# TWO-WAY ARCHING OF REINFORCED MASONRY WALLS UNDER BLAST LOADS

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**ABSTRACT**
The enhancement of arching action to masonry behavior has long been recognized. In the current study, the behavior of reinforced concrete block walls supported on four sides, to enforce two-way arching, is experimentally investigated. The walls were subjected to different levels of scaled-distances representing a wide range of threat levels within the wall's impulsive regime. The uniformity of the blast pressure and impulse was ensured by a specially designed test enclosure that also diminished the wrap-around and clearing effects. In general, the results demonstrated the beneficial effect of two-way arching on the flexural behavior of reinforced masonry walls under impulsive loading. The results are expected to contribute to better understanding of masonry wall response to blast loads and to the growing masonry blast performance database. The generated results are expected to contribute to the masonry design provisions in future edition of the recently introduced Canadian Standards CSA S850-12 "Design and Assessment of Buildings Subjected to Blast Loads".

**KEYWORDS**: arching, blast loading, blast scaling, experimental testing, out-of-plane, reinforced masonry

## INTRODUCTION

This paper examines the mechanics of reinforced masonry infill walls response to controlled blast loading. This research is critical to the acquisition of new reliable information for engineers, architects and designers, as well as to facilitate the evaluation of the currently available design guidelines. This information is necessary to ensure the structural integrity of existing structures and, if required, their repair/re-fortification. Documenting the effect of blast on reinforced masonry walls in a controlled environment with well-defined boundary conditions gives high quality data for interpretation in future building standards.

The importance of reporting this information in general, is recognizing that approximately 70% of the existing building inventory in North America is masonry [1], and a large percentage of the world's population live in or utilize masonry components. It is also significant as most available research data refers to either steel or concrete. In addition, experiments required to provide this information are generally expensive and difficult to mimic in a controlled environment for several factors, which include material and construction costs, transportation, test setup, explosives, test ranges, to name but a few.

Blast events, whether deliberate or accidental, result in a loading case that certain civilian structures could be subjected to, thus determining the effects of blast is essential. The detailed focus of this paper will be on the response behavior of reinforced masonry infill walls subjected to blast loading. The response parameters of interest include both wall deflections and failure modes. Within a larger test program, the experimental results of three masonry infill wall specimens, confined by four rigid supports (simulating upper and lower rigid floor beams, and left and right rigid columns), subjected to blast loading will be reported in this paper. Arching affect will be reviewed in detail and its significance with regard to masonry wall performance will be documented herein.

**ARCHING**

Arching (see Fig. 1) can occur when masonry walls under out-of-plane bending are restrained at the supports. The restraining action produces large in-plane compressive (thrust) forces within the wall. In order for this arching action to take place and fully develop, it is critical that the wall is fully restrained at the rigid supports [2] with no gap. As a result, arching can increase the capacity and significantly enhance the performance of reinforced masonry walls.

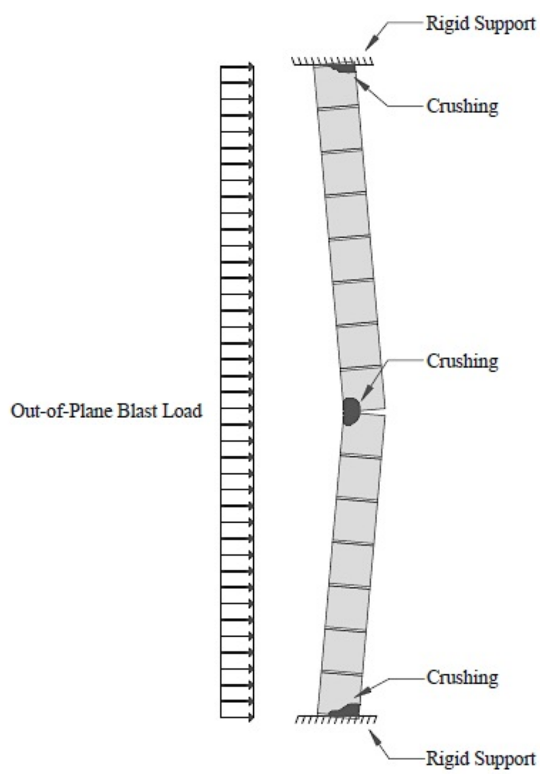


**Figure 1: Arching Mechanism**

**SCALING LAWS**

Scaling laws can be used to extrapolate results obtained from reduced scale testing to the prototype (full-scale) case [3]. The most common rule in scaling blast waves is the Hopkinson-Cranz cubed root scaling, which is used to predict the dimensionless properties of blast waves from large-scale explosions based on much smaller tests preformed [4].

The scaled-distance dimensionless parameter Z can be produced from the same blast source and detonated in the same atmosphere.

$$Z = \frac{R}{E^{1/3}} \tag{1}$$

Where R is the distance from the centre of the explosion and E is the total energy of the explosive [4]

In a controlled test, the Hopkinson-Cranz cubed root scaling can be used to considerably reduce the amount of explosive required for testing and to expedite and simplify free-field high explosive testing. In addition to explosive scaling, structural scaling of the masonry infill wall with a scaling factor of one-third, was selected. As such, the weight of the explosive and distance was reduced achieving the comparable blast wave pressure and impulse as a full-scale test would.

## EXPERIMENTAL INVESTIGATION

The experimental program and test specimens were selected as part of a larger test program aimed at producing a masonry blast performance database (MBPD). This study focuses on the response of three identical fully grouted reinforced masonry walls, experiencing two-way arching and tested under three different levels of blast loading. The blast charge weights were 5, 10 and 25 kg of Pentex Booster, which has a 1.2 equivalency ratio of TNT based on total energy [5]. Equivalency values are often used to relate the performance of different explosives.

**Table 1: Shot Schedule**

| Pentex Charge Weight (kg) | Equivalent TNT Charge Weight (kg) | Scaled Distance ($m/kg^{1/3}$) |
|---|---|---|
| **5** | **6** | **2.75** |
| **10** | **12** | **2.18** |
| **25** | **30** | **1.61** |

The scaled distances represent different levels of blast threats whereas even a small bomb at a small stand-off distance can cause significant damage or even progressive collapse of an unprotected structure. The scenarios considered in this paper presented TNT charge weights that vary from 100 to 1000 kg in size at a 15 m stand-off distance. With proper scaling, the three selected TNT charge weights 6 kg, 12 kg, and 30 kg have been chosen to cause minor, moderate and severe damage levels to the three masonry walls. The third-scale 1,000 mm x 1,000 mm x 63.33 mm thick fully grouted masonry wall specimens, shown in Fig. 2(a), were constructed. These walls have a 0.33% vertical reinforcement ratio designed and constructed according to the masonry design standard S304.1-04. The wall specimens represent a full-scale 3.0 m by 3.0 m, reinforced masonry wall with rigid steel beams and columns surrounding it and forcing two-way arching to develop.

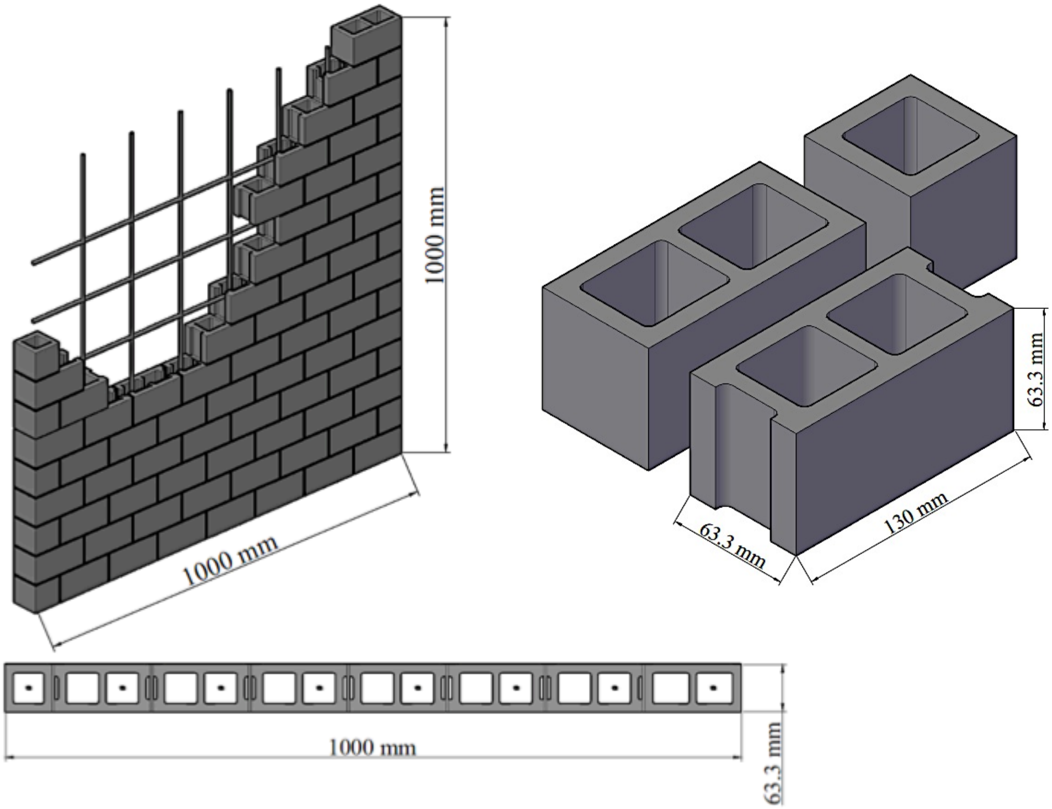


**Figure 2: Masonry wall specimen and plan view and the third-scale masonry block**

## MATERIALS

Third scale concrete blocks, shown in Fig. 2(b) above, were manufactured at McMaster University's Applied Dynamics Laboratory (ADL). These dimensions represent exactly one third true replica model of the standard 20 cm concrete masonry unit (190 mm x 190 mm x 390 mm).

To evaluate the masonry block compressive strength, eighteen random one third-scale masonry blocks were tested with an average compressive strength of 20.1 MPa and a coefficient of variation (COV) of 12.44% according to CSA A165.1 [6] and S304.1-04 [2]. The masonry blocks compressive strength was based on the average net cross-sectional area 4789 mm$^2$. Grout cylinders strength had an average value 22.4 MPa with a COV of 14.2% based on CSA A179 [7]. Type-S mortar cubes were tested according to CSA A179 [7] with an average of 28.8 MPa with a COV of 3.1%. The masonry prims were tested in accordance to ASTM standards [8] with an average compressive strength of 18.7 MPa with a COV of 10.2%.

The three experimental walls were design as two-way action walls. As such, the reinforcement was symmetrical in both vertical and horizontal directions. The steel reinforcement used was D4 bar with a cross sectional area of 26 mm$^2$, Young's Modulus (E) of 232.2 GPa and an average yield stress ($f_y$) of 477 MPa with a COV of 1% tested according to ASTM A615-12 [9].

**BOUDARY CONDITIONS**

The test specimen was used to simulate an exterior steel framed structure with masonry infill wall panels. These infill wall panels were built with no gap between the wall and the surrounding frame, thus forcing two-way arching action to develop. To simulate the steel frame with no gap, a 5x9 C-Channels was used to construct the wall on top of and when the masonry wall was finished another C-Channel was mortared in place on top of the wall. Two vertical C-Channels were welded to the top and bottom C-Channels shown in Fig. 3(a). Figure 3(b) shows the round stock bar welded around the entire perimeter of blast frame to create a knife-edge support for the steel frame surrounding the walls during blast testing.

**(a)** **(b)**

**Figure 3: Boundary Conditions: a) Wall Specimen; b) Blast Frame**

**TEST SET UP**

The experimental setup was built and transported to the test range at a Canadian Forces Base located in Ontario. The blast frame was placed at a 5 m stand-off distance from the centre of the explosive charge. Wing and a parapet walls were used to minimize the clearing effect and helps create a uniform pressure on the wall specimen [10]. In addition, a steel box enclosure (bunker) formed the rest of the test frame behind the wall to prevent the wrap-around effect, which was in turn supported by a 1.5 m cube concrete barrier blocks to shield the rear and side faces of the frame.

In the test set up shown in Fig. 4, four linear displacement potentiometers were internally mounted (not shown) to measure the displacement from the blast load. Each of these potentiometers was placed at a critical location to capture the entire wall deformation profile in both the horizontal and vertical directions to verify symmetry. Three piezoelectric pressure transducers were used to record the pressure profile from the blast wave. In addition, one pressure transducer was also located inside the blast frame to verify that no interior over-pressure developed inside the test bunker during the blast load.

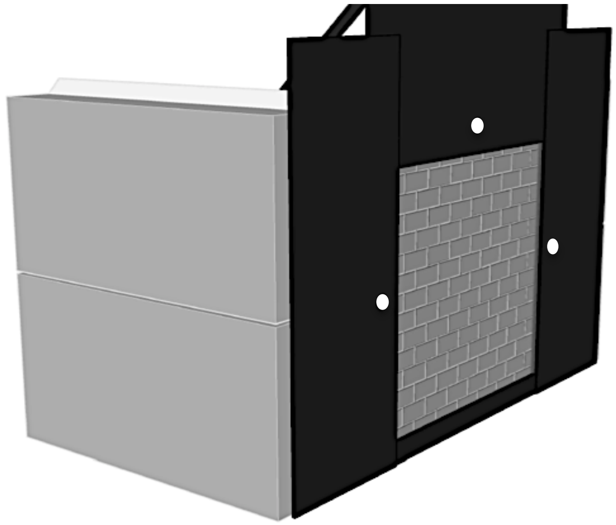

**Figure 4: The blast bunker**

## BLAST WAVE PROPERTIES

Figure 5 below shows an ideal incident blast wave signature. The main properties are the Peak incident pressure $P_s$, the positive phase duration $T^+$ of the explosion, and the Positive Impulse $I_s$. In most studies of blast waves the negative phase of the blast wave is usually ignored [5]. These properties were recorded from free-field transducers surrounding the test bunker.

Peak reflected pressure, positive phase duration and reflected impulse were all recorded/calculated from the measurements of the three pressure transducers located on the test frame.

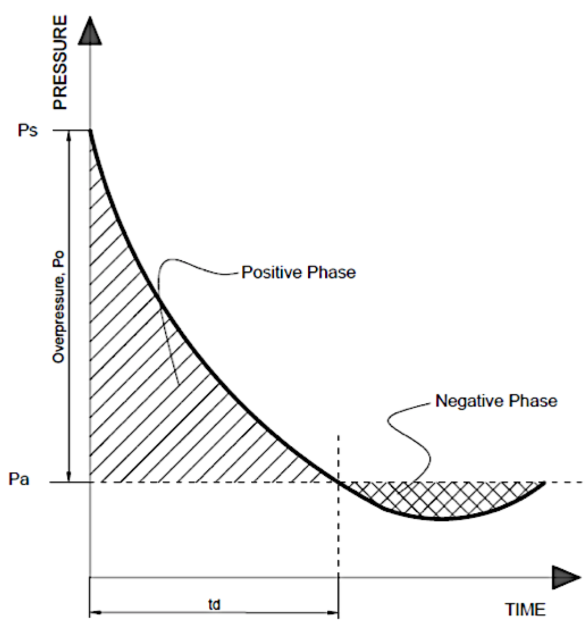


**Figure 5: Ideal Blast Wave**

The modified Friedlander equation [5] was used to confirm the maximum peak pressure and positive phase duration transducer measurements. The impulse was calculated from the area under the Modified Friedlander curve. Fitting the Modified Friedlander equation over the full positive phase and the observed upper half positive phase gives comparable results to the experimental data, which then can be used later in a numerical analysis, shown in table 2 below. The observed half positive phase Modified Friedlander fit was done to check the accuracy of the peak pressure of the full positive phase Friedlander fit.

$$P(t) = P_{max}\left[1 - \frac{t}{T_{dur}}\right] e^{-\alpha(t/T_{dur})} \qquad (2)$$

These results were verified from ConWep [11] to predict blast wave parameters from a 5 m stand-off distance and compared in Table 2 below. During the experimental tests the blast wave properties were recorded for every shot using the pressure transducers as mentioned before.

**Table 2: Pressure and Impulse estimates**

| | **ConWep Predictions** | | **Observed Full Positive Phase Duration - Modified Friedlander** | | **Observed Half Positive Phase Duration - Modified Friedlander** | |
|---|---|---|---|---|---|---|
| **Pentex Charge Weight (kg)** | **Peak Pressure (kPa)** | **Impulse (kPa.ms)** | **Peak Pressure (kPa)** | **Impulse (kPa.ms)** | **Peak Pressure (kPa)** | **Impulse (kPa.ms)** |
| **5 (11 lb)** | **420** | **450** | **357** | **427** | **327** | **488** |
| **10 (22 lb)** | **810** | **750** | **928** | **867** | **950** | **848** |
| **25 (55 lb)** | **2010** | **1480** | **1867** | **1491** | **1844** | **1505** |

## EXPERIMENTAL RESULTS

Visual observations as well as the recorded displacements were used to discuss the formation of crack patterns and the development of wall failure modes. The recorded data was also used to generate the deflected shape of the wall specimen and to evaluate the maximum wall deflections.

## WALL DISPLACEMENTS AND ROTATIONS

The blast load was chosen to cause different damage and deflection levels from the CSA S850-12 blast standard [12]. The lateral displacement profiles along the vertical axis for the masonry wall specimens are shown in Fig. 6 below. The rotation was taken at the arc tangent over the ratio of maximum displacement to the effective displacement length. The effective length is taken from the mid-span of the boundary to the mid-span of the wall. The 6 kg of TNT shot produced a maximum displacement of 17.7 mm with a corresponding rotation of 2°. In the CSA S850-12 standard, the response limits for reinforced masonry is 2° for flexure and combined flexure and axial compression. This specimen falls in the moderate damage category. The second shot of 12 kg of TNT resulted in a 6° rotation, which falls within the heavy damage category for flexure failure. Finally, the third shot of 30 kg of TNT resulted in a 22° rotation, which places it in the blowout damage category for flexure. All the walls failed in flexure and for the highest charge weight case of 30 kg of TNT, there was evidence of punching shear failure at the wall corners.

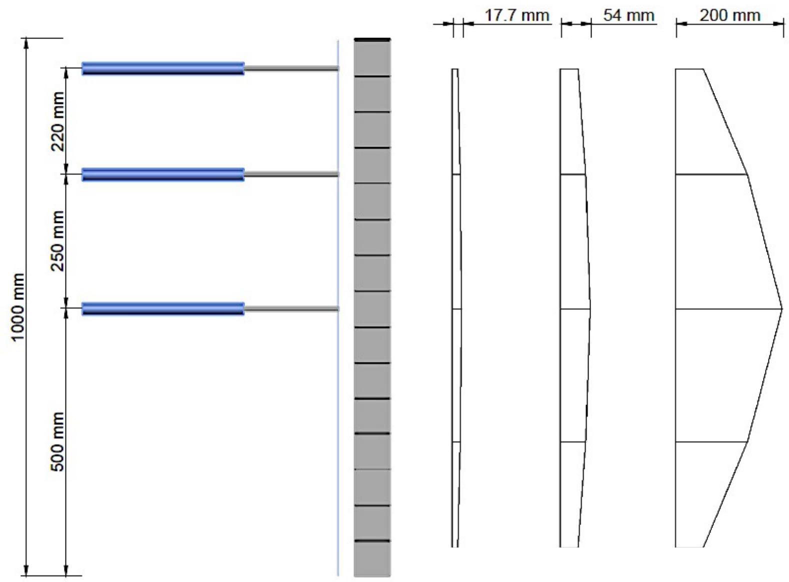


**Figure 6: Wall Displacement Profiles**

## FAILURE MODES AND CRACK PATERNS

The test walls were thoroughly inspected after each of the three shots and all forms of damage was recorded. Crack patterns from the three masonry specimens are presented in Figure 7. The most common mode of failure in the arching masonry walls was crushing of the masonry at the boundary regions as shown in Figure 7(c). This crushing near the boundary confirmed the development of the arching mechanism. Flexural cracking also occurred at the supports due to hogging moment resulting from the wall rotational restraints developed by the steel frame, followed by cracking at the walls central positive moment region. As a result, a three-hinged arch formed when the wall is viewed from its side. For the second shot, the wall specimen had a typical flexure failure with superficial damage. In the third shot, the second wall specimen developed a flexure failure combined with a shear failure in the corners as shown in Fig 7 (b). The CSA S850-12 standard does not give limits for shear or combined shear and flexure failures. The last shot with the highest charge weight of TNT, resulted in a complete blowout with major crushing damage from the arching effect.

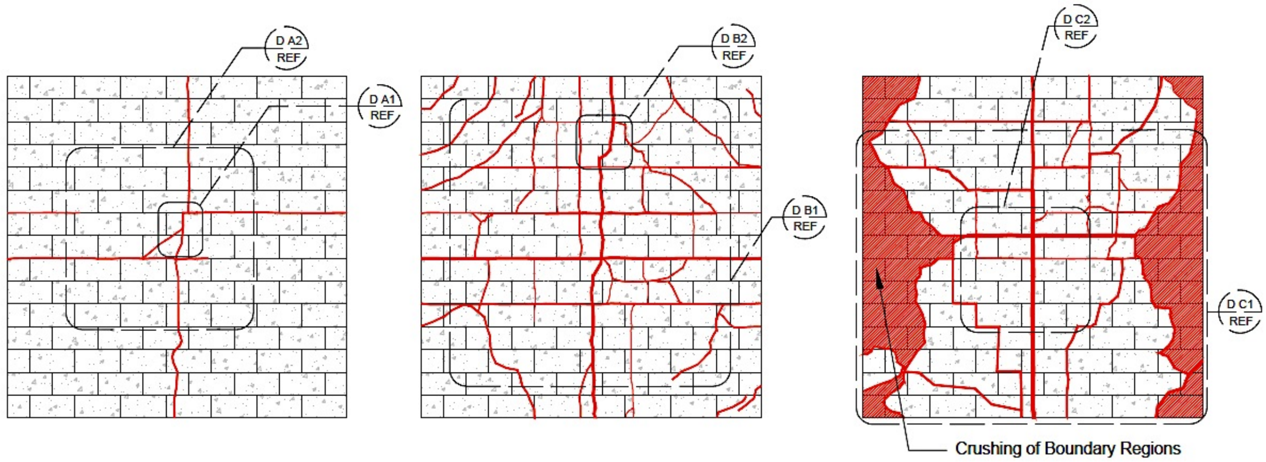


**Figure 7: Failure Modes: a) First shot; b) Second shot; and c) Third shot**

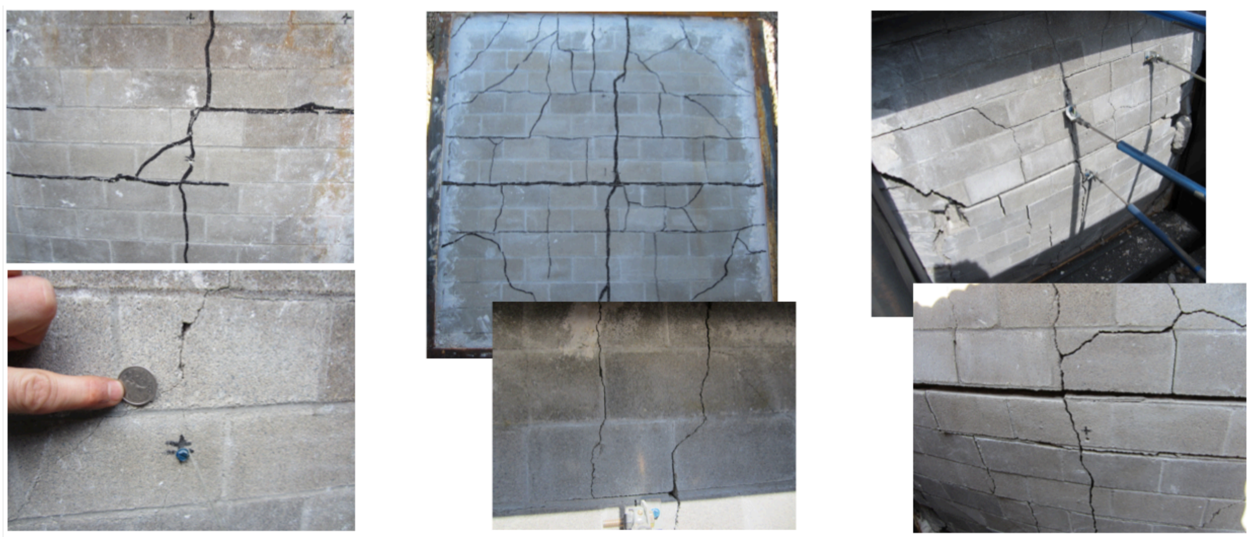

**Figure 8: Details of Failure Modes: a) First shot; b) Second shot; and c) Third shot**

## CONCLUSIONS

The reported experimental results demonstrate the beneficial effect of two-way arching on the out-of-plane response of reinforced masonry walls under blast load. The governing failure mode of the three experimental wall specimens was flexure with some signs of shear. Enforcing arching action to develop by-design presents a cost-effective way to enhance the capacity of reinforced masonry wall against blast loading. The arching effect can also limit the amount of flying debris. Within the larger Masonry Blast Performance Database (MBPD) project, which is currently being conducted at McMaster University, the experimental test results are expected to contribute to quantifying the arching response of masonry walls under blast. This study would also contribute to future revisions of the CSA S850-12 standards.

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