vehicle barriers.
- Stationary vehicle bomb - parking and roadways.
- Placed bomb - unobstructed space.
- Standoff weapon - building separation.

Selection of the design charge size to be used for each instance should not be arbitrary, but rather consistent with the attractiveness of the building itself and others nearby as terrorist targets. The designer must take into account each structure's social, economic, and patriotic significance, as well as any installed security systems and other deterrence measures. The Department of Defense (DoD), Department of State (DoS), and General Services Administration (GSA) have developed specific requirements for military, embassy, and federal buildings, respectively. However, key portions of these criteria are only available to designers of specific projects to which they apply. The 1999 ASCE report referenced at the end of this article 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.

Blast Loading

The shock wave from an external explosion causes an almost instantaneous increase in pressure on nearby objects to a maximum value. This is followed by a brief positive phase during which the pressure decays back to its ambient value, and a somewhat longer but much less intense negative phase during which the pressure reverses direction. For most structures this phenomenon can be approximated using a triangular impulse load with zero or minimal rise time and linear decay. The parameters of this equivalent load are calibrated to match the maximum reflected pressure (p_r) and total reflected impulse (i_r) of the actual load's positive phase, so that the design duration $t_d = 2i_r/p_r$. The negative phase is neglected because it usually has little effect on the maximum response.

The designer can estimate p_r and i_r for a given combination of R and W using Z and published curves. 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, computer programs can perform these calculations and provide much greater accuracy. One such software product, *AT Blast*, is available for downloading free of charge (**www.oca.gsa.gov**) from GSA.

Structural elements that must withstand or transfer external blast pressures must be analyzed and designed accordingly. The same is true of internal elements, particularly elevated floor slabs, if windows or doors are not expected to remain intact during a blast event. Failure of these components will permit the blast pressures to propagate within the building. 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.

Element Modeling

An element loaded by a blast can be modeled approximately as an elastic-plastic dynamic system with a single degree of freedom (SDOF) corresponding to its maximum blast deflection. The element's effective mass, elastic and elastic-plastic stiffnesses, and available yield and ultimate strengths are derived from its actual physical configuration and properties. Tables summarizing these parameters are available in several of the references listed at the end of this article.

When a particular element is continuously connected to an adjacent one, a portion of the latter's mass can often be added to the element's own. For example, the designer can include the mass of 20% of the wall on each side of an integral pilaster and the full tributary length of metal panels attached to girts. However, any stiffness contribution from adjacent elements should usually be neglected. When the mid-span and end moments of inertia are unequal, the designer should use the average value. The same is true of the available moment capacities at the two ends of a fixed/fixed element.

Structural Materials

Most materials used in actual construction have strengths that exceed their specified minimum values by 10% or more. In addition, the short duration of a blast load results in high strain rates that increase the design strength by at least another 10%. Consequently, for dynamic design, the specified strength can be multiplied by a factor of 1.21, except that for structural steel with F_y > 50 ksi a factor of 1.10 is recommended. The designer can also take advantage of the increase in concrete strength with age, which for ordinary Portland cement is on the order of 10% at six months and 15% at one year or more. Material-specific interaction equations account for the reduced moment capacities available to withstand a blast load because of the stresses already present due to the dead load and a realistic portion of the live load, usually 25-50%. For dynamic analysis and design, all strength reduction or resistance factors are set to unity.

Reinforced concrete, properly detailed, is generally preferred for blast-resistant structures. Concrete masonry may also be used for exterior walls, but must always be reinforced and even then has a considerably higher potential for unacceptable brittle failure and subsequent fragmentation, especially if only cells containing reinforcing bars are grouted. Cavity walls are more effective than single wythes because the outer layer of brick will contribute additional mass and absorb many of the casing fragments produced by an external explosion. Stiffness values should be based on the average of the gross and cracked section moments of inertia.

Structural steel, especially when utilized in moment-resisting frames, can tolerate a considerable amount of deflection during a blast event without collapse. However, exterior cold-formed steel wall panels or sheathed studs are often not practical for blast-resistant structures and can increase fragment hazards to building occupants. For strong-axis bending of open-section structural or cold-formed steel elements, lateral bracing of the compression flange or torsional bracing of the cross section is required at plastic hinge locations and at a spacing small enough to preclude lateral-torsional buckling.

Element Response

The designer can calculate the expected response of an element to a triangular blast impulse using published curves or a computer program capable of performing a nonlinear time-history analysis of the SDOF system. An example of the latter is *Nonlin*, available for downloading free of charge (**www.app1.fema.gov/EMI/nonlin.htm**) from the Federal Emergency Management Agency (FEMA). The relevant parameters for each element include the following ratios:

- Blast impulse duration to natural period of vibration (t_d/T).
- Maximum dynamic load to available ultimate strength (F_o/R_u).
- Maximum expected deflection to yield deflection (ductility ratio μ).
- Span length to maximum expected deflection (deflection ratio D).

μ and D correlate with the expected amount of damage to an element in a blast event, which is restricted by the level of protection that the structure must provide to its occupants and contents based on their nature, quantity, function, and importance. D_{min} is related to the maximum end rotation (Θ_{max}); for example, for one-way elements other than cantilevers, assuming plastic hinge formation at mid-span and fixed ends and a linear deflected shape between hinges, $D_{min} = 2 / \tan \Theta_{max}$. Several of the references at the end of this article describe the damage associated with qualitative levels of protection and suggest corresponding Θ_{max} and D_{min} (or Θ_{max}) values for various combinations of element type and material. DoD has recently developed more detailed and less conservative response limits that are currently available only to its contractors.

When $\mu > 1$, the element must actually be capable of undergoing the plastic deformation associated with its calculated μ and D values without suffering unacceptable damage. This requires careful detailing of members and especially connections. Although code requirements and industry guidelines for structures in high-seismic regions are helpful, they are not sufficient for blast design. Because of the localized nature of an explosion, such provisions must be followed even for elements that are not part of the lateral-force-resisting system, especially on the exterior. In case a primary supporting element does fail because of a blast, the structural system should include alternate load paths so that progressive collapse of additional bays will not follow. Multistory buildings are especially vulnerable in this respect, and should have enough inherent redundancy to survive a local failure at the ground floor level.

For shear design, it is usually adequate to check an element's end connections for the equivalent static reactions produced by a uniformly distributed load with a total magnitude of R_u or $2F_o$, whichever is smaller. Supporting elements can then be conservatively designed to have ultimate strengths adequate to resist these loads. Since the shear failure mode of concrete and masonry elements is relatively brittle, it is essential to provide appropriate reinforcement at and near supports. The designer must also account for the elastic rebound of an element subsequent to its maximum deflection, which will induce stresses opposite to those caused by the blast pressure itself. Appropriate provisions for this effect will also improve the element's ability to withstand a load reversal, which may occur if an adjacent or supporting element fails during a blast event.

Conclusion

Although it is not practical to design buildings to withstand any conceivable terrorist attack, it is possible to improve the performance of structures should one occur in the form of an external explosion. By maximizing standoff distances and hardening key elements, designers can give building occupants a reasonable chance of escaping death and serious injury during such an event. Building owners need to understand the factors that contribute to a structure's blast resistance and provide input throughout the design process to ensure that appropriate threat conditions and levels of protection are being incorporated.

Further Information

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