OUT-OF-PLANE BEHAVIOR OF REINFORCED MASONRY SHEAR WALLS WITH BOUNDARY ELEMENTS

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ABSTRACT

Although boundary elements have been demonstrated to enhance the in-plane performance of reinforced concrete block shear walls under seismic loading, research evaluating their effect on the walls' out-of-plane performance (e.g., due to earth pressure, wind loading, or blast loading) is very scarce. As such, current blast standards do not assign unique design requirements or response limits for reinforced concrete block walls with boundary elements due to the limited number of relevant studies published when these standards were originally developed. To address this knowledge gap, an experimental program has been conducted to investigate the out-of-plane performance of four scaled seismically-detailed reinforced concrete block axially loaded walls with boundary elements under quasi-static displacement-controlled cyclic loading. The resistance function of the walls and the corresponding damage sequence, as well as the ductility capacity, were also used to assess the walls' out-of-plane performances. The experimental results in the current study demonstrated the importance of considering the two-way bending mechanism associated with reinforced concrete block walls with boundary elements when their performance is evaluated under out-of-plane loading demands.

KEYWORDS: *boundary elements, experimental resistance functions, out-of-plane, reinforced masonry*

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INTRODUCTION

Reinforced masonry (RM) shear walls can be subjected to out-of-plane loading that may deteriorate their performance. This is because RM walls, already detailed to have a ductile in-plane behavior, do not necessarily exhibit similar behavior when subjected to out-of-plane loading [1]. This out-of-plane loading can result from either a hazard scenario (e.g. blast and wind) or an out-of-plane instability due to in-plane loading [2], [3]. As such, the out-of-plane performance of RM walls recently attracted the interest of several researchers [4]–[6]. One classical way to enhance the out-of-plane performance is to use pilasters. Recently, Boundary Elements (BEs) were also introduced in several standards [7], [8] to enhance the in-plane seismic performance of RM shear walls. This enhancement is credited to the use of a dual-layer of vertical reinforcement and closed ties at the BE regions that improve both strength and strain capacities of the wall.

When experimentally investigated in the in-plane direction by [9] and [10] at the component-level, RM shear walls with BEs achieved higher ductility capacities compared to conventional RM shear walls with rectangular cross-sections. At the system-level, two buildings without and with BEs were constructed and their performance was evaluated by [11]. Although both buildings were designed to have similar in-plane ultimate strength, the building constructed with BEs showed higher ductility capacity and less strength degradation at high drift levels.

The out-of-plane performance of RM walls with BEs has been barely investigated in the literature. The first experimental study was conducted by [12] to evaluate the performance of such walls when subjected to blast loading and showed that BEs provided partial supports to the wall edges. This facilitated transferring the applied loads through the horizontal reinforcement and subsequently formed a two-way bending mechanism in the wall web. These walls were also reported by [13] to have higher ultimate strength, compared to conventional RM walls, due to the BEs configuration and reinforcement details. However, the influence of BEs on the wall damage mechanism and displacement response beyond the ultimate strength was not well investigated to date.

The objective of the current study is to experimentally investigate the influence of the aspect ratio and axial load on the out-of-plane performance of RM walls with BEs at high displacement demands (i.e. post-ultimate strength). In this respect, an experimental program was carried out on four half-scaled RM walls, having different heights, under out-of-plane quasi-static cyclic displacement-controlled loading. The study first presents a description of the experimental program that includes the wall selection procedure, the material used in construction, and the test setup. Afterward, the experimental results are assessed, in terms of the wall resistance function and damage sequence, to demonstrate the influence of the aspect ratio and axial load on the wall out-of-plane performance.

EXPERIMENTAL PROGRAM

The experimental program was designed to evaluate the out-of-plane performance of RM walls with BEs. The test matrix included walls with different aspect ratios and axial loads. All walls were subjected to a displacement-controlled quasi-static out-of-plane cyclic loading until they reached a strength degradation to 80% of the maximum strength to capture the post-ultimate strength behavior. The following subsections provide details on the wall selection, material properties, and construction, as well as the test setup and instrumentation used to monitor the wall's performance.

Wall Selection

The tested walls had a length, l_w, of 1,450 mm, corresponding to 2900 mm in full-scale. Since the wall web has been shown to result in a two-way bending mechanism [12] and [13], the aspect ratio (i.e. wall height-h_w - to length ratio) was expected to be a key parameter in terms of the out-of-plane load distribution. To evaluate this attribute, Walls 1 and 4 had an aspect ratio (A_R) of 1.0 to maximize the two-way bending mechanism, while Walls 2 and 3 had A_R of 1.20 and 0.73, respectively.

Since RM walls with BEs are commonly investigated and classified as a seismic force-resisting system, the four tested walls were designed and seismically detailed in accordance with the *special* RM shear walls type requirements in the in-plane direction according to the American standards [7]. All four Walls had a vertical reinforcement ratio (ρ_v) of 0.47%. and horizontal reinforcement ratio (ρ_H) of 0.16%. Moreover, for an economical design, standards related to out-of-plane behavior [14] recommends that RM walls should not have a brittle flexural behavior when subjected to blast loading. This was verified in the current study by performing a preliminary sectional analysis, where the steel reinforcement yielded before the masonry reached the crushing strain (e.g. in *Wall* 1, BEs reinforcement bars yielded at a flexural moment of 23 kN.m, while the cross-section reached its ultimate compression strain at approximately 30 KN.m). It is also worth mentioning that vertical reinforcement bars in the BEs were allowed to sustain compression stresses due to the confinement ties provided [8].

Several previous studies [15]–[17] showed the negative influence of the axial load on the corresponding wall in-plane ductility capacity. However, to the best of the authors' knowledge, all the out-of-plane experimental investigations on RM walls with and without BEs [12], [13], [18]–[20] considered only non-load bearing walls (i.e. no external axial load but self-weight). To address this, *Walls 1,2, and 3* were subjected to axial compression stress of 10% of their corresponding axial compressive strengths throughout the test. The influence of the axial load (P_{axial}) on the wall out-of-plane performance was then investigated through *Wall 4* that was similar to *Wall 1* but with zero axial compression stress, as can be seen in Table 1.

Table 1: Test Matrix of RM walls with BEs

<table>
<tr><th>Parameter</th><th>h_w (mm)</th><th>l_w (mm)</th><th>A_R (%)</th><th>ρ_v (%)</th><th>ρ_H (%)</th><th>t (mm)</th><th>t_{BEs} (mm)</th><th>$\frac{P_{axial}}{f'_{m} \cdot A_g}$</th></tr>
<tr><td>Wall 1</td><td>1,500</td><td>1,450</td><td>1.00</td><td rowspan="4">0.47</td><td rowspan="4">0.16</td><td rowspan="4">90</td><td rowspan="4">190</td><td>10%</td></tr>
<tr><td>Wall 2</td><td>1,750</td><td>1,450</td><td>1.20</td><td>10%</td></tr>
<tr><td>Wall 3</td><td>1,050</td><td>1,450</td><td>0.73</td><td>10%</td></tr>
<tr><td>Wall 4</td><td>1,500</td><td>1,450</td><td>1.00</td><td>0%</td></tr>
<tr><td colspan="9">T : Thickness of grouted wall web
t_{BEs} : Thickness of grouted boundary elements</td></tr>
</table>

Material Properties

The standard hollow concrete blocks (190 mm thickness × 190 mm height × 390 mm length) commonly used in North America were scaled down by half (95 mm thickness × 95 mm height × 185 mm length) and used for the wall construction [19], [21]. A total of 69 masonry prisms were assembled and grouted during the construction to evaluate the average compressive strength of masonry (f'_{av}), according to Canadian standards [8]. These prisms were two cells by one cell and four blocks high (90 mm thickness × 375mm height × 185mm length). The prisms had a f'_{av} of 11.2 MPa (coefficient of variation C.O.V = 13.4%). Similarly, the bars used in the walls were tested through direct tension tests to determine their yield (f_y) and ultimate (f_{ult}) strengths, according to Canadian standards [22] as well. The average f_y was 459 MPa (C.O.V = 4.6%) and 436 MPa (C.O.V. = 1.3%) for bars #3 (area =73.3 mm^2) and M10 (area=100 mm^2), respectively. Similarly, the average f_{ult} recorded was 664 MPa (C.O.V. = 3.4%) and 605 MPa (C.O.V. = 1.0%) for the same bars. D4 bars (area =25.4 mm^2) were used as horizontal reinforcement in the wall web and as ties in the BEs. These bars had average f_y and f_{ult} of 517 MPa (C.O.V. = 6.9%) and 573 MPa (C.O.V. = 5.7%), respectively.

Wall Construction

All walls were constructed on a concrete foundation to provide a realistic bottom structural restraint. Thus, the wall's vertical bars were extended in the foundation to ensure an adequate development length. The ties in the BEs were installed every 65mm to provide the required confinement, according to [8]. An experienced mason laid the courses with a half-scale face-shell bed joint (i.e. approximately 5 mm). The web was built in a running bond pattern using the standard half-scaled stretcher and half-block units following the common North American practice. Meanwhile, the BEs were built in a stack pattern to facilitate the construction procedure using custom-made c-blocks, as shown in Fig. 1. These blocks were notched to accommodate the wall horizontal reinforcement in the BEs that was placed either every other course based on the design. The horizontal reinforcement formed 180° hook around the outermost vertical bars from one side and bent from the other side 90°, as shown in Fig. 1. This configuration is mainly to maintain the required development length from both sides while facilitating the placement of the horizontal reinforcement during construction. The continuity of the wall's vertical reinforcement was simulated by laying extra six courses above the top support level to ensure an adequate development length. At the top support level, two channels were installed from each side using bolts to 1) transfer the axial load to the wall; and 2) provide the wall with a connection to the test setup.

BEs were symmetrically aligned with their wall web axis in all previous in-plane ([9],[10],[11]) and out-of-plane ([12],[13]) studies. However, in consultation with designers and contractors, BEs forming one flush surface with the wall web were thought to facilitate the adoption of this system in construction practice as it is architecturally more appealing. As such, all walls in the current study followed this BEs configuration, as shown in Fig. 1. Subsequently, all walls were loaded on their flush surface, however, the influence of applying this load from the non-flush surface on the wall behavior may require further study.

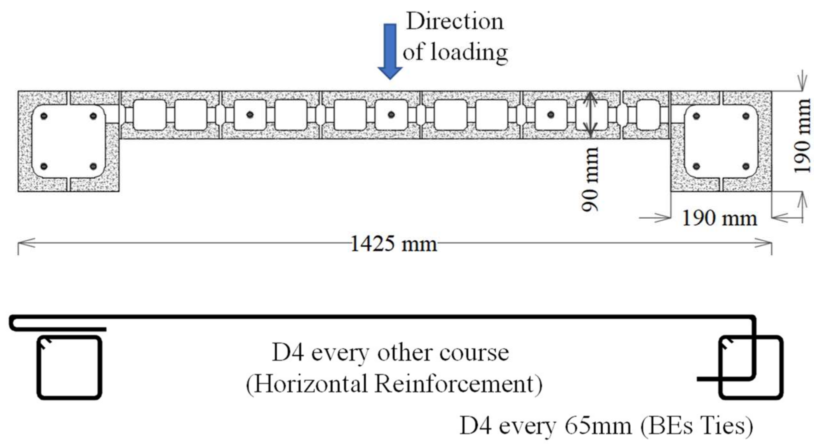

Figure 1: Cross-section of the tested walls and their reinforcement details

Test Setup

The test setup used was divided into two main systems, as shown in Fig. 2. The first system contained a self-reacting frame and a horizontal actuator to provide the out-of-plane loading. The second system included a vertical system to apply the required axial load on the wall. While the wall foundation was anchored and prestressed to the self-reacting frame, the top support channels were attached to two stiff horizontal beams that restrained the wall displacements in the out-of-plane direction but allowed for the vertical displacements. These beams were pulled down from each side by two vertical actuators with a capacity of 110 kN each, which exerted the required axial load on *Walls* 1, 2, and 3 (i.e. 10% of its axial capacity). This force-controlled vertical system maintained the same axial load from each side throughout the test to prevent any in-plane loading.

For the horizontal loading system, the out-of-plane loads were applied through a displacement-controlled hydraulic actuator, with a capacity of 800 kN and a maximum cyclic stroke of 500 mm, that was positioned at the center of the wall, as shown in Fig. 2. The actuator load was uniformly distributed on the wall through nine secondary hydraulic actuators that experienced the same hydraulic pressure and were mounted on a rigid frame connected to the actuator, as can be seen in

Fig. 2. This approach was to maintain the same load on all secondary actuators throughout the test while having different displacements. This was an essential criterion during the design stage of the test setup because RM walls with BEs, unlike conventional RM walls, were expected to form a two-way bending mechanism in their webs (i.e. different horizontal displacements at the same height). The secondary horizontal actuators were connected to the wall by rubber pads (300m×300mm×60mm) to avoid any stress concentration or punching shear while not restraining the wall deformations.

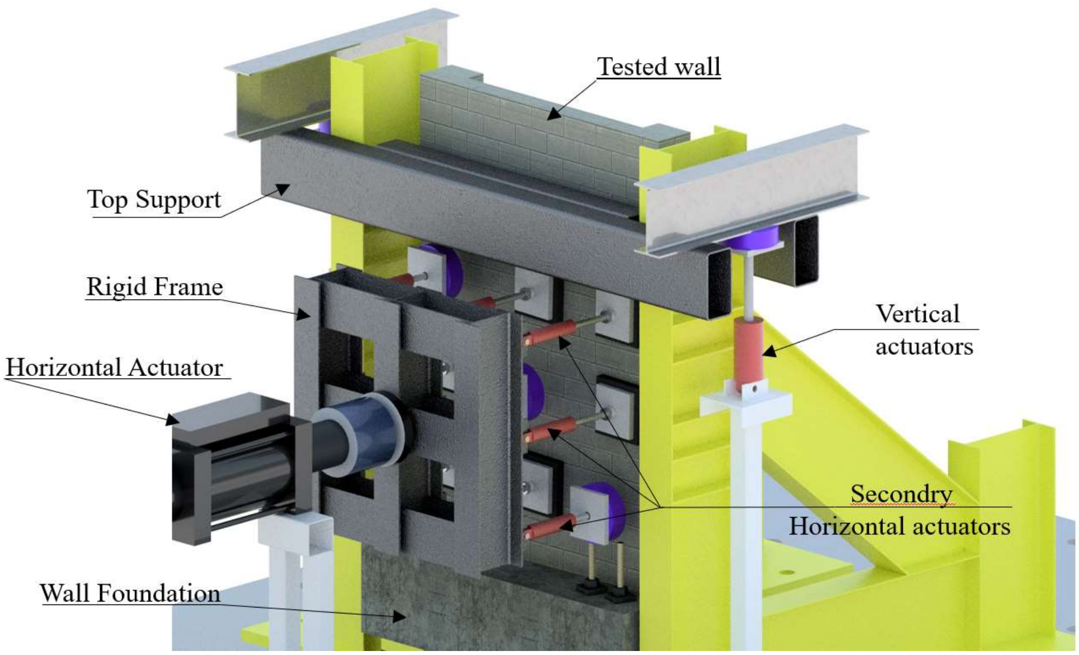

Figure 2: Test setup

Instrumentation and Test Procedure

The out-of-plane wall displacements at the web and BEs were monitored at mid-height of the wall, by two displacement potentiometers. In addition, nine strain gauges were mounted on the bars prior to construction to capture the initial yielding of these bars and the extent of this yielding throughout the web and BEs.

The tested walls were subjected to a displacement-controlled out-of-plane unidirectional cyclic loading, while the axial load level was maintained constant throughout the test. In each cycle, the target displacement at the wall center was increased by a value equivalent to a support rotation (i.e. defined as the angle enclosed between the vertical centerline of the wall and the chord from the support to the center of the web) of 1/8 degree. Support rotation was used in the current study to coincide with the current blast design standards [14] as a parameter that quantifies the damage state of RM walls. This loading procedure continued until the tested walls reached 80% strength degradation of the peak out-of-plane strength, which was considered a failure criterion in this experimental program.

TEST RESULTS

Figure 3 shows the resistance function (i.e. load-displacement relationship) of the tested walls based on the horizontal displacements at the wall center and the corresponding support rotations. The elastic strength, P_e, point was considered in the current study to represent the onset reinforcement bar yielding based on the strain gauge records. The wall peak strength, P_{peak}, point, was considered when all the critical cross-sections yielded. Beyond P_e, the stiffness of the wall decreased, and the wall attained a peak strength, P_{peak}. A summary of the wall strengths, displacements (Δ) and support rotation (θ_s) is presented in Table 2.

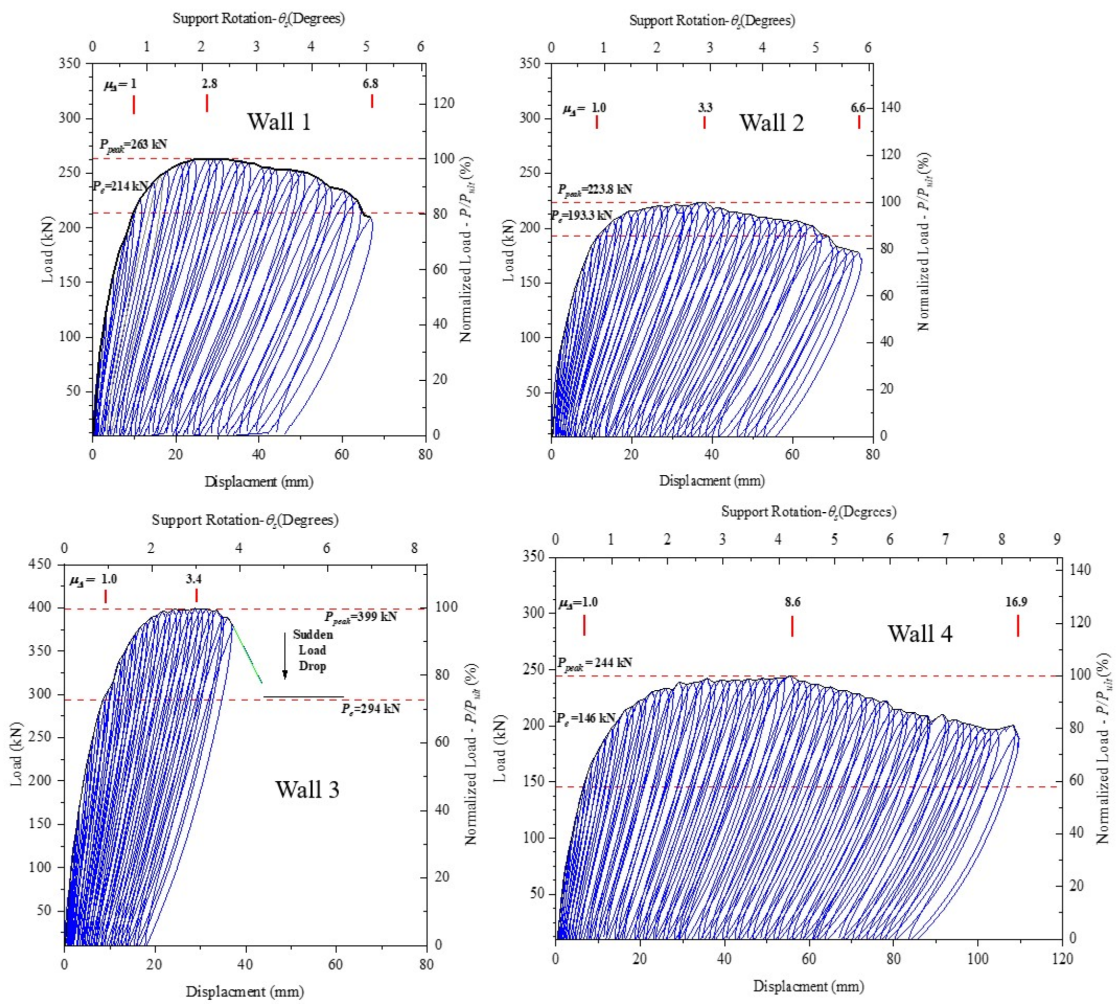

Figure 3: Hysteresis loops of the tested walls

Table 2: Summary of experimental wall strengths, displacements, and support rotations

Parameter	P_e (kN)	Δ_e (mm)	θ_e (degrees)	P_{peak} (kN)	Δ_{peak} (mm)	θ_{peak} (degrees)	$\Delta_{80\%}$ (mm)	$\theta_{80\%}$ (degrees)
Wall 1	214	9.77	0.75	263	27.66	2.1	66.82	5.1
Wall 2	193	11.54	0.76	223	38.15	2.5	76.42	5
Wall 3	273	7.22	0.75	400	28.8	3.1	37.33	4.1
Wall 4	146	6.47	0.49	244	55.56	4.2	109.28	8.3

Although *Walls 1* and *4* had the same aspect ratio, the axial load (P_{axial}) affected their P_e values. As presented in Table 2, *Wall 1* had higher P_e than *Wall 4* by 46%, which was mainly attributed to the high compressive stresses on the cross-section of *Wall 1* that counteracted the tension stresses that resulted from the out-of-plane flexural stresses and subsequently delayed reinforcement yielding. However, the peak resistance, P_{peak}, of *Wall 1* was only 10% higher than that of *Wall 4*. This is because the axial load increased the compression forces and the compression block depth; which subsequently reduces the wall's cross-section flexural lever arm. To further validate this observation numerically, sectional analysis using strain compatibility was carried out for *Walls 1* and *4*. The results of the peak flexural capacities were 37.0 and 30.2 kN.m for *Walls 1* and *4*, respectively, with only 22% difference, whereas their corresponding elastic flexural capacities were 29 kN.m and 19 kN.m, with a 52% difference.

According to the current North America blast design standards, a wall reaches a hazardous damage state (i.e. likely to fail) when its support rotation exceeds 2˚. However, as can be seen in Fig. 2, all the walls achieved high support rotation values (i.e. above 4˚) before their resistances degraded to 80% of their peak strength. For example, *Wall* 4 had vertical support rotation of 4.1˚ at 20% resistance degradation, as shown in Fig. 2. At a similar support rotation, (i.e. 4˚), all of the walls had some permanent deformations and excessive cracking, but no collapse. This behavior discrepancy shows the large level of conservatism in the current blast design limits that were originally developed based on a limited number of experimental and analytical studies, mainly of stiff non-civilian buildings/structures (e.g. bunkers).

Although *Wall 2* had a higher Δ_{Peak} than that of *Wall 4*, *Wall 2* had lower ductility capacity (μ_Δ) than *Wall 4* by 20% as shown in Fig. 2. This enhanced ductility performance reflects the influence and benefits that may arise from the wall two-way response mechanism. However, with the formation of the yield lines and at 80% resistance degradation, *Walls 2* and *3* had essentially similar ductility capacities of 6.6 and 6.0, respectively. It is important to point out that *Wall 3* in particular experienced local damage at the top support in the web. This local damage caused a sudden 16% drop in the wall resistance.

The BEs of all walls attained similar displacement values that were almost 60% of those at the wall web as shown in Fig. 4. This observation confirms that all walls experienced a two-way bending mechanism throughout the test. However, *Wall 4* showed a higher ratio between the BEs and web displacements (i.e. compared to all other walls). This can be attributed to the absence of the axial load that reduced the stiffness of the BEs (Paulay and Priestley 1992; Bonet et al. 2011) and subsequently limited the stiffness of the web in the horizontal direction.

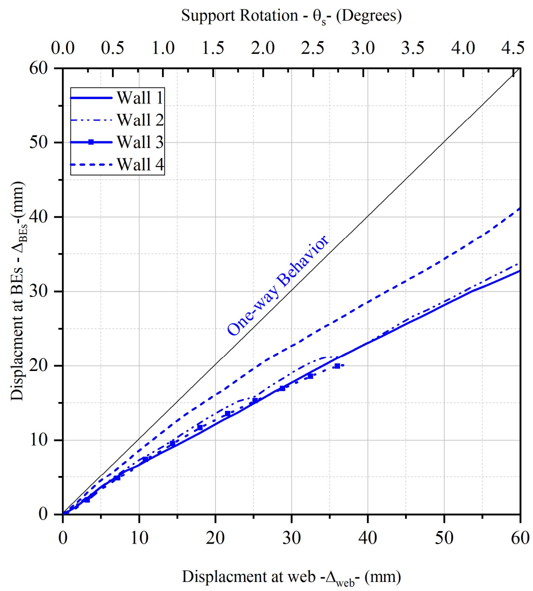

Figure 4: Web and BEs displacements

CONCLUSIONS

The influence of the different design parameters on the wall resistance function was highlighted, especially at high displacement demands. In this respect, all walls were able to sustain high displacement demands compared to those corresponding to blast standards threshold values, and flexural crushing damage was the dominant mode of failure for all walls. The influence of wall aspect ratio and axial load on the wall performance was discussed and compared.

All walls were able to sustain high displacement demands compared to those predicted by current blast standards. However, axial load level as small as 10% of the wall axial capacity had a significant negative influence on the wall out-of-plane displacement response and ductility capacity as shown from Walls 1 and 4. Therefore, it is critically important to consider the axial load effects when analyzing the wall response especially when progressive collapse is a concern.

Although the current study investigated four RM walls with BEs with different design parameters, there are still a few aspects that were not included (e.g. BEs dimensions, BEs spacing, and material properties and the effect of load application from the non-flush surface). Therefore, more experimental and analytical studies are still needed to facilitate the adoption of RM walls with BEs as an out-of-plane resistant system when designed using the relevant Canadian design standards (i.e. CSA S304).

ACKNOWLEDGEMENTS

The financial support for this project was provided by the Natural Sciences and Engineering Research Council (NSERC) of Canada. Support was also provided by the McMaster University Centre for Effective Design of Structures (CEDS), funded through the Ontario Research and Development Challenge Fund (ORDCF) of the Ministry of Research and Innovation (MRI). Provision of mason time by the Ontario Masonry Contractors Association (OMCA) and the Canada Masonry Design Centre (CMDC) is appreciated.

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