PERFORMANCE OF TWO-WAY REINFORCED CONCRETE BLOCK MASONRY INFILL WALLS UNDER BLAST LOADS

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ABSTRACT

With the introduction of the new Canadian Standards for blast resistant design of buildings (CSA S850-12), there is an urgent need to quantify the performance of masonry infill walls against such extreme loads. The focus of the reported study was on evaluating the performance of such walls subjected to air blasts generated by high explosives. The tests included an array of wall design parameters, charge weights and standoff distances. These sets of unique charge weights and standoff distances present a range of scaled-distances, reflecting different explosive threat levels. It was found that the boundary conditions and test setup configuration had major effects on the wall two-way bending behaviour. Observed damage modes included flexure, as well as unexpected shear and combinational flexure-shear patterns. With no reference to these additional damage modes in the blast standards, it is imperative that if further research in this area shows shear being a major contributor to masonry infill wall damage that code provisions are modified to reflect this. This study forms a part of a major research initiative by McMaster University to generate the essential Masonry Blast Performance Database (MBPD) that will facilitate better understanding of reinforced masonry performance under explosions for designers, code committees, regulators and other stakeholders.

KEYWORDS: blast loads, infill wall panels, out-of-plane capacity, reinforced concrete masonry, scaled-distances, two-way bending

INTRODUCTION

Explosive events, whether intentional or accidental, can have serious implications on both the building and its users. It is of special importance that not only the building remains functional to a certain extent (depending on the target level of building performance) following the blast event, but that is also provides for life safety and minimization of injuries resulting from such extreme loading conditions. Common beam and column frame design leads to the extensive use of non-loadbearing infill walls, typically constructed from concrete block masonry. Infill walls encompass a large proportion of surface area over the building envelope and the pressure resulting from an external explosion can result in a large force when applied over the area, resulting in large displacements in the out-of-plane direction. Similar to other structural materials, concrete block masonry is vulnerable to blast and being the first line of defence for external explosions (as the main part of the building envelope), its resistance is critical for both the building's structural integrity and the safety of its occupants.

As a result of recent deliberate blasts and accidental explosions, research initiatives into blast-structure interaction are becoming increasingly prevalent worldwide. Significant advancements have been made in this field, including the newly developed *CSA S850-12: Design and Assessment of Buildings Subjected to Blast Loads*, which has outlined basic design guidelines to further protect structures and their occupants. As it currently stands, there is a significant knowledge gap in the understanding of reinforced concrete block masonry response to blast loading. This shortcoming leads to the necessity of significant research being undertaken to quantify the basis for recent code developments. As a result, McMaster University has undertaken a major research initiative to generate a Masonry Blast Performance Database (MBPD), a critical resource in the understanding of masonry performance under blast.

PROJECT BACKGROUND AND TEST SETUP

A significant parameter in the study of structural response to blast is typically referred to as the *scaled-distance*. By equating scaled-distances, combinations of unique standoff distances and charge weights can be identified that achieve self-similar blast wave characteristics (i.e. identical peak over-pressures, etc.). Unique sets of differing scaled-distances may also be used to represent different explosive threat levels. Researchers may use this phenomenon to their advantage by replicating very large explosive events by simply reducing the standoff distance between the test component and the charge centre. This has significant implications in the reduction of cost and the increase in safety of testing. A very common scaling technique is known as "cube-root" scaling developed by Bertram Hopkinson (1915) [1]. It states that the scaled-distance Z is a function of the standoff distance R in metres (m) and the charge weight W in kilograms (kg), as presented in Equation 1 [1]. For the purpose of experimentation, all charge weights are expressed in terms of an equivalent TNT explosive. A common technique used in the industry.

$$Z = {}^{R}\!/_{W^{1/3}} \qquad (1)$$

The type of explosive used in the testing was Pentex^{TM} Duo 16-454 Cast Booster with a TNT equivalency ratio of 1.2 based on the total energy released as well as the heat of combustion of the reaction [2,3]. As a result, all charge weights are to be multiplied by a factor of 1.2 to draw comparison between their effects and observed characteristics of a TNT explosive event.

Two types of external explosions typically studied are *Free-Air* and *Surface* blasts. Free-air explosions represent those which are at a significant distance from any surface, including the ground, resulting in a *spherical* blast wave moving in all directions [2]. Surface blasts, which were implemented in this testing, result when the charge is in direct contact or very close proximity to the ground. As a result a *hemispherical* blast wave is generated, with a stronger side-on overpressure than free-air due to the ground reflection [2].

Blast test results are typically highly dependent on several factors during the test setup. There are two important phenomena known as the *clearing effect* and the *wrap-around (engulfing) effect* which if not accounted for, may have significant implications on test results. Firstly, the clearing effect is due to the finite size of the target (wall). Near the free edges, rarefaction waves are created and move towards the centre, decreasing the peak over-pressure [4]. To combat this, steel wing walls and a parapet, as shown in Figure 1-a, were positioned directly adjacent to the wall, moving the free edge a significant distance away from the wall and rendering the clearing effect negligible. Secondly, the wrap-around effect refers to an infiltration of high pressure behind the loaded wall, decreasing its response and showing erroneously higher specimen capacities [4]. This effect may be limited in two ways, the addition of the wing walls and parapet, to increase the time travelled by the blast wave to the back of the test component, as well as enclosing the specimen within a bunker-type structure, thus preventing the pressure wave from traveling to the rear of the tested wall and affecting its response.

More obviously, the chosen boundary conditions have a significant impact on test results affecting the behaviour of the wall (one-way vs. two-way bending), the deflected shape, and more importantly the effective system stiffness. In order to allow the wall to undergo two-way simply supported action as specified, steel channels were fixed to each corner. Although these semi-rigid corners do cause some fixity, their size relative to the rest of specimen allows the wall to deflect in a simply supported manner. Each wall was placed in the blast frame, where it was ensured that the steel corners were fitted flush to a 2 in. steel round stock which was positioned at a 45 degree angle as shown in Figure 1-b. The round stock was positioned behind the wall relative to the charge, with no support on the front face of the wall and provided a sufficient rotational axis. These boundary conditions adequately simulate non-integral infill wall boundary conditions and facilitate modelling of the wall performance later on.

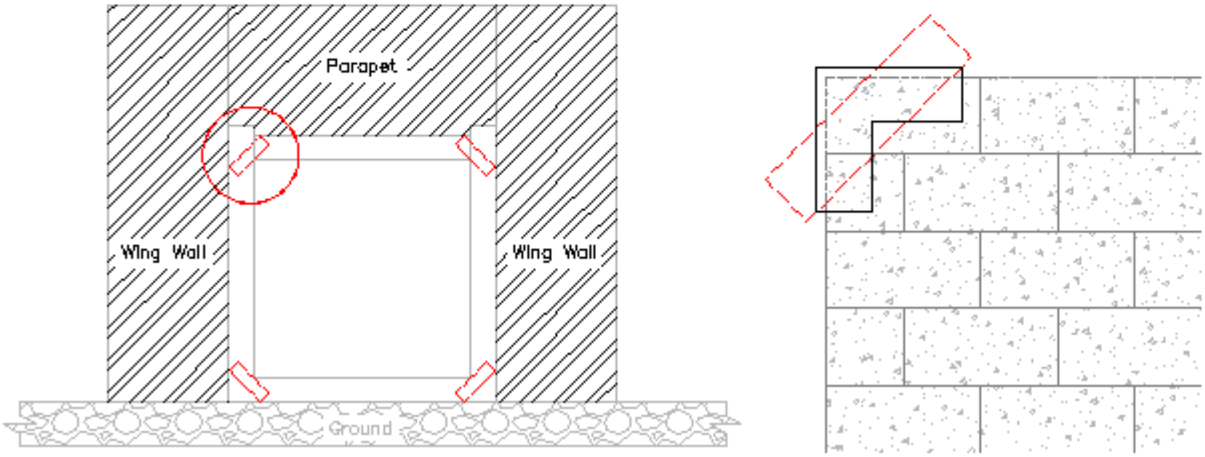

Figure 1: Blast Bunker: a) View from Charge Centre; b) Wall Connection Detail

TEST MATRIX

Testing of samples was completed as part of a larger arena test program that involved other contributing members of the MBPD research group. Wall specifications were selected in an attempt to best match common structure design techniques. As such, a representative 3 m length by 3 m height wall constructed with standard 190 mm concrete block was chosen. In order to increase efficiency as well as facilitate safer handling and testing, 1/3 scale wall specimens were fabricated and used in testing. This was accomplished by scaling the dimensions as well as the constituents, including aggregate size in block production, mortar and grout. As a result, the scaled wall specimens had dimensions of 1 m length by 1 m height by a width of 63 mm. Table 1 presents the tested material properties conforming to ASTM Standards [5,6] for the individual constituents, highlighting the modulus of elasticity E, the reinforcing steel's yield strength σ_y and ultimate strength σ_u, as well as the masonry compressive strength $f'm$.

Table 1: Material Properties

Property	D7 Bar	Concrete Block Masonry Prism	Mortar Cube	Grout Cylinder	Concrete Blocks
E (MPa)	230,394	14,278	-	-	-
C.O.V.	10%	14%	-	-	-
σ_y *(MPa)*	484	-	-	-	-
C.O.V.	4%	-	-	-	-
σ_u *(MPa)*	546	-	-	-	-
C.O.V.	2%	-	-	-	-
f'_m *(MPa)*	-	18.2	28.1	23.2	20.1
C.O.V.	-	11%	10%	12%	12%

The walls were reinforced in a doubly symmetric manner (vertically and horizontally) ensuring a consistent reinforcement ratio between specimens. The selected steel reinforcement bar size was type D7 and when scaled appropriately, represents a 25M bar at full scale. This was selected as it characterizes an upper limit of bar sizes typically used in conventional reinforced concrete block masonry construction. Individual wall specimens were subjected to different charge sizes, representing a multitude of different threat levels. Charge sizes consisted of equivalent TNT weights of 6, 12 and 30 kg. Table 2 as follows presents a subset of the test matrix used and is a subset of a larger test matrix, which included the variation of other reinforcement ratios. *D7F* represents a wall with every vertical cell and horizontal course reinforced with one D7 bar. Figure 2-a depicts the typical reinforced masonry wall specimens that were tested and how the aforementioned steel channel corners were connected to the wall in order to bear against the test frame and impose the required boundary conditions. Figure 2-b demonstrates typical placement of the steel mesh reinforcing bars in the fully reinforced wall specimens.

Table 2: Test Matrix and Schedule

Wall Type	Equivalent TNT Charge Weight, W (kg)	Scaled-Distance, R (m/kg$^{1/3}$)
D7F	6	2.75
	12	2.18
	30	1.71

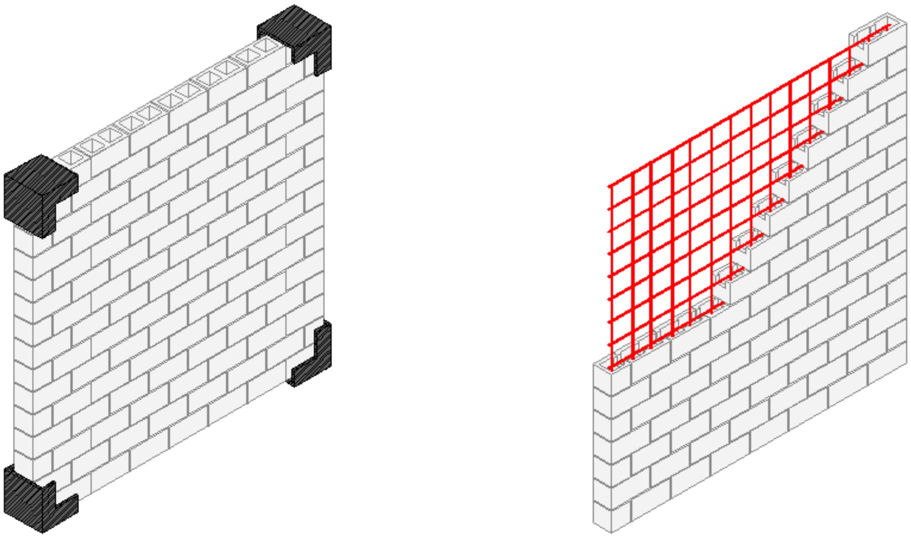

Figure 2: Infill Wall Specimens: a) Boundary Conditions; b) Steel Mesh

EXPERIMENTAL RESULTS AND ANALYSIS

CSA S850-12 defines threshold levels of damage and performance limits when analysing the response of reinforced concrete block masonry walls. As shear is typically an undesirable brittle type of failure, these limits refer strictly to flexural behaviour. An attempt, however, is made to relate them to the combinational failure observed during testing. Table 3 outlines the different damage levels and their assigned deformation performance limits depending on either the ratio of maximum deflection to that causing yield μ_{max} or rotation θ_{max}. Where a dash (-) is shown, the corresponding parameter is not applicable as a response limit. These damage levels range from superficial, being minor cosmetic damage, to blowout, being a complete loss of structural integrity.

Table 3: Reinforced Masonry Response Limits (CSA S850-12) [7]

Response Limits (Damage Level)	μ_{max}	θ_{max}
Superficial	-	-
Moderate (*B1*)	1	-
Heavy (B2)	-	2°
Hazardous (B3)	-	8°
Blowout (B4)	-	15°

Initially it was expected that flexure would be the governing behaviour in the wall specimens. As a result of the boundary condition design and placement, the expected deflection profile was perfectly symmetrical resulting from two-way bending of the square wall with no deflection at each corner connection. This deformation pattern is expected to cause a series of concentric circular damage patterns (cracks) along with a prominent vertical and horizontal crack at each mid-span as shown in Figure 3-a. After the first few trials it became increasing apparent that the walls were undergoing both out-of-plane flexural and shear deformation, leading to combinational damage. This is attributed to the difficulty in replicating the desired simply-supported boundary conditions, resulting in the imposition of some restraint at the supports. As a result of the shear action, damage consisted of diagonal cracks close to the supports and moving concentrically towards the centre, similar to what is shown in Figure 3-b. This damage pattern can be compared to typical punching shear observed in reinforced concrete slabs. The last and most common damage mode was the case of combined flexural-shear. This resulted in a combination of the individual damage patterns with concentric circles near the middle and diagonal cracking near the supports as is shown in Figure 3-c. Although this combined damage mode was the most common, it will be shown later on that typically one of the modes governed at higher levels of wall damage.

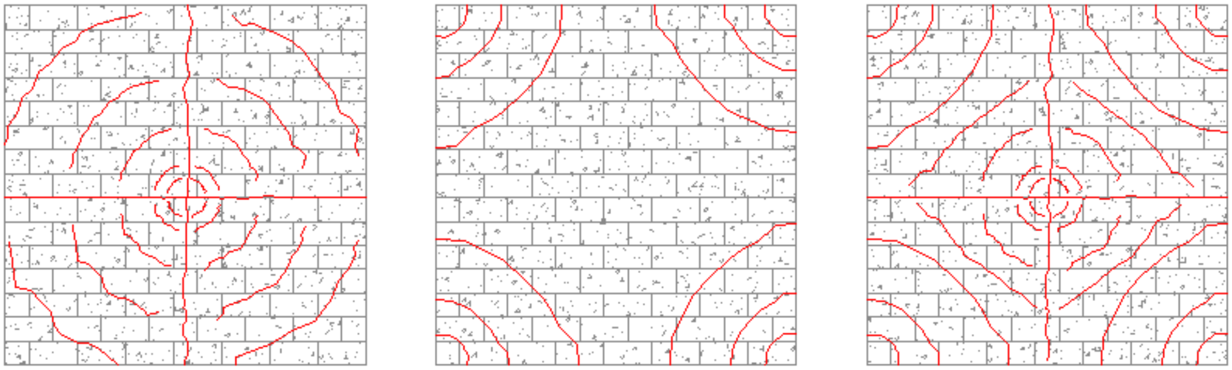

Figure 3: Ideal Damage Patterns: a) Flexural; b) Shear; c) Combined Flexural-Shear

In order to better explain the damage patterns observed in each test, a subset of the wall damage levels were determined qualitatively [7], while attempting to conform to classifications outlined by CSA S850-12. A summary of these results are displayed in Table 4. As can be seen, the largest scaled-distance (lowest threat level) caused superficial damage with very minor cracking at the boundary supports only. The intermediate scaled-distance caused a combined flexural-shear damage pattern, which was qualitatively considered to be in the moderate range. The smallest scaled-distance, being representative of the largest threat level, had evidence of combined flexural-shear damage, however, the test specimen approached failure due to shear induced damage near the supports leading way to its damage pattern being classified as hazardous. The fact that this wall specimen failed in shear gives way to the conclusion that the flexural capacity of the walls are significantly larger than the shear capacity.

Table 4: Wall Test Qualitative Damage Levels

Wall Type	Scaled Distance, R (m/kg$^{1/3}$)	Qualitative Level of Damage	Governing Damage Mode
D7F	2.75	Superficial	None
	2.18	Moderate	Combined
	1.71	Heavy	Shear

Although damage levels that are based on qualitative inspection can be useful, it is important to quantify these results to allow their use in a design situation. In order to analyse the peak response of each specimen and compare it against the performance limits as outlined in CSA S850-12, the mid-span deflection response history was analysed for each of the tested infill wall specimens. This deflection was then converted to an approximate rotation by taking the arctangent of the ratio of deflection to the *effective deflected length*. This effective length was determined to be the diagonal distance from the centre of the wall boundary support to the mid-span location as it is approximately perpendicular to the major axis of rotation. Table 5 outlines the results for each of the wall specimens. The test specimen with the largest scaled-distance (lowest threat level) had a response that resulted in a superficial damage classification. The threshold between the superficial and moderate damage levels are based on the deflection exceeding that which causes yield. As there was negligible plastic deformation in the wall at the end of the response history, it is assumed that this value was not reached. Both of the infill walls, which were subjected to the intermediate and smallest scaled-distances (increasing in threat level), experienced mid-span responses to classify them in the heavy damage range, with the intermediate being very close to the moderate-heavy damage threshold (2°).

Table 5: Wall Test Results

Wall Type	Scaled Distance, R (m/kg$^{1/3}$)	Mid-Span Deflection (mm)	Mid-Span Rotation	Damage Level *CSA S850-12* [7]
D7F	2.75	13	1.1°	Superficial
	2.18	26	2.1°	Heavy
	1.71	68	5.5°	Heavy

The final technique in damage classification was by using the simple damage graph provided in CSA S850-12 [7] and depicted as follows in Figure 4. This graph is based entirely on the relation between the charge weight and standoff distance and shows the threshold levels for each of the prescribed levels of damage. Caution needs to be taken as this graphical representation makes no provision for the assemblage material type, boundary conditions, or the specific response of the structural component and is considered to be a low-level screening tool in rough prediction of damage levels and extent resulting from possible blasts.

By finding the intersecting points for each of the three charge weights at the standoff distance of 5 m, the expected damage levels were superficial for both the small and intermediate charge weights and a moderate level of damage for the largest charge weight. These intersecting points are labelled with the red markers as presented in Figure 4.

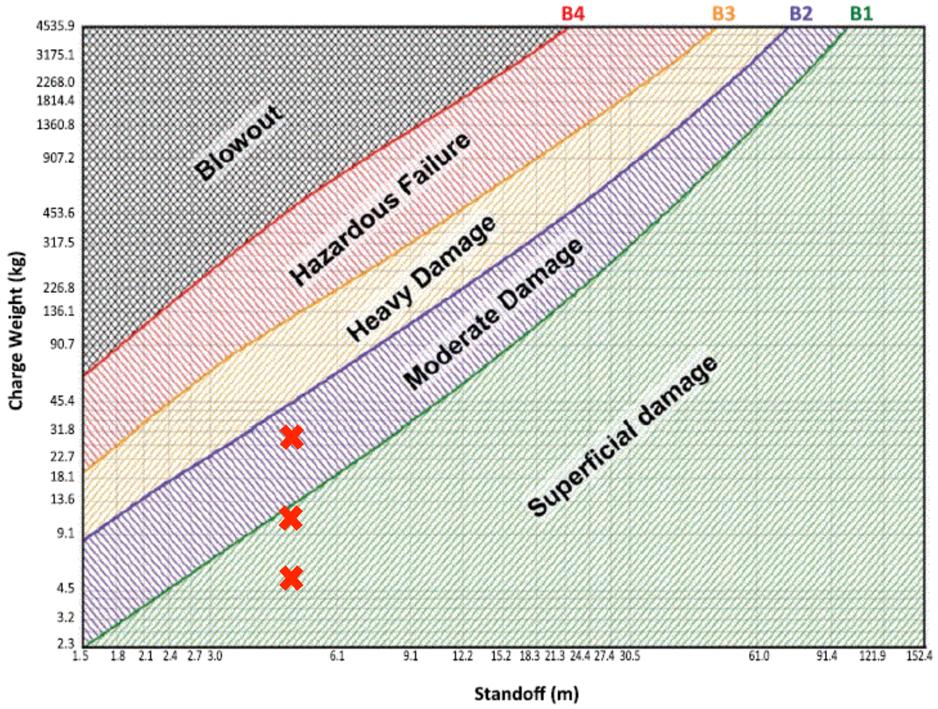

Figure 4: Expected Damage Levels from Charge Weight-Standoff [7]

As was expected a decrease in the scaled-distance, consequently an increase in the threat level, caused damage in each of the wall specimens to increase in severity. By comparing the resulting damage for each of the three aforementioned techniques, it becomes apparent that discrepancies exist in the classification of damage levels. Each method proved to hold consistent for the lowest threat level, with each classifying the damage level as superficial. For the intermediate threat level, both of the qualitative and quantitative methods classified damage in the realm of moderate-heavy. Finally, when comparing the results for the largest threat levels, all three techniques gave a wide range of inconsistent results. The difference in these methods is attributed to many factors related to their development but also to the fact that they do not account for the possibility of shear failure, although very common under blast loading, and the loss of structural capacity in the out-of-plane direction. This most likely resulted in some amount of rigid body motion in the lesser damaged wall portions, not accounted for in the pure flexural performance limits outlined in CSA S850-12. An observation can also be made that the low-level chart method seems to be quite inaccurate when compared to the others at increased threat levels, due to its ambiguity in materials, behaviour and damage mechanisms as discussed previously.

CONCLUSION

Due to the relativity new interest in the area of structure response to explosive events, there is a limited understanding of the performance of many commonly used structural assemblages. This extends to an understanding of the performance of reinforced concrete block masonry infill walls. Although the *CSA S850-12: Design and Assessment of Buildings Subjected to Blast Loads* is a major advancement in the protection of structures against explosive events, its relative newness leaves room for modifications and improvements in areas where the current knowledge base may be limited.

This research set out to investigate the response of a simply supported reinforced concrete block masonry infill wall which was expected to undergo two-way flexural behaviour. Through testing however, it brought light to the idea of combined failure of these specimens as well as the implications of the boundary conditions on the response. Although not fully encompassing, this research provides a starting point for better understanding of the response of reinforced masonry infill walls to blast loading. It is important to recognize that wall response behaviours as well as damage patterns were observed that have no reference in the CSA S850-12 blast standards in terms of the performance limits or levels of damage. It is imperative that if further research in this area shows that shear action is a major contributing factor to the damage (and ultimately failure) of the masonry infill wall specimens, similar to the case of reinforced concrete components, then relevant provisions should be developed and considered in the design standards.

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