Resistance of Historic Unreinforced Masonry Walls to Air-Blast Loads

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Blast resistant analysis and design of historic structures can be challenging. Original designs of these structures utilize historic construction methods and materials, and were often not intended for abnormal loading scenarios such as air-blasts.

When an external explosion imposes an air-blast load on a heavy, external wall system, the air-blast pressure must overcome the inertia forces of the wall itself before putting the system into motion and causing damage. In the case of thick, unreinforced masonry walls, these forces are very large and therefore the resulting damage is less than one would initially imagine.

Background

Prior to the 20th century, unreinforced masonry construction was the primary building material for both residential and commercial construction. As a result, unreinforced masonry structures constitute a large portion of existing buildings, many of which hold historical and architectural importance.

Beginning in the early 1980s with terrorist attacks in Lebanon and Kuwait, high-profile and high-risk civilian federal buildings have been designed to resist the effects of explosive attacks. With each major attack on the United States' interests, more attention has been paid to this low probability/high consequence threat scenario. As a result, recent work has been dedicated to the design and analysis of masonry structures to resist air-blast loads.

Air-Blast Effects

Before explicitly addressing air-blast effects on a particular building system, it is important to understand the effects of explosions themselves.

An explosion is a rapid release of energy in the form of light, heat, sound, and a shock wave. The shock wave consists of highly compressed air traveling radially outward from the source at supersonic velocities. Pressures reduce rapidly with distance and can be amplify by a factor of up to thirteen when reflected off a building surface. These pressures decay exponentially with time and their duration is typically measured in milliseconds. Diffraction effects at reentrant corners of the building may confine the air-blast and prolong its duration. Late in the explosive event, the shock wave becomes negative, creating a high-intensity drag pressure. This wind picks up and carries flying debris from the building.

Air-Blast Effects on Heavy Unreinforced Masonry Buildings

When a wall is first subjected to an air-blast load it experiences out-of-plane flexure, producing tensile strains on the interior face of the wall and compressive strains on the exterior. Once the maximum positive deflection associated with the out-of-plane flexure has been attained, the wall will begin to vibrate due to rebound forces created by negative blast pressures. The wall undergoes negative deflection and curvature, causing tensile strains to develop on the exterior face of the wall and increasing shear stresses at wall supports.

Windows

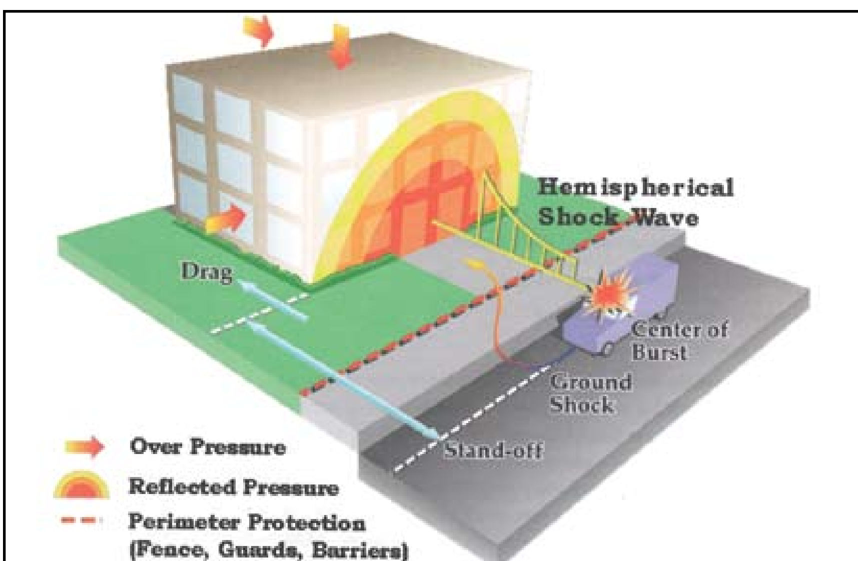
When designing exterior masonry wall systems to resist air-blast, it is important to begin the analysis with the window glass. A primary goal of building envelope design for blast is to ensure that the supporting walls are stronger than the glass itself. This provides a balanced design of the envelope so as to control the spread of potential damage if a larger-than-designed for weapon threat is applied to the wall. This is based on the assumption that the failure of the glass will release some of the blast pressure, thereby reducing the blast load applied to the remaining structure.

The glass should be designed by balancing manufacturing limitations against air-blast response requirements. The key is to design the glass layup such that it meets the air-blast response requirements while limiting over-strength. The maximum capacity of the glass is then analyzed to determine the pressure at which the glass will release from the framing systems, and this is the design blast pressure that imparts load to the supporting walls.

Anchorage

The next step in designing masonry infill walls is to ensure that the windows can be adequately anchored to the supporting walls. In considering historic structures, there are many conditions that can make this a challenging design requirement.

The ideal placement of a window in a supporting wall is at the center of the wall depth. This allows the maximum "edge distance" for the anchors to resist both inward and outward forces. In non-historic retrofits, it is often acceptable to change the location of the windows relative to the wall depth. However, this is rarely an acceptable modification in historic buildings. If adequate edge distance is not available, alternative anchorage details or wall retrofits will be required.



Air-blast pressure effects on buildings

Damage to masonry buildings

While the masonry piers between windows are generally constructed of solid masonry, it is common to find voids in the walls below window sills. If voids occur at the windows, anchoring the window into the sill is not possible without drilling diagonally into the masonry behind. This is a costly endeavor, and one which contractors are often reluctant to undertake.

Depending on the size and placement of the windows relative to the floor systems, the head or sill may be only inches away from spandrel beams or, in the case of steel frame structures, the concrete encasement of beams. For concrete members, anchorage of the windows will be relatively straightforward. In the case of concrete-encased steel members, constructability considerations may require finding alternate solutions for window anchorage.

Other Constraints

As with all structural retrofits on historic structures, there are other constraints to consider when developing design solutions. These may include:

- Interior Finishes: interior finishes, especially below the windows, are often designated as remaining and may be fragile, as in the case of HVAC equipment.
- Floor system: several of the retrofit solutions require that retrofit elements be attached to the existing floor system. Older floor construction systems may not be able to support these additional dead loads.

Wall Analysis

It is best to begin calculations assuming that the window can be anchored to the walls at all four sides, distributing the forces from the windows to the supporting walls at the head, sill, and jambs.

A common configuration for windows in historic unreinforced masonry buildings, especially those constructed in the late 1800s and the early 1900s, is to have two or three windows per structural bay. This creates masonry piers between individual window openings. These piers tend to be critical supporting wall elements.

Two computational models for analyzing wall response are described below.

Simply-Supported

A conservative approach to modeling the resistance of an unreinforced masonry wall for an air-blast load is to represent the wall as a slender member subjected to a uniformly-applied dynamic load. It is assumed that there is no contribution of axial compressive forces at the top and bottom of the wall, and the wall is analyzed as a simply-supported beam. The flexural resistance of the wall is dependent on the compressive stresses from its own self weight, and the tensile strength as defined by the mortar's modulus of rupture. Because unreinforced masonry has little tensile resistance, the flexural capacity of the wall is minimal, resulting in extensive cracking and brittle failure at the interior face of the wall.

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Damage to masonry buildings

Rigid Supports

Another model, based on the military tri-services technical manual TM5-1300 (the recognized air-blast resistance design manual throughout the United States) assumes that the top and bottom supports are completely rigid and provide restraint against elongation. Strength comes from compressive blocks that form at the top, bottom and mid-height hinge locations of the wall, behavior known as a compressive membrane phenomenon. This model also assumes that the mortar joints will be cracked, disregarding what little flexural tensile strength remains in the masonry. The deflected wall "wedges" itself between floor slabs and also forms a plastic hinge at mid-height. This model takes into account that masonry infill walls will often have a gap at the top, either from a mortar joint or by design that accounts for flexure of the floor systems above.

Retrofits

Once the basic calculations on the windows and walls have been performed and the constraints have been identified, design of retrofit solutions can begin. In a perfect world, the windows would be anchored at all four sides and the surrounding wall elements would be able to support the design loads. This is rarely the case; therefore multiple options for retrofitting these window wall systems are considered.

Steel Supporting Frames

The most straightforward retrofit is to install steel frames, interior to the existing walls, which support the window systems. This solution is appropriate where the wall piers are not able to support the additional air-blast load imposed by the windows. This retrofit is often unacceptable to architects as it either creates an uneven wall surface or requires reducing the overall room size by furring out the walls.

Shotcrete Walls

In some cases, other loading condition requirements may be combined with air-blast requirements to develop multi-purpose solutions. Where progressive collapse or seismic design requirements would benefit from shotcrete walls, this may be used as an air-blast retrofit of unreinforced masonry walls as well. Window systems could be mounted in the new concrete wall system. This would be an especially useful technique for relatively larger blast loads.

Fiber Reinforced Polymer (FRP)

Another retrofit method is to apply vertical FRP composite strips along the inside face of the masonry wall. FRP composites have significant stiffness and tensile strength in the direction of the fibers, and can be highly effective in increasing the wall's out-of-plane flexural capacity. Additional advantages of this method are that it is relatively unobtrusive to the architectural detailing of the wall and existing structure, and its application process is not labor intensive, requiring little disruption to building occupants.

The flexural capacity of a FRP-retrofitted unreinforced masonry wall can be assessed using basic moment-equilibrium relations, similar to that of a steel-reinforced masonry wall. The tensile strength of the masonry is disregarded and all tensile resistance is assumed to be provided by the FRP. The flexural resistance can then be computed as a function of the compressive strength of the masonry, the tensile strength of the FRP, the thickness of the masonry panel, and the value of the applied axial force.

Blast tests have demonstrated it is unlikely that the wall's predominant failure mode will be failure of the FRP. Also, tests of unreinforced masonry units to out-of-plane air-blast loading have demonstrated that shear failure at the supports is a predominant failure mechanism. The FRP reinforcing provides no additional shear resistance to the wall section, and if connections at the walls supports do not allow transfer of excessive shear forces to other structural elements, shear failure at the wall supports can occur. Also, connections at wall supports are instrumental in preventing the out-of-plane flexural collapse towards the front side of the wall due to rebound forces.

Conclusion

While not considered an ideal building material, unreinforced masonry infill walls constitute a large stock of structural systems throughout the world's historic buildings. Analysis techniques, supported by air-blast testing data, can estimate the capacity of these wall systems for extreme out-of-plane loading. Existing walls, including windows and supporting structure, are a complex system that should be analyzed from a capacity-based approach when designing a viable retrofit solution.▪

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