STRUCTURAL DESIGN

discussions on design issues for structural engineers

Concrete Detailing for Blast

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Introduction to Blast

An explosion is a rapid release of energy taking the form of light, heat, sound and a shock-wave. This shock wave is a condensed air pressure wave that travels outward from the source at supersonic velocities. When the wave encounters a surface, such as a building face, it is reflected and can amplify up to thirteen times. The duration of this loading can vary depending on the geometry of the structure; for example, re-entrant corners can further amplify air-blast waves and elongate load duration. After the initial pressure wave travels through an area, it is followed by a negative wave that creates a vacuum as shown in *Figure 1*. This not only causes load reversals on structural elements, it also turns hazardous debris into flying projectiles.

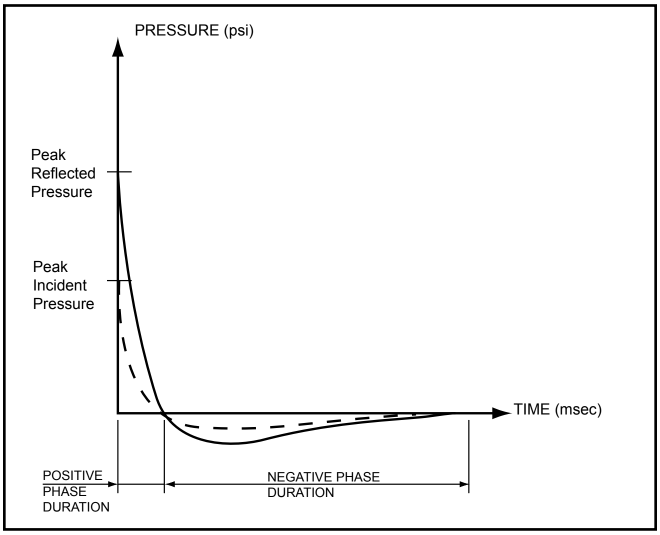

Figure 1: Typical blast pressure versus time

Explosive pressures are many times greater than any other loads for which a building is designed, so the goals in blast engineering are modest by necessity. We have to accept that some building damage and injuries may occur, and the building may not be useable after an incident. The primary goal for high population buildings is to save lives. In order of priority, this is accomplished by:

1) preventing the building from collapsing
2) reducing flying debris
3) facilitating evacuation and rescue/recovery efforts

Evacuation, rescue and recovery efforts can be significantly improved through effective placement, structural design, and redundancy of emergency exits and critical mechanical/electrical systems. Reducing flying debris generated by failed exterior walls, windows, and other components can be highly effective in mitigating the severity of injuries and the risk of fatalities. Concrete detailing is most important for the first priority – preventing the building from collapsing. Ductile detailing of primary members and connections allows for large deformations while maintaining load-carrying capacity.

When a weapon is placed relatively close to the structural element, it may cause shattering of the concrete in the immediate vicinity – a phenomenon referred to as breach. When the weapon is placed farther away from the elements, the explosive effects change from breach to direct shear, and eventually to flexural response. Direct shear occurs when airblast pressures are highly concentrated in a relatively small area close to the element's support. As the weapon is placed farther away from the structure, the airblast pressure distribution changes resulting in a flexural response.

Blast Detailing

A blast is a localized, highly irregular, and potentially non-uniform load. In blast design, it should be assumed that structural elements will be loaded beyond their yield strength and up to failure. Thus the detailing of reinforced concrete elements is of great importance. Desirable structural element performance under blast loading can be achieved through the following general measures.

- Limit concrete compressive strengths to 5,000 psi or less, since elements with higher strength concrete will experience more brittle modes of failure when subjected to inelastic yielding.
- Design for load reversals, which can subject elements to loads for which they were not designed; for example, tension in a column due to floor slab uplift. This affects both longitudinal reinforcing placement and connection designs.
- Ensure that the ratio of the steel reinforcement's actual tensile strength to actual yield strength is not less than 1.25 for sufficient yield capability.
- Locate lap splices outside of the hinge region of an element as predicated by the design airblast threat.
- Design lap splices as tension splices. With blast, localized loading locations are unpredictable and hinge regions could be located anywhere along the length of the member.

Reinforced concrete columns and floor systems are the most important structural systems for protecting the building from collapsing, and are also the most vulnerable to airblast loading. *Figure 2* shows the succession of pressures on a building due to an external weapon.

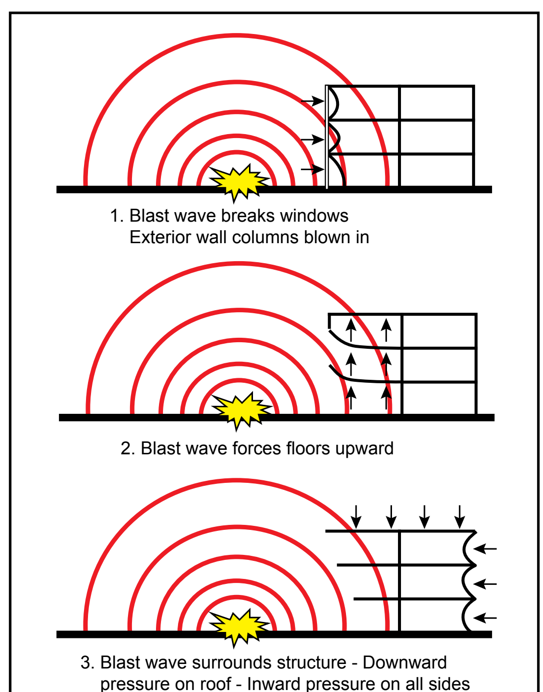

Figure 2: Succession of blast pressure on a building

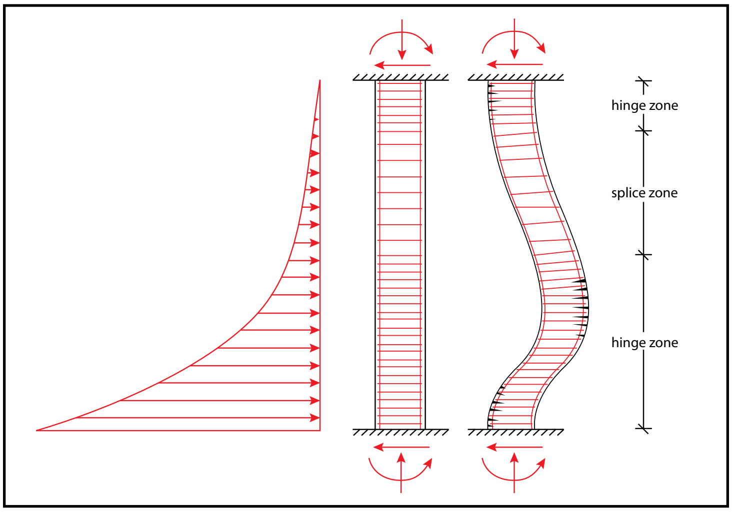

Figure 3: Column subjected to non-uniform air-blast loading

Columns

Failure of a single structural column may have a devastating effect on the overall structural integrity of a building. For tall buildings, the structural columns can carry substantial axial load due to gravity, and therefore it is prudent to include the effect of axial load in the blast analysis. The axial load in reinforced concrete columns increases the bending capacity of the column, due to the large imbalance in concrete tensile and compressive strengths. Axial load reduces stiffness and strength in tall and slender columns due to the buckling phenomenon, which may result in catastrophic failure of the column.

In considering the distribution of airblast pressure along the height of the column, loading is often approximated as uniform by assuming a plastic hinge forms at mid-height of the column. This simplification is inaccurate for columns located in close proximity to the explosion. As shown in *Figure 3*, a non-uniform distribution of airblast loading could result in a plastic hinge located below mid-height of the column, which could potentially result in a large shear demand at the bottom of the column. If the deflected shape is improperly predicted, this shear demand can be significantly underestimated.

The location of the splice and hinge zones will depend on the expected location of the design airblast threat. If the column is located in a parking garage, its threat may come from a close-in parked vehicle weapon. For above-grade perimeter columns, the more likely weapon location would be far-range, depending on the perimeter standoff distance. *Figure 4* illustrates the plastic hinge zones for a far-range weapon scenario – a loading that may be approximated as uniform.

Below are column detailing practices that generally result from airblast loading analyses.

- Specify ASTM A706 reinforcement, which has a larger ratio of ultimate to yield strength, providing more ductile behavior at hinge regions.
- Control the longitudinal reinforcement ratio such that the yield moment exceeds the cracking moment and the column is not over-reinforced (see ACI 318, section 21.4.3.1). Good practice is to ensure that column longitudinal reinforcement does not exceed six percent of the gross area, which also serves to avoid congestion in the splice zones.
- Concrete spalling and crushing decrease the column's ability to accommodate large plastic deformation without significant strength degradation. Provide closely spaced hoops for adequate confinement of concrete. This increases the capacity of the concrete in compression and helps prevent buckling of the longitudinal bars after the concrete crushes.
- Provide closely spaced ties or spirals along the entire column height when airblast loads are non-uniform as shown in *Figure 3* (preferably comply with ACI 318, section 21.4.4.1).
- Provide spacing of closed-hoop confinement reinforcement at column hinge regions to comply with ACI 21.4.4.4.
- Design lap splices as tension splices and locate them outside of plastic hinge regions (see ACI 318, section 21.4.3.2). It may be more practical for interior short columns to have splices located in the level above, where longer splice lengths can be accommodated. Alternatively, mechanical splices can be used, provided that they have the capacity to develop the tensile strength of the spliced bar (see ACI 318, section 21.2.6).

Beams and Slabs

When designing the floor system, consider three possible loading scenarios: direct airblast loading (including uplift), redistribution of loading in the case of a lost element, and the impact of falling debris from floors above.

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The expected location of the weapon will dictate the floor system design. The roof system is typically designed for downward pressures as the building is engulfed by the shock wave from an exterior airblast event (step 2 in *Figure 2*). Depending on the perimeter standoff distance, the outer bay may require hardening to protect the floor systems from uplift after the loss of the exterior envelope (step 3 in *Figure 2*). An interior threat, such as one in a parking garage, would load the floor below with significant downward pressures, and the floor above with upward pressures. A multi-story garage would require that each floor system be designed for both upward and downward loading.

The primary goal when designing a blast-resistant floor system is to focus on containing the damage to the secondary elements in one bay. This can be achieved by ensuring that the floor system design is balanced; that is, the capacity of the secondary elements is less than that of the primary elements, such as the beams and girders along column gridlines that serve to brace columns and maintain the building's stability. More specifically, this means following the load path from one element to the next and checking that the ultimate capacity increases correspondingly.

The detailing guidelines below focus on providing ductility to ensure that the beam's full capacity can be achieved and the floor system has the integrity to handle all three loading scenarios described above.

- Provide spacing of closed hoop confinement reinforcement at beam hinge regions (see Figure 5) and at lap splice regions based on the smallest of the following (ACI 21.3.3.2):
  - o beam effective depth / 4
  - o 8 x diameter of longitudinal bars
  - o 24 x diameter of hoops
  - o 12 inches
- Provide confinement reinforcement at areas outside of hinge and splice regions at a spacing no more than half the beam effective depth (ACI 21.3.3.4).
- Ensure that both top and bottom longitudinal reinforcing are continuous throughout the length of beams and slabs.
- Design lap splices as tension splices, locate them outside of plastic hinge regions (see ACI 318, section 21.4.3.), and stagger them.

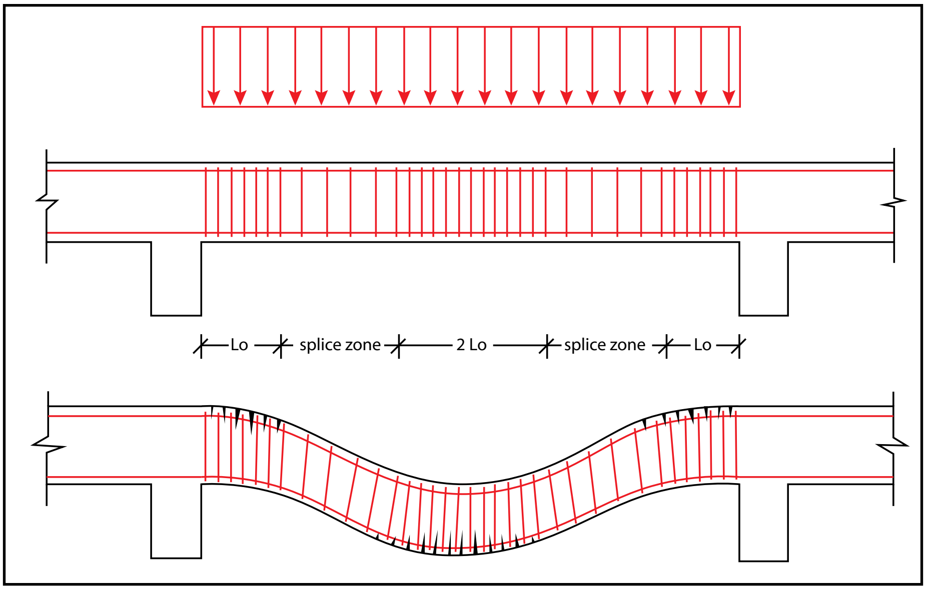

Figure 5: Beam Subjected to downward air-blast loading

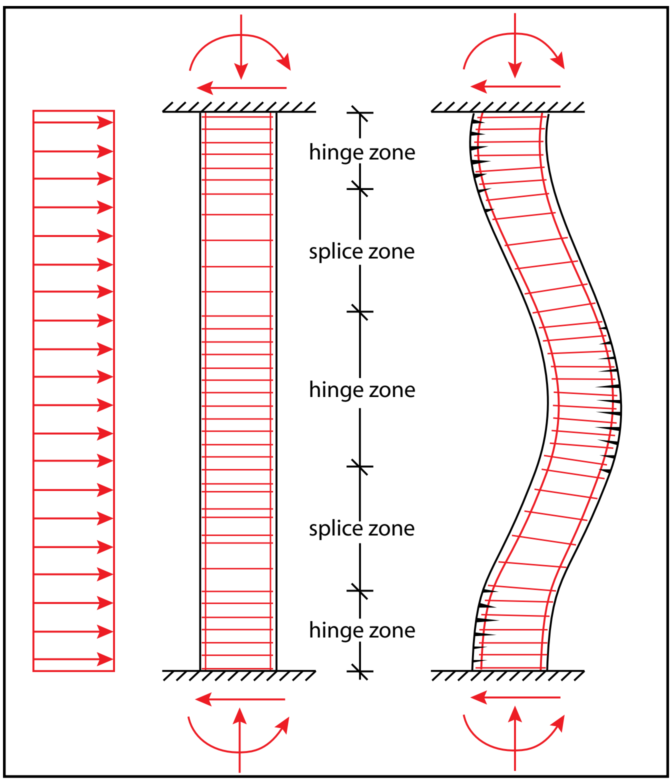

Figure 4: Column subjected to far-field air-blast loading

Conclusion

The above enhancements to the structural design through detailing would provide robustness, ductility and redundancy for extreme loading scenarios such as airblast and progressive collapse. Many of the suggested ductile detailing measures are derived from the American Concrete Institute standard ACI 318 and US Department of the Army TM5-1300, *Structures to Resist the Effects of Accidental Explosions*. ▪

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