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RESPONSE OF ARCHING UNREINFORCED MASONRY WALLS TO BLAST LOADING

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ABSTRACT

Recent events have drawn considerable attention to the vulnerability of structural and non-structural elements subjected to blast loads. Unreinforced masonry (URM) concrete walls are commonly constructed as exterior infill panels. These walls are conceived as a source of hazard to building occupants when an external explosion occurs outside the building. The present experimental results show that forcing URM walls to arch against rigid supports significantly enhances their out-of-plane blast resistance. A total of 12 full-scale URM concrete walls were constructed and tested using live explosives. In this paper, the results of two of these walls will be presented. Reflected blast pressure and impulse as well as the wall's central deflection-time history were recorded for each shot. In addition threat level and damage were correlated with the charge size and the stand-off distance. The walls resistance was significantly improved by forcing the walls to arch through provision of arching thrust resisting support conditions.

KEYWORDS: arching, blast load, dynamic response, unreinforced masonry.

INTRODUCTION

In the past, blast resistant design was mainly considered for essential governmental buildings, military structures, and petrochemical facilities. However, recent threats and tragic events targeting civilian and commercial buildings have resulted in devastating consequences, often causing hundreds of deaths and injuries. Consequently, the structural engineering community has recently started to pay more attention to analysis and design methodologies of new civilian buildings to withstand blast loads. Since the majority of existing buildings are not designed to resist such extreme loads, to deal with safety of these structures, economic blast retrofit strategies are necessary for their blast damage mitigation and hardening.

Due to its economic benefits, accessibility, aesthetics and functionality, masonry is one of the most widely used construction materials in North America. For example unreinforced masonry (URM) buildings are commonly used as infill walls in framed structures. However, recent strong dynamic load events, such as the Tangshan 1976, Northridge 1994, and, Turkey 1999 earthquakes, showed that the main cause of personal injury and loss of life during earthquakes is the failure of poorly detailed and designed bearing or infill walls under out-of-plane loads, rather than in plane loads, [1, 2].

Consequently several retrofit techniques have been developed to enhance the out-of-plane load capacity for URM structures. These techniques have the potential to increase the out of plane blast resistance of such walls [3]. Among these methods is adding mass through injecting grout to fill the hollow units or cavity between wythes or by increasing the wall thickness using single or double sided jacketing made of in-situ concrete. Although these techniques may be sufficient to add strength and stiffness to URM structures, they are usually time consuming and labour intensive, [4,5].

It is currently widely accepted that treating infill walls as non-structural elements and completely ignoring their interaction and connection details with the confining frames would result in a perceived vulnerability to out-of-plane loads. If the infill and the frame are treated as one composite system, the out-of-plane stiffness and load capacity of the wall increase significantly. This creates a situation where, if properly detailed and analyzed, masonry buildings may not necessarily require significant hardening in contrast to the situation when the wall and the frame are treated separately. Based on later premise in this paper, an economic hardening technique to enhance the out-of-plane blast resistant capacity of URM walls is developed and evaluated. The technique is based on the well known arching action as will be described in the following section.

ARCHING ACTION

For arching walls, most experimental data suggest that, after the initial cracking of the URM infill wall, the out-of-plane strength depends on the compressive strength of the masonry rather than the tensile strength. This phenomenon was first described in [6], in which a theory based on arching action of one-way URM panels butted up against rigid supports was developed. The theory showed that the out-of-plane capacity of URM panel with end restrains can be greatly enhanced, and the wall can sustain significantly higher lateral loads than those calculated based on traditional bending analyses. This theory assumed that after the development of tension cracks at both the centre and the ends of the wall, the wall may be treated as two identical rigid bodies, rotating about their ends until either the masonry crushes or the bodies snap-through. The mechanism of arching action is illustrated in Figure 1. This theory is limited to URM walls with uniform solid cross section. The term arching arises from similarity of the deflected shape of the wall to a three-hinged arch as shown in Figure 1.

The great enhancement in the out-of-plane capacity of URM panels due to arch action has encouraged our researcher team to investigate the response of arching URM panels subjected to blast load both experimentally and analytically.

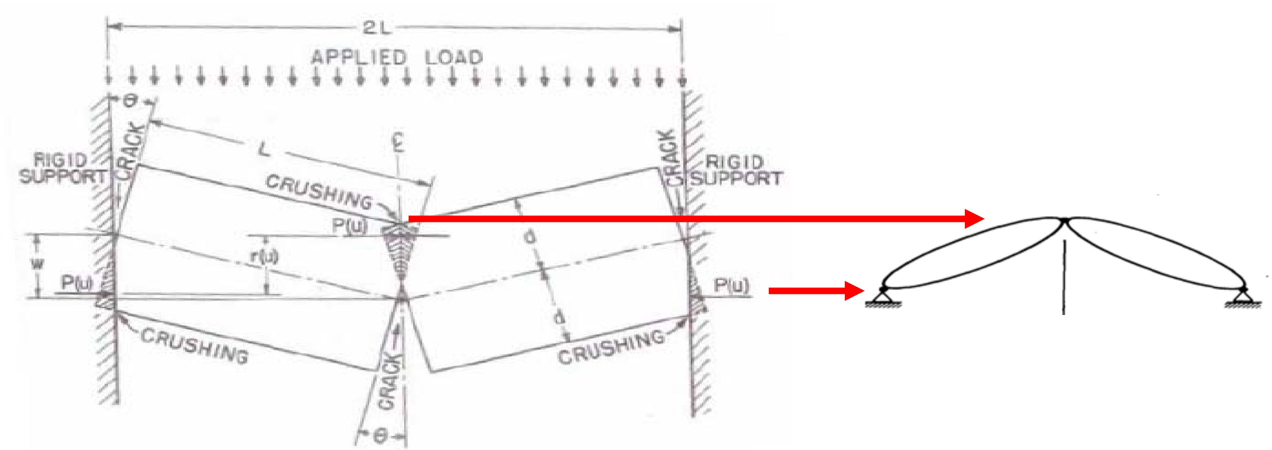


Figure 1: Arching Mechanism [6]

Free field blast load tests, were conducted [7] to demonstrate the ability of masonry walls to provide blast resistance. A total of eight walls were constructed and arranged in an octagonal arrangement. An explosive charge was placed in the centre of the octagon, with the charge size and type designed to provide a blast pressure of 35 kPa (5 psi). The parameters studied in the experimental program were the reinforcement effects on clay brick and concrete block panels, and horizontal arching effects. It was found that, an 8 in. (200 mm) arching brick wall, without any reinforcing steel, had the same resistance as a 9 in. (225 mm) non-arched reinforced brick masonry wall of equal span. In addition, a blast design method for arching URM solid brick panels using design curves based on the experimental results was proposed in the same study [7]. Another blast design method for solid masonry beams butted against rigid supports was suggested by McKee and Sevin [8]. The method can be used to enabled predict the maximum blast load that a certain panel can sustain or it can be applied to design an URM panel for a given blast load.

EXPERIMENTAL PROGRAM

Two URM walls were built by the Canada Masonry Centre training staff, Mississauga, Ontario and tested under blast loads generated by substantial quantities of high explosives in a Canadian Forces Base test range. The testing program and the results are described in the following section.

URM WALL SPECIMENS

The walls were built by an experienced mason using Type-S mortar and standard 190-mm (nominal 20 cm) two-cell concrete blocks. All mortar batches were proportioned by weight for better quality control, and any mortar batches that were not used within 1 hour were discarded to avoid any strength reduction. The mortar flow was measured and three 2-in. (51 mm) cubes were taken for each mortar batch. The dimensions of each wall were two and a half hollow concrete blocks wide (990 mm) and eleven courses high (2,190 mm). All walls were face-shell mortar bedded with 10 mm mortar joint and with all mortar joints concavely tooled. Each wall was built over a 38 mm wooden base, and all the walls and the prisms were built in a running bond to simulate common construction practice.

TEST SET-UP

One of the main problems that occur in free field blast testing is the blast wave clearing effect. This phenomenon is accompanied with both pressure drop and uncertainties associated with blast wave parameters [9]. Two ISO steel containers (A and B) were used in this test set-up to reduce the clearing effect phenomenon as was confirmed later by in-container pressure measurements during blast testing. The nominal dimensions for each container are 20 ft (6.10 m) long, 8 ft (2.40 m) wide, and 8 ft (2.40 m) high. The container and the URM wall are shown in Figure 2. To ensure access to the container, a 1m x 2m opening was cut from the back of the container, and a steel door was installed to prevent the propagation of the blast wave from the back of the wall as shown at Figure (2a). In order to avoid the clearing effect around the specimen, and to ensure a uniform pressure and impulse on the wall, the specimen was surrounded by three sacrificial wing walls, one on each side and one on the top as shown in Figure (2b).

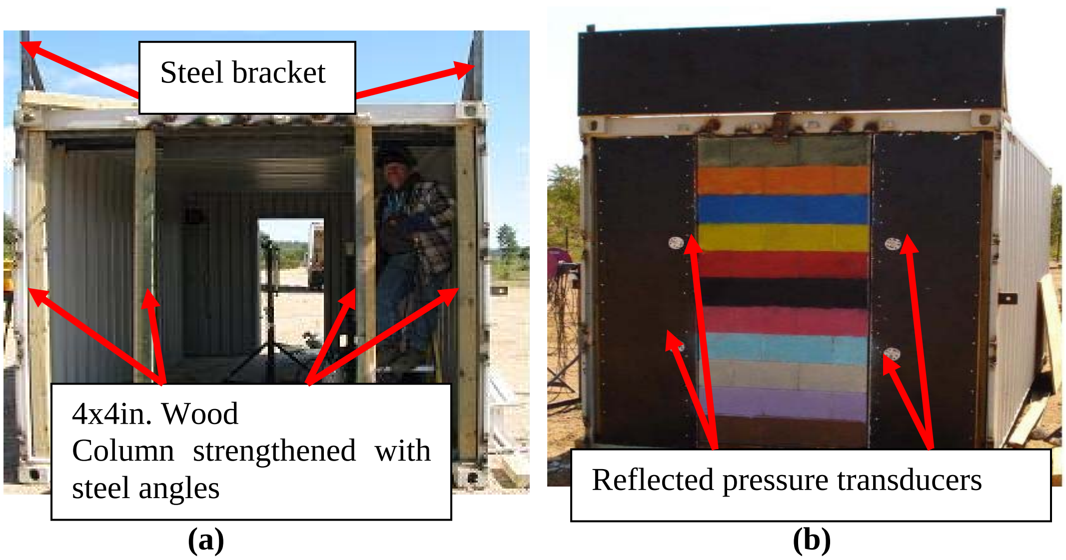
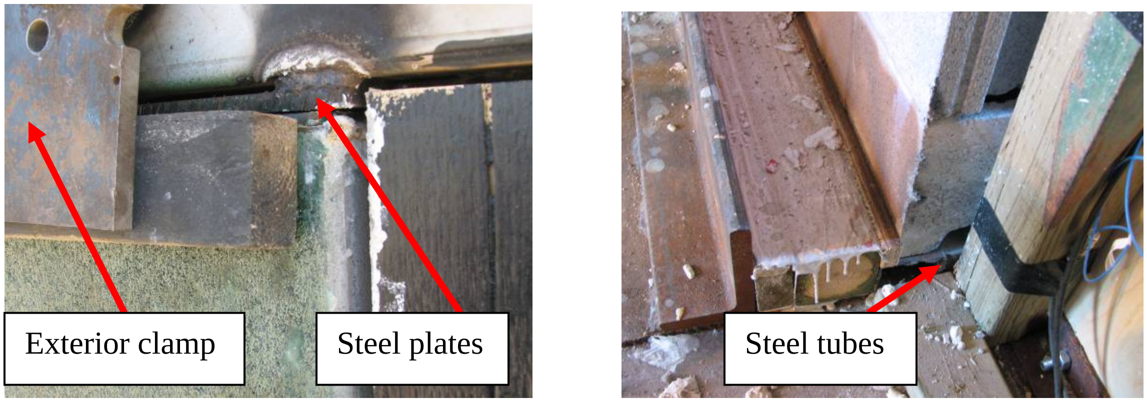


Figure 2: ISO steel container, (a) Before implementing wing walls and specimen, (b) After completing test-setup

The URM walls were supported along their top and bottom edges. At the bottom ends, each of the two face shells were supported on a hollow rectangular 3 in. wide by 2 in. high (75 x 50 mm) steel section as shown in Figure (3b). Two 6 mm thick steel plates were used as shims and placed between face shell at the top of the wall and the steel frame of the container as shown in Figure (3a). These end conditions were designed to enforce rigid arching and to provide uniform support conditions. In addition, two clamps were used, one at the top and the other at the bottom on the outside and the inside of the container. The outer clamp was used to prevent the pull-out of the specimen during the negative blast load phase, while the inner one was used to prevent the sliding of the specimen during positive phase of the blast load.



(a) **(b)**

Figure 3: Boundary conditions for URM wall Specimens

INSTRUMENTATION AND TEST PROCEDURE

Four reflected pressure transducers (RF) were used to measure the reflected pressure for each container as shown in Figure (2b). Only one LVDT (Linear Variable Differential Transducer) was used to measure the central wall deflection at the mid-height of the sixth course. The stand-off distance varied between 3.0 m and 20 m. The charge weights varied between 15 kg and 250 kg of Ammonium Nitrate Fuel Oil (ANFO). All the charges were surface burst and were detonated at the ground level. A total of nine shots were detonated, the first wall (W1) located in Container (A) was subjected to six shots and the other wall (W2) in Container (B) was subjected to three shots. Detailed data of charge size, stand-off distance and pressure gauges locations are illustrated in Table 1. For safety reasons, all personnel were evacuated to a safe distance of 300 m to 500 m, depending on the charge size before detonation. After each detonation, all the data recorded were checked and specimens were thoroughly inspected.

Table1: Test matrix

Shot No.		6	7	8	9	10	11	12	13	14
ANFO Charge(kg)		15	25	50	75	153	30	30	100	250
Container (A)		W1	W1	W1	W1	W1	W1	-	-	-
Container (B)		-	-	-	-	-	-	W2	W2	W2
Stand-off Distance (m)	RF1	19.4	19.4	19.4	19.4	17.0	3.0	-	-	-
	RF2	19.4	19.4	19.4	19.4	17.0	3.0	-	-	-
	RF3	19.4	19.4	19.4	19.4	17.0	3.0	-	-	-
	RF4	19.4	19.4	19.4	19.4	17.0	3.0	-	-	-
	RF5	-	-	-	-	-	-	20.0	20.0	17.0
	RF6	-	-	-	-	-	-	20.0	20.0	17.0
	RF7	-	-	-	-	-	-	20.0	20.0	17.0
	RF8	-	-	-	-	-	-	20.0	20.0	17.0

The two main parameters describing a typical blast threat are the charge weight and the stand-off distance. Correlating the wall damage to the threat level is necessary for designing new blast-resistant building or to harden existing structures. In the current experimental program, the criteria used to measure the damage level for URM walls as well as the threat level are based on those originally proposed in [10].

EXPERIMENTAL RESULTS

In this experimental program all wall top and bottom courses were prevented from in-plane movement by unyielding rigid steel frame members as described earlier. Thus, the walls collapse strength was greatly enhanced by arching action. The walls were supported only at their top and bottom ends, but were unrestrained along their sides, which limited the rebound resistance to the walls shear capacity at supports [9].

POST-BLAST OBSERVATIONS

Although both walls were subjected to successive blast shots, minor damage was observed. As mentioned earlier, each specimen was carefully checked after every shot and the damage, if any, in the mortar, or the blocks was recorded. The criterion to terminate testing was based on the level of deterioration of mortar bed joints. This is attributed to the fact that the out-of-plane capacity of an arching URM wall depends only on the masonry compressive strength after the occurrence of the first mortar crack.

(a) **(b)**

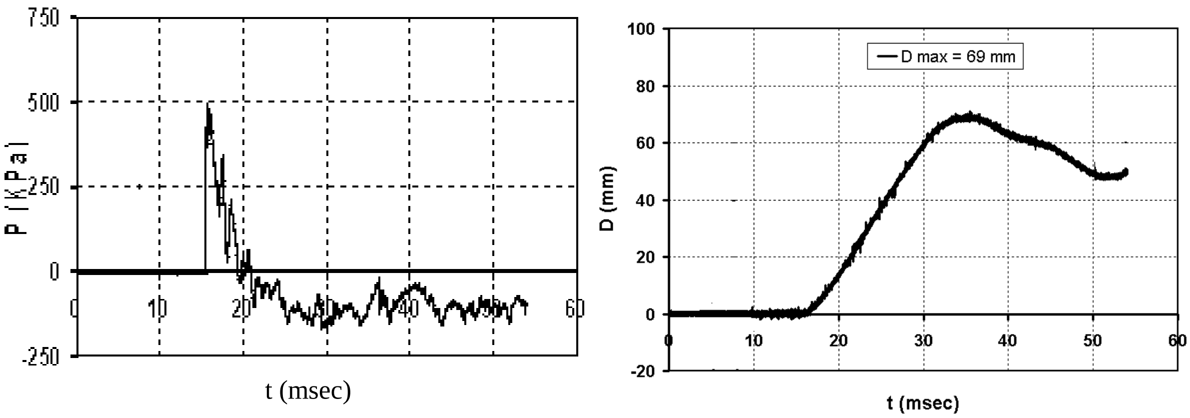
Figure 4: Typical post blast observed damage of Wall W2 charge 250 kg ANFO at 17.0 m stand-off distance

The photographs in Figure 4 were taken after wall W2 was subjected to a peak pressure of 500 kPa, produced by a 250 kg ANFO charge at a stand-off distance of 17.0 m. It is clearly shown that the wall was able to sustain the blast load without collapse. On examining the front face of the wall, it was found that, only the mortar bed joint was damaged at the mid-height region of the wall from the outside as shown in Figure (4b). This level of resistance was made possible by the boundary condition of the wall that enabled it to arch, and thus, act as two rigid segments; the first segment comprising the upper six courses and the second segment the lower five courses.

Each part rotated around the mortar bed joint on the compression side which was completely crushed. In addition, deterioration of mortar bed joints was also observed at the top and bottom courses. Originally, it was thought that the boundary conditions at the top and bottom of the wall provide complete fixity, thus prevent the first and the last course from rotating, leading to the formation of the three-hinged arch above the bottom and below the top courses. On the other hand, only minimal damage was observed at the mortar bed joints on the rearing surface of the wall.

PRESSURE AND DEFLECTION TIME HISTORIES

Both pressure and deflection time-histories were recorded for every shot, using pressure transducers and LVDT. Figures (5a and b) shows typical pressure- and deflection-time history profiles recorded for wall W2 due shot#14.



(a) Pressure – time profile **(b) Deflection – time history profile**

Figure 5: Typical post blast observed damage of Wall W2
charge 250 kg ANFO at 17.0 m stand-off distance

The maximum central wall deflection was measured to be 69 mm; the descending branch of the deflection-time history was attributed to the decay of the blast wave with time. It is clearly shown that the maximum deflection occurs at time greater than the positive phase duration of the blast, which is a characteristic of the impulsive nature of the blast load.

DISCUSSION OF ARCHING RESULTS

Walls W1 and W2 were tested to determine their capacities as rigid arches. The two walls were subjected to successive shots by increasing charge weights until failure occurred. The corresponding peak reflected pressure, maximum centre deflection, damage level, and, threat level for each blast event are listed in Table 2. It is clearly shown that the criteria used to define both the damage and the threat levels, are relate favourably to the experimental results. Note, the higher the threat level, the heavier the damage observed.

Table 2: Correlation between threat, damage levels and experimental results

Wall	Shot No.	ANFO Charge (Kg)	Standoff Distance (m)	Peak Pressure (Kpa)	Deflection (mm)	Threat Level	Damage Level
W1	6	15	19.4	50	2	Low	No
W1	7	25	19.4	55	6.6	Low	No
W1	8	50	19.4	80	12	Low	No
W1	9	75	19.4	107	26	Medium	Light
W1	10	153	17.0	175	34	Medium	Heavy
W1	11	30	3	*	*	High	Collapse
W2	12	30	20.0	64	7	Low	No
W2	13	100	20.0	145	17	Low	No
W2	14	250	17.0	500	69	High	Heavy

* Wall was completely destroyed

No visual cracks were observed in wall W1 up to Shot#7. After Shot#8, fine vertical hair line cracks appeared in the bed mortar joints on the back face of wall W1. After Shot#9, wide horizontal cracks in mortar bed joints appeared at approximately mid-height of the back face of the wall. After Shot#10, wider horizontal cracks formed in the mortar bed joints on both front and the back face of W1, leading to significant deterioration of the mortar joints on the front face.

Wall W2 was subjected to three successive shots as indicated in Table 2. Practically no cracks were observed after both Shots#12 or #13. However, heavy damage was observed after Shot#14, with wide horizontal cracks forming at mid-height of the wall in mortar bed joints on both faces of the wall. In addition, fully damaged mortar parts were observed on the front face of the wall at mid-height and at both supports.

CONCLUSIONS

The results obtained from experimental program, and supported by available literature led to the following conclusions:

1- The use of the ISO containers significantly minimized the blast-clearing phenomenon.
2- The support conditions provided in the current test allowed the walls to efficiently undergo arching action.
3- Arching action eliminated or reduced to a great extent the vulnerability of the tested URM walls to failure under blast-generated out-of-plane loads.
4- The provision of rigid supports for the walls was shown to be a simple and cost effective, hardening technique. The technique also prevented wall tipping out of the frame even under high blast loads.

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