Blast Loading Retrofit of Unreinforced Masonry Walls

With Carbon Fiber Reinforced Polymer (CFRP) Fabrics

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Buildings, bridges, pipelines, industrial plants, dams, etc. are vital components of the infrastructure of any country, and as such, they are likely targets of terrorist attacks. The vulnerability of these facilities to blast events has been well documented in the media and scientific communities. As a result, many government agencies and private companies around the world now require any new facility that holds significant strategic importance to be designed to address blast resistance of structural and non-structural components.

Traditional design and construction methods exist to properly address blast loads during the design phase. However, blast protection alternatives for existing buildings and other infrastructure that were designed well before this need was identified are highly desirable. For example, an existing building taken over by the military or an embassy may increase its strategic importance and may have to undergo substantial blast protection reinforcement.

Carbon fiber and glass fiber reinforced polymer (FRP) retrofit systems have been gaining acceptance in the structural engineering community as a viable answer to these important needs. FRP's are composite materials made of high strength glass or carbon fibers immersed in an epoxy matrix. The fibers are weaved into a fabric, which is saturated with epoxy resin and applied to the surface of the component requiring retrofit. Once the resin cures the material turns into an adhered laminate that provides an additional source of tensile reinforcement and/or confinement. The fact that thousands of FRP retrofit projects have been completed around the world to provide seismic upgrades, rehabilitation of deteriorated infrastructure, blast protection, among other uses, as well as the increasing body of published research and design literature available, are a testament to the level of maturity that this industry has achieved.

Figure 1: CFRP fabric installation on URM wall

In simple terms, a blast load is generated when an explosion sets in motion a surrounding mass of air, creating a high speed shock wave that travels in radial directions from the detonation point. As a result, a nearby building will be subjected to a short duration (impulse) load, whose intensity will depend on the power of the explosive device and distance between the building and the detonation point. Moreover, the dynamic characteristics of the impulse load will generate inertial forces in the building that will be directly proportional to its mass.

Most structural components of a building have some degree of blast resistance. The adequacy of such resistance can be established by existing analytical or experimental methods. For example, a blast wave penetrating an enclosed space can be modeled by lateral loads on walls, downward loads on the floor slab, and uplift loads on the ceiling slab and columns. If the structural components are made of reinforced concrete, one key issue is the position of the steel reinforcement in beams and slabs taking on the uplift loads, since the uplift intensity could reverse the gravitational loading effect and generate negative bending effects in regions where insufficient or no steel reinforcement is present. One solution to this problem is to place FRP strips at these locations.

The existence of interior or exterior (perimeter) walls made of unreinforced masonry (URM) could pose a significant risk under blast loads. These walls are seldom used in newer buildings as interior walls, since gypsum board or other removable wall systems are more convenient. However, they are still used as exterior walls due to security reasons. In older buildings, URM walls are also used as interior walls. Although existing design codes require a minimum of steel reinforcement in URM walls, many URM walls in older buildings have no steel reinforcement.

Previous experience has shown that when a URM wall is subjected to a near blast event, the intensity of the load and its dynamic effects may be enough to cause catastrophic failure of the wall, generating structural disintegration where wall debris become high speed projectiles, maximizing property destruction and human casualties. Therefore, it is highly desirable to design a blast protection system that can take on the blast and, if structural collapse of the wall is inevitable, contain all wall debris within the system.

Figure 2: URM wall test specimens ready for blast test

The objective of this article is to present an FRP blast protection system for non-bearing URM walls, and to show the results of a blast test recently performed on the system at the Energetic Materials Research and Testing Center (EMRTC) of New Mexico Tech.

Test Specimens

Two non-bearing URM walls, of approximately eleven feet in height, 8 feet in length and 8 inches in thickness were constructed using typical 16- x 8- x 8-inch masonry blocks and a standard mortar mix. No mortar or steel reinforcement was placed inside the cells in order to simulate the worst case condition.

One of the URM walls was retrofitted on both faces with carbon fiber fabric (CFRP), considering the following construction sequence: first, a layer of tack coat was applied to the wall surface. The purpose of the tack coat was to seal the wall surface, smooth out small imperfections and hold up the weight of the saturated CFRP strips; second, the CFRP strips were saturated in epoxy resin and placed on the tack coated surface. *Figure 1* shows the installation of the CFRP fabric over the tack coated surface.

Both URM walls were constructed on allocated spaces of a reaction building at the EMRTC facility. The walls were simply supported at top and bottom only, and detached from the reaction building on the vertical sides. This construction method simulated the typical method used in building for non-bearing walls, where detachment from the main building on the vertical sides is used to avoid interaction between walls and the main structure. Bolted and welded steel angles were provided on the top and bottom of the CFRP retrofitted wall to provide mechanical anchoring of the CFRP fabric.

A blast source consisting of 240 pounds of explosive (equivalent to 200 pounds of TNT) was placed in a cylinder with aspect ratio (length/diameter) equal to 1.0, at a height of 3 feet and at a distance of 30 feet from the URM

Figure 3: Instrumentation on the interior of the reaction building room

walls. This blast source was intended to reproduce the effects of a car bomb explosion occurring on a side street in front of the wall. *Figure 2* shows both test wall specimens and the blast source.

Based on the above blast source information, the CFRP retrofit was designed for a peak reflected lateral blast pressure of 200 psi. A typical compressive strength value of 1500 psi was assumed for the masonry, and the true 7.62-inch masonry unit thickness was used to determine the flexural strength of the retrofitted wall. Given the relatively low compressive strength of the masonry, structural calculations showed that crushing of the masonry would occur before achieving the tensile strength of the CFRP. Moreover, due to the dynamic nature of the behavior, it was expected that crushing would occur first on the outside face of the wall due to the deflection caused by initial blast wave, followed by crushing of the inside face due to a pseudo-elastic rebound deflection generated by the inertial forces. CFRP fabric was placed on the outside face to account for the tensile forces generated by the rebound deflection.

The following instrumentation was used to record the CFRP retrofitted URM wall response:

1) A reflected pressure gage was installed approximately 6 feet above the ground on the partition wall of the reaction building that separated the un-retrofitted and retrofitted URM walls. This gage was used to measure the actual reflected pressure on the wall due to the blast event, so that it could later be compared with the design reflected pressure.

2) A laser gage was installed inside a protective housing at a distance of eleven inches from interior face of the wall, to measure the wall deflection at a point coincident with the geometric center of the wall.

3) An interior pressure gage was installed on the floor behind the laser gage. This gage was required in order to measure the pressure intensity inside the room during the blast event.

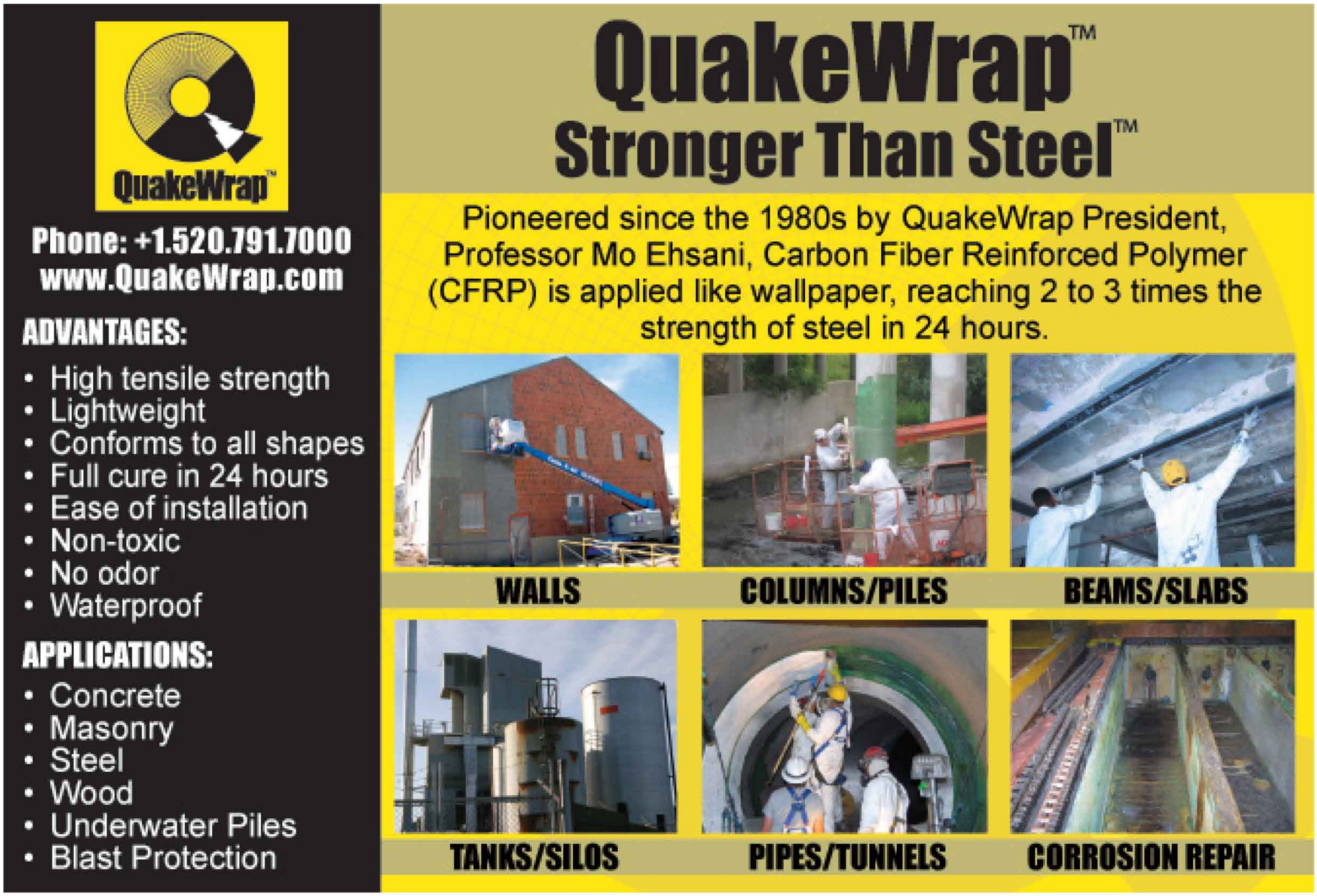
4) Four high speed cameras were installed: one at a lateral point away from the reaction building to capture the arrival of the shock wave, one at a lateral point inside the room to capture the inbound and rebound deflection, one at a far away point to capture the explosion of the charge and one on the back of the room to capture the overall interior environment due to the blast event.

Figure 3 illustrates some of the instrumentation installed on the inside of the room. Visible in the figure is the laser gage mounted on the steel post, the interior pressure gage on the floor (inside the aluminum casing behind the laser stand) and the interior lateral high speed camera window on the left wall. Also visible in this figure is the interior bottom steel angle used as mechanical anchor for the CFRP fabric.

Blast Test Results

The test was fired at 2:38 pm on February 5th, 2008. The response values measured by the instrumentation were as follows:

1) Peak reflective pressure: The maximum value was measured at 192 psi, which was just



4% lower than the retrofit design value of 200 psi. *Figure 4* shows the reflective pressure time history.

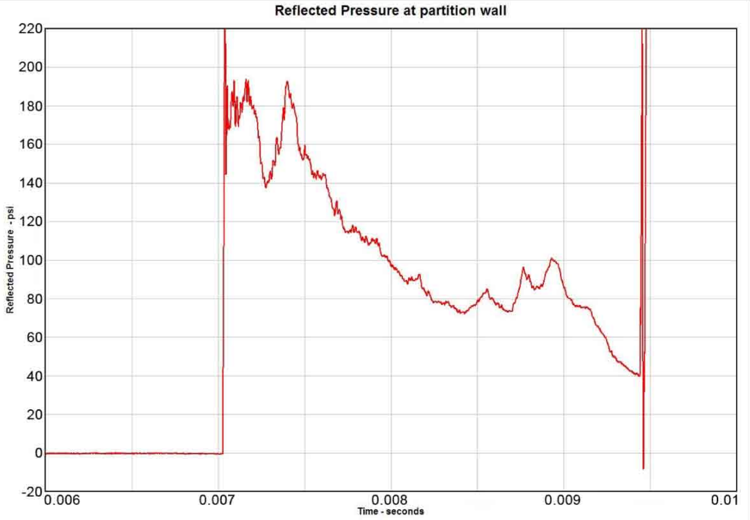


Figure 4: Reflective pressure time

2) Peak lateral deformation: The maximum deformation was measured at approximately 9 inches. The deformation time history plot is given in *Figure 5* (negative values indicate wall movement towards the inside of the room). From *Figure 5*, it can be observed that there is no elastic rebound deformation due to the inertial forces. This was most likely caused by the crushing failure of the masonry, which generated an over-damping effect that eliminated the oscillations about the zero deformation line. As a result of the crushing failure of the masonry, a permanent deformation of about 2.5 inches was measured after the blast event. The figure also shows that oscillations of about 0.25 inch in amplitude with periods of 0.15 to 0.2 seconds occur after the first motion. These appear to be due to vibration of the instrument stand, and are unlikely to represent true motion of the wall.

3) Peak interior pressure: The maximum value was measured at 4.2 psi. Blast wave leakage occurred between the gaps on the vertical edges; these gaps increased significantly due to the wall deformations. Therefore, if these gaps had been sealed, the peak internal pressure would have been significantly lower. As a reference, eardrum rupture and lung damage occur at about 5 psi and 10 psi, respectively; therefore, 100% survival rate, with minimal injuries would be expected for any occupant of the room with the CFRP retrofitted wall. As will be shown later, the CFRP contained all the debris and no wall projectiles were seen in the room, which is a highly desirable feature for minimizing potential injuries and property damage. *Figure 6* shows the internal pressure time history. The noisy and chaotic shape of the curve is typical of internal pressure reading in closed rooms.

As mentioned above, crushing failure of the masonry occurred as predicted by the structural calculations. Also, CFRP anchorage failure occurred on the top edge of the outside face of the wall due to insufficient development length. Under static conditions, a simply supported wall would have very little tensile force demands at the edges, so CFRP anchorage failure is usually not a concern. However, under dynamic conditions, the inertial forces of the disintegrated mass of crushed masonry forced the CFRP to act as a membrane, placing significant tensile demands on the edges. The use of a proper development length would have meant extending the CFRP beyond the steel angle anchoring system and into the parapet of reaction building, which was avoided to minimize residual CFRP fabric adhered to the building exterior. *Figure 7 (See page 20)* shows CFRP anchorage failure occurring at the upper left corner of the wall.

Figure 7 also shows the state of the retrofitted and un-retrofitted URM walls after the blast test. The un-retrofitted URM wall suffered catastrophic failure, with masonry debris scattered all the way to the back of the room. Although the internal pressure was not measured on the room enclosed by the un-retrofitted wall, it would be safe to assume that it exceeded 45 psi, considering that the shock wave entered the room with minimal energy dissipation due to the collapse of the wall. The 45 psi value represents the threshold for less than 1% survival rate, which means that massive loss of life and property would have occurred in the room with the un-retrofitted URM wall due to the combination of high pressure and masonry projectiles.

It can be observed from *Figure 7* that the CFRP retrofitted wall remained standing, even though the masonry inside was practically reduced to debris. It can also be seen that all the debris was contained by the CFRP. The high speed camera video taken from the inside shows evidence that no masonry debris projectiles were present in the room enclosed by the retrofitted wall and that all the debris was contained by the CFRP fabric. The inside lateral video camera clearly captured the deformation behavior of the wall during the blast event, including the effects of the crushing failure of the masonry. The lateral exterior video camera illustrated the effect of the arrival of the shock wave on both URM walls.

Figure 5: Displacement time his-

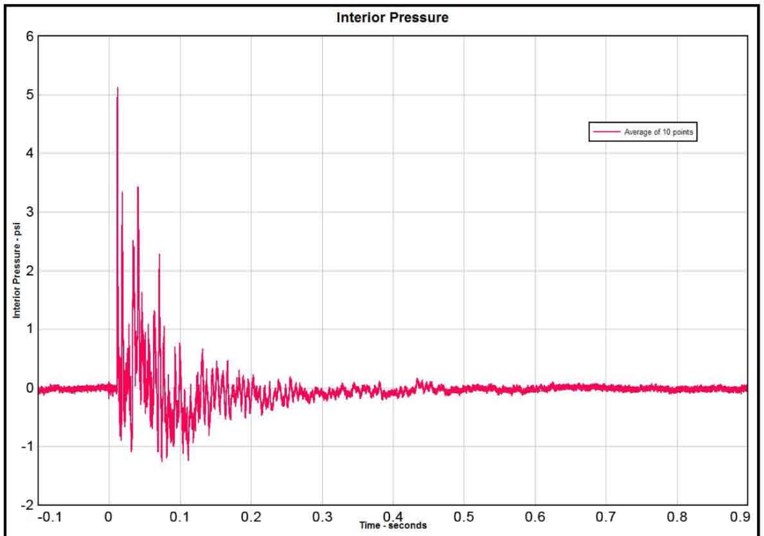


Figure 6: Internal pressure time history