13TH CANADIAN MASONRY SYMPOSIUM
HALIFAX, CANADA
JUNE 4TH – JUNE 7TH 2017

EFFECT OF BOUNDARY ELEMENTS CONFINEMENT LEVEL ON THE BEHAVIOUR OF REINFORCED MASONRY STRUCTURAL WALLS WITH BOUNDARY ELEMENTS

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ABSTRACT

Recently, there is a global trend of promoting higher building performance with lower cost and lower environmental impact. Reinforced masonry (RM) systems have the inherent benefits of fire protection, structural durability, energy efficiency and cost effectiveness. Recent research efforts toward enhancing the lateral performance of RM walls are reflected in the current Canadian national building code and masonry design standards by introducing a new ductile RM walls category with lateral force reduction factor of 3.0. Consequently, promoting RM shear walls as a potential seismic force resisting system (SFRS) alternative in mid-rise buildings. One way of increasing the wall ductility is by introducing boundary elements to enhance the ultimate compressive strain and wall curvature ductility by increasing the confinement level at wall's end zones. In this study, three half-scale RM walls with boundary elements specimens, flexural dominated, were constructed to be tested under a reversed cyclic moment and lateral loading. These walls represent the plastic hinge zone located in lower storey panel of 10-storey RM shear wall building. The current study investigates the effect changing the transverse reinforcement ratios in the wall boundary element on the RM shear wall lateral response. This paper presents the experimental work and the predicted results of the three walls. Consequently, this study contributes to the understanding of the lateral response of RM shear walls with high aspect ratio (height to length ratio) with an ultimate goal of enhancing the seismic hazard safety of RM mid-rise buildings in Canada.

KEYWORDS: *boundary elements, confinement, masonry, mid-rise buildings, ultimate strain*

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INTRODUCTION

With increasing environmental and economic concerns, there is a global drive to raise the efficiency of building design process. Design optimisation is required to promote higher building performance with less cost and less environmental impact. Design process enhancement could be achieved by optimising the material utilisation within the structural components. Reinforced masonry construction has known benefits of better fire protection, structural durability, energy efficiency and cost reduction [1]. However, there is still a big misconception that masonry structure cannot develop the required ductility to resist earthquake loads. Reinforced Masonry Shear Walls (RMSW) with boundary elements has the added benefit of enhanced ductility by optimising the materials used in wall construction.

In general, the failure modes of shear walls are diagonal shear cracking, bed joint sliding shear, and flexural failure. Unlike the other two modes, flexural failure is characterised by its favourable ductile behaviour, due to vertical reinforcement yielding, the formation of plastic hinge and crushing of masonry and grout [2].

Several researchers studied the effect of vertical and horizontal reinforcement ratio, axial load, and wall aspect ratio (height to length ratio) on wall's lateral response. In 1980 Priestley and Bridgman [3] showed that confining the end zone of reinforced masonry walls prevents bar buckling and bond failures. Shedid et al. [4] tested seven RMSW with three different end configurations (rectangular, Flanged, and end-confined). The results showed that using flanged and confined boundary element increased wall's ductility by 39% and 106% respectively. Also, the measured drift at 20% drop from peak load is 1.0%, 1.5% and 2.0% for rectangular, flanged and confined boundary elements walls respectively. Moreover, 40% reduction in the required vertical reinforcement in flanged and end-confined walls compared to rectangular walls were achieved. Kapoi 2012 [5] tested eight full-scale unconfined RMSW and studied the effect of concentrated reinforcement at the end zones of the masonry walls. Kapoi concluded that the performance of evenly distributed reinforcement wall was very similar to walls with concentrated reinforcement regarding displacement ductility. However, walls with concentrated reinforcement found to dissipate 50% more energy. Banting 2013 [6] tested fully grouted half scale RMSW with boundary elements to investigate the effect of confinement on wall drift and delaying vertical reinforcement buckling. The results showed that confining delayed the buckling of vertical reinforcement and delayed the crushing of the grout core. Moreover, face shell spalling in the compression toes did not cause an abrupt drop in resistance. Thus, these research efforts showed that adding boundary elements at RMSW ends enhance the wall ductility and limits wall toes damage. Moreover, introducing a boundary element at the wall ends provide out-of-plane stability, decrease the required length of compression zone and increase curvature capacity at max load. All these advantages can be achieved with even less vertical reinforcement ratio compared to RM rectangular walls [2].

This study pushes the boundaries by testing the plastic hinge zone in a ten storey RMSW building having an aspect ratio of 11, whereas the RM shear wall with highest tested aspect ratio was 4.5

(i.e. tested by Ahmadi [7]). Furthermore, this study utilises a new boundary element block (i.e. similar to available pilaster blocks but with different dimensions) that allows designers to decrease the spacing between hoops in the boundary elements and thus increasing the confinement ratio. This new boundary element block eliminates the limitations associated with regular concrete blocks (i.e. stretchers) utilised in previous studies [1] [2].

SPECIMEN AND WALL COMPONENTS

Three half-scale RMSW with boundary elements specimens, which are designed to be flexure dominated, were constructed to be tested under a reversed cyclic moment and lateral loading. These walls represent the plastic hinge zone located in lower storey panel of 10 storey building. Walls were built using half-scale standard concrete blocks (stretcher) for the web area, and boundary element blocks units for the boundary elements having the dimensions shown in Figure 1.

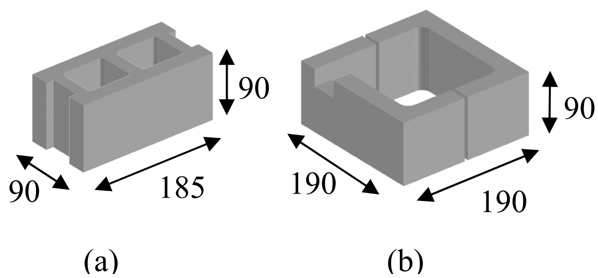


Figure 1: Block and Boundary Elements Dimension

Wall height was proposed 36.5 m based on 3.65m typical storey height. Due to height and testing equipment capacity limitations, dimensions were divided by two to represent the half scale specimen. Thus, the wall height (h_w) is deemed to be 18.85m. Boundary element length (L_b) and width (B_b) have been selected to represent one standard masonry concrete block with a length of 190mm. On the other hand, web length (L_w) of 1335 mm, and web thickness (b_w) of 90 mm were utilised in the three walls. This result in an overall wall length (L_w) of 1715mm (see Figure 2).

SPECIMEN DESIGN AND CONSTRUCTION

Wall flexural capacity was calculated using CSA S304-14 [8] procedure without taking into consideration the material reduction factors (i.e. ϕ_m and ϕ_s). Shear walls were designed to provide shear and sliding resistance with safe margin to avoid un-desirable shear failure. Deformed wires shear reinforcement D8 (diameter = 8.11 mm) were used, 90°/180° hook alternatively [9], spaced at 285 mm along the walls height. In addition D8 horizontal reinforcement with 180° hook were embedded in the boundary element and extended inside the web with sufficient development length to resist the shear flow between boundary element and the web (see Figure 3). As shown in Table 1 three different spacing between transverse reinforcement were implemented in the boundary elements 60 mm, 45 mm and 30 mm in wall 1, wall 2 and wall 3 respectively. Transvers reinforcement ratio (ρ_{sh}) shown in the fifth column of Table 1 is defined as shown in Equation 1 where V_{sh} is hoop steel volume, S is vertical hoops spacing and, A_c is concrete area confined by the center line of the hoop.

$$\rho_{sh} = \frac{V_{sh}}{SA_c} \tag{1}$$

Walls were constructed at Concordia structural laboratory by professional Masons. The web was built using running pattern and, boundary elements were built using stack pattern. Wall construction started with casting the footing with the full length of vertical reinforcement. Then the first course was laid for full wall length including boundary elements C-shaped pilasters. At this stage, the outer C-shaped pilasters were not laid up. As a result, this technique allows the Mason to insert the horizontal reinforcement from wall sides, place the reinforcement cage and conduct the required inspection. The walls were constructed and grouted on two halves to mimic the low-lift grouting done in practice. Finally, reinforced concrete top loading beam was c to transfer actuator forces to the wall. Figure 4 shows wall's construction process.

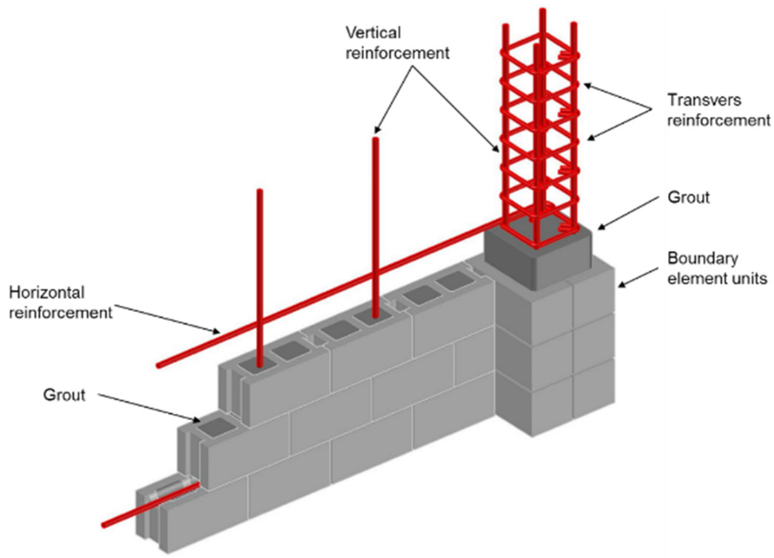


Figure 2: Wall Components

Table 1: Walls Reinforcement Details

Confg.	Boundary Element						Web			
	L_b mm	B_b mm	ρ_v %	ρ_{sh} %	# Vert. bars	Hoops size@spacing	L_w mm	b_w mm	# Vert. bars	Horiz. Bars size@spacing
Wall 1	190	190	0.79	0.0163	4#3	D4@60 mm	1335	90	4#3	D8@285 mm
Wall 2	190	190	0.79	0.0218	4#3	D4@45 mm	1335	90	4#3	D8@285 mm
Wall 3	190	190	0.79	0.0327	4#3	D4@30 mm	1335	90	4#3	D8@285 mm

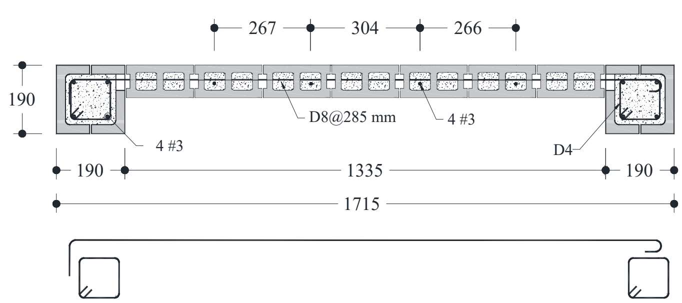
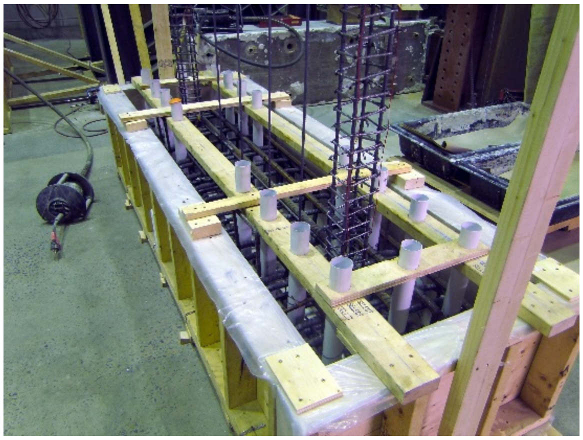
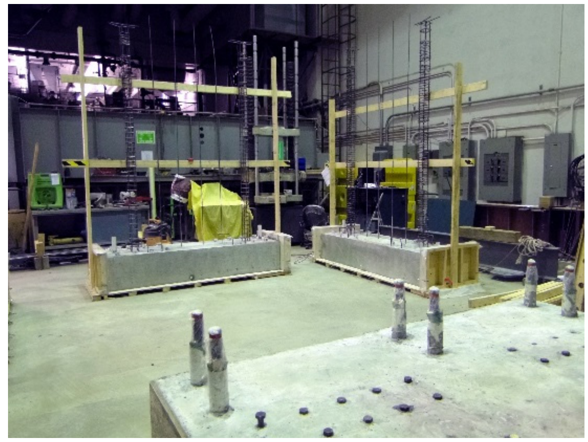


Figure 3: Wall's Typical Section



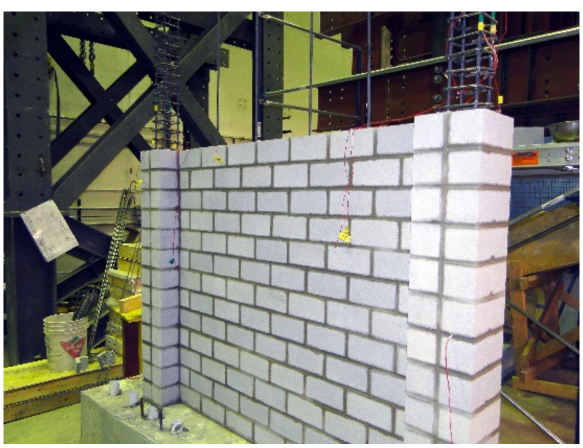
(a) Wall footing reinforcement



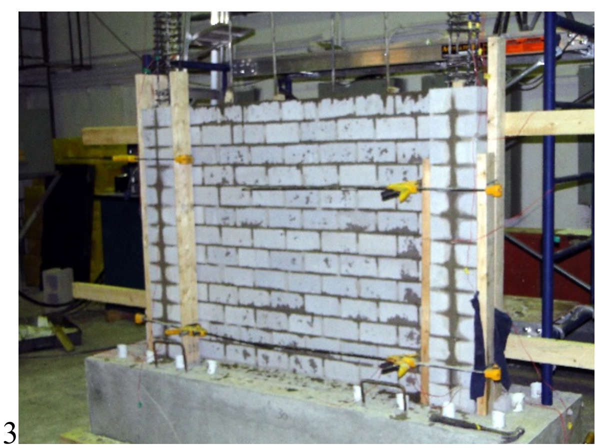
(b) Wall footings

(c)1^{st} and 2^{nd} masonry courses

(d) Mid-height wall construction

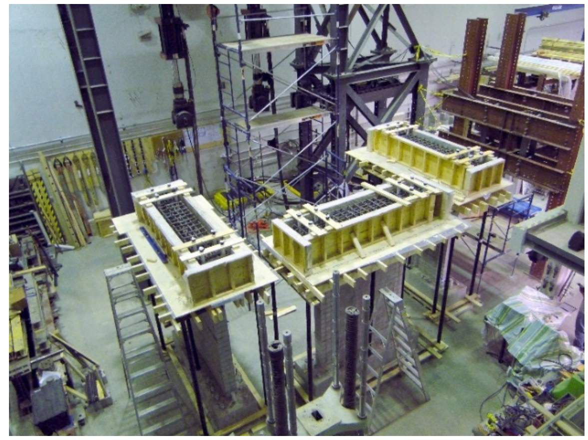


(e) Closing boundary elements



(f) Grouting half wall height

(g) Full height wall



(h) Top beams

Figure 4: Wall Construction Sequence

TEST SET UP

Tests will be conducted using a specialised test setup steel frame equipped with three attached MTS actuators for load application. The test setup allows the application of displacement increments in a quasi-static pattern to observe walls full lateral behaviour. The reaction frame shown in Figure 5 is designed to support two vertical and one horizontal actuator. The capacity of each of the three MTS digitally-controlled actuators could is 750 kN in compression and tension with a maximum stroke of 400 mm. The test setup allows testing shear wall's plastic hinge zone panels when subjected to constant axial load along with synchronised cyclic moment and shear force at the top of the tested panel generated by the vertical actuators. The structural floor has six tie-down pairs of anchorages. Heavily reinforced concrete pad (transfer footing) was constructed to tie specimen footing to the laboratory's strong floor. The transfer footing is secured to the strong floor via twelve 2" high-strength threaded rods to prevent sliding and overturning of the specimens. Wall footing is a 2300× 640×400 mm reinforced concrete footing. This foundation will be secured to the base foundation by eighteen (out of available forty-four) 1" high tensile threaded rods as shown in Figure 6 a.

INSTRUMENTATION

Six string potentiometers (P1-6) will be attached to a rigid support from one side, and the other side will be attached to the specimen. P1 to P3 will track wall's top displacement, whereas, the measured displacement values will be used to draw the force-deformation relationship. P4 and P5 will measure wall's lateral deformation at different heights, and they will are spaced at approximately 1100 mm. P6 will measure footing sliding (if any). Nineteen LVIT's will be mounted on the wall ends to measure wall curvature (L1 to L12). Relative displacement between the web and boundary elements; and web and top and bottom footings will be reported by (L13 to L15). Finally, diagonal shear deformations will be tracked by (L18 and L19). Twenty strain gauge will be installed on the outermost bars in each wall as shown in Figure 7a to capture the yield initiation and propagation over the loading history.

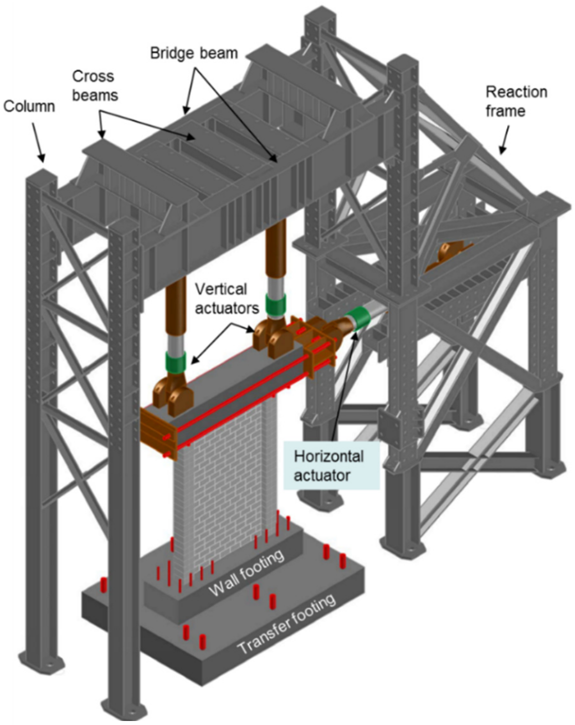
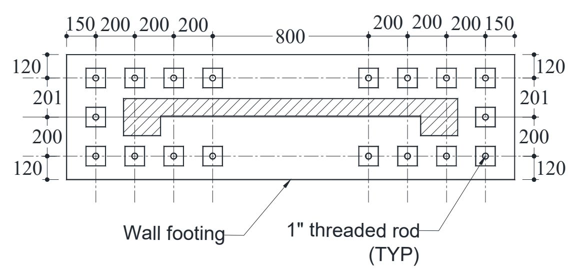
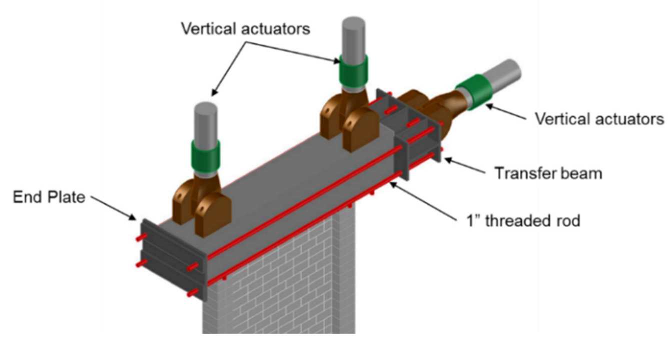


Figure 5: Test Set Up



(a)

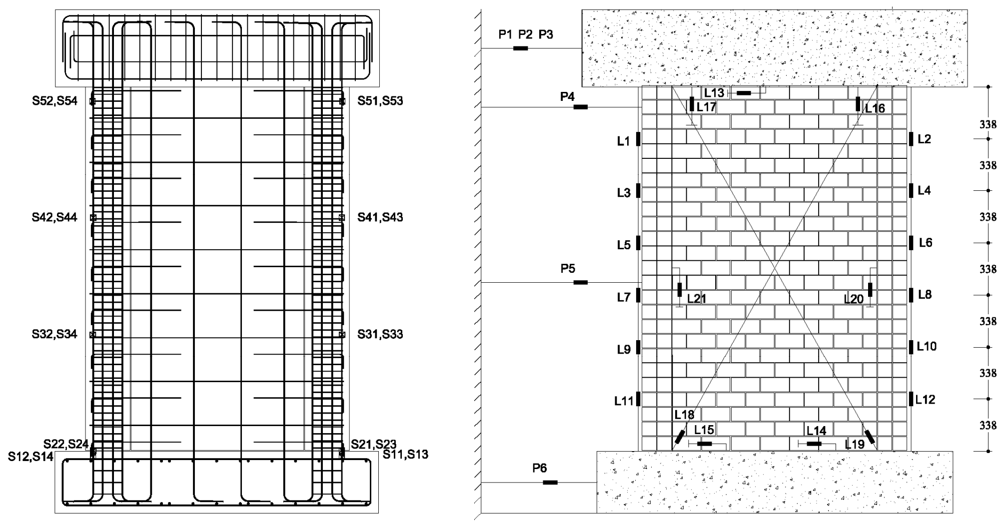


(b)

Figure 6: (a) Wall Foundation Layout, (b) Loading Beam Detail

LOADING PROTOCOL

Birely [10] studied the behaviour of concrete shear walls with confined boundary elements and concluded that shear span (effective height) has an influence on the wall's response mode, where it affects the lateral capacity of a well-designed and detailed ductile wall. The reason is attributed to the change of the response mode from flexure to compression-shear in the boundary elements zone. Also, the study revealed that the reduction in the effective height has an impact on the lateral drift capacity and reduction in the wall's cyclic response capacity and leads to a sudden loss of strength.



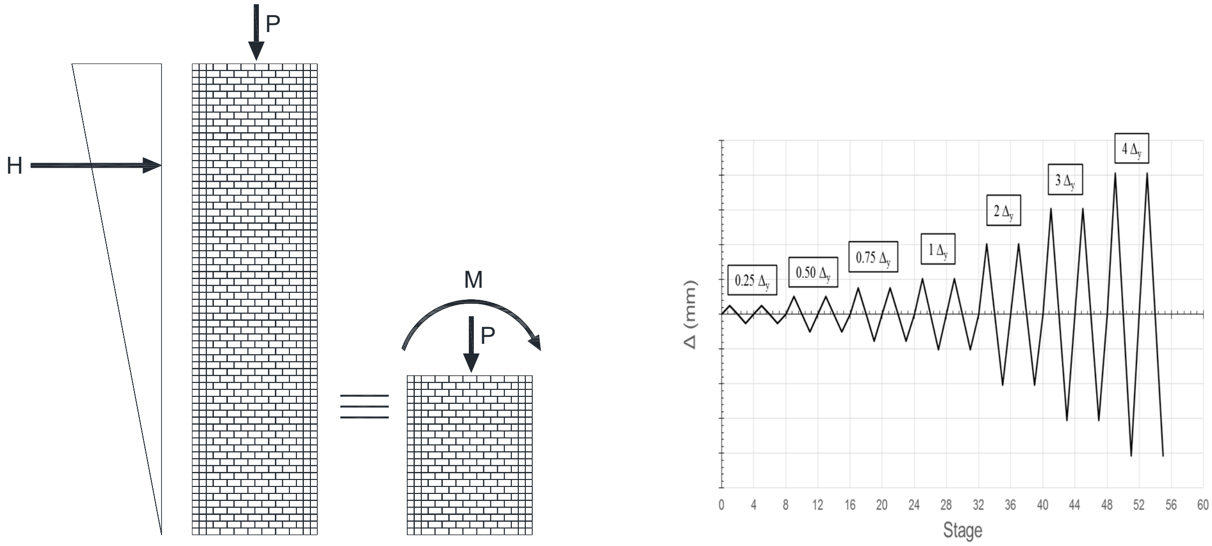
(a) (b)

Figure 7: Instrumentation Layout (a) Strain Gauge Location, (b) LVIT and Potentiometer Location

Test and analysis conducted by Laura et al. [11] on mid-rise concrete walls concluded that the suggested effective height for mid-rise shear walls ranges from 50% to 70% of wall height. Based on that, the selected lateral load shape to be used in this study is the inverted triangular shape which provides effective height 66.67% of the wall's height. The horizontal actuator is used to apply the load at the centre of the top loading beam. Two vertical actuators are used to apply the axial load and top moment to simulate the demand moment induced from upper stories shear. Figure 8b shows the displacement control loading protocol of the horizontal actuator. The horizontal excitation will be applied in reversed cyclic pattern. Each two cycles is meant to achieve a specific target displacement. Before reaching the wall's yielding point, yielding of the outermost vertical reinforcement, target displacements are applied as a fraction of the estimated yield displacement Δ_y ($0.25\Delta_y$, $0.50\Delta_y$, $0.75\ \Delta_y$). The remaining cycles will be applied as multiple of the actual yield displacement ($2\Delta_y$, $3\Delta_{y...}$). The test will be carried in sequential stages starting by applying the axial load by the two vertical actuators then the horizontal actuator will advance until it reaches the required target displacement. Following that, the top moment will be introduced through the vertical actuators according to the horizontal actuator load cell readings.

PREDICTION OF WALLS PROPERTIES

Walls theoretical properties were determined and summarised in Table 2. From tensile test for vertical rebars, the yield strain and the yield stress obtained was 0.002 and 460 MPa respectively. The yield lateral load (Qy), the yield curvature (ϕy) and yield displacement (Δy) were obtained using elastic analysis for the wall section. The extreme fibre ultimate compressive strain in the grouted masonry boundary element units (ε_{mu}) was calculated by using equation (2) driven from CSA S304 (2014) cl.16.11.6 [11][6]."



(a) (b)

Figure 8: (a) Lateral Load on Wall specimen, (b) Horizontal Actuator Displacement Control Loading Protocol

$$\varepsilon_{mu} = \frac{A_{sh} A_{ch} f_{yh}}{6k_n A_g f'_m S h_c} - \frac{1}{300} \tag{2}$$

Moreover, the ultimate lateral load ($Q_{u\ 0.0025}$, $Q_{u\ \varepsilon mu}$) were computed using the equivalent stress block described in CSA S304-14 [8] assuming ε_{mu} is either equal to 0.0025 or the value obtained from Equation 2 respectively. Subsequently, the corresponding ultimate curvature ($\phi_{u\ 0.0025}$, $\phi_{u\ \varepsilon mu}$) and ultimate displacement ($\Delta_{u\ 0.0025}$, $\Delta_{u\ \varepsilon mu}$) were calculated accordingly. The ultimate displacement values were calculated at the top of the wall specimen. As the plastic hinge length is affecting the value of the plastic deformation,the ultimate wall displacement was obtained using plastic hinge length numerical models provided by three different equations, Equations 3,4 and 5, proposed by Priestley (1992) [2], CSA S304-14 [8], and Bohl and Adebar (2011)[12], respectively. Yield and ultimate curvature and displacement are calculated based on equations provided by Paulay and Priestly 1992[2] in two location.

$$L_{p1}=0.5\ L_w \tag{3}$$

$$L_{p2}=0.5L_w + 0.1\ h_w \tag{4}$$

$$L_{p3}= (0.2L_w + 0.05h_w)(1.0-1.5P/f'_mA_g)<0.8L_w \tag{5}$$

The prediction calculations revealed that wall's properties are affected by plastic hinge length value and the calculated value of ultimate strain. Table 3 shows the displacement ductility values $\mu_{\Delta 1}$, $\mu_{\Delta 2}$ and $\mu_{\Delta 3}$ calculated based on deferent plastic hinge length shown in equations 3, 4 and 5 respectively and using $\Delta_{u\ \varepsilon mu}$. Also, it shows the value of wall's curvature ductility μ_ϕ. Increasing the confinement ratio resulted in an increasing of the wall's ultimate compressive strain. Thus, accompanied by higher curvature and displacement ductility as shown in Table 3. Also, increasing the plastic hinge zone length resulted in an increasing in the ultimate curvature and displacement ductility. Therefore, wall's predictions revealed that more experimental research work is needed in the area of estimating the plastic hinge zone length and ultimate compressive strain for RMSW with boundary elements.

Table 2: Wall Calculated Properties

Wall's properties	Wall 1	Wall 2	Wall 3
Q_y (kN)	35.74	35.74	35.74
C_y (mm)	429.92	429.92	429.92
ϕ_y (rad/mm)$\times 10^{-6}$	1.62	1.62	1.62
Δ_y (mm)	10.22	10.22	10.22
$Q_{u\ 0.0025}$ (kN)	61.87	61.87	61.87
$C_{0.0025}$ (mm)	140.91	140.91	140.91
$\phi_{0.0025}$ (rad/mm) $\times 10^{-5}$	1.77	1.77	1.77
$C/L_{w\ 0.0025}$	0.08	0.08	0.08
$Q_{u\ \varepsilon mu}$ (kN)	62.16	62.95	64.26
$C_{\varepsilon mu}$ (mm)	137.01	125.65	102.91
$\phi_{\varepsilon mu}$ (rad/mm) $\times 10^{-5}$	2.37	4.34	9.56
$C/L_{w\ \varepsilon mu}$	0.08	0.07	0.06
$\Delta_{0.0025}$ (using L_{p1})	36.59	36.59	36.59
$\Delta_{\varepsilon mu}$ (using L_{p1})	46.39	78.48	163.91
$\Delta_{0.0025}$ (using L_{p2})	53.25	53.25	53.25
$\Delta_{\varepsilon mu}$ (using L_{p2})	69.24	121.59	260.98
$\Delta_{0.0025}$ (using L_{p3})	41.47	41.47	41.47
$\Delta_{\varepsilon mu}$ (using L_{p3})	53.09	91.12	192.38

Table 3: Calculated Values for Displacement and Curvature Ductility

Config.	Wall 1	Wall 2	Wall 3
μ_ϕ	14.67	26.79	59.08
$\mu_{\Delta 1}$	3.79	6.26	12.85
$\mu_{\Delta 2}$	9.04	16.18	35.18
$\mu_{\Delta 3}$	4.48	7.56	15.77

CONCLUSIONS

The presented work is a part of an ongoing research program at Concordia University. The presented test matrix investigates the effect of changing the confinement ratio in the wall's boundary elements on the lateral response of reinforced masonry shear walls, RMSW, with boundary elements. New boundary element blocks were utilised in wall's boundary elements allowing various lateral reinforcement spacing. Therefore, this will give the designer the flexibility of choosing different reinforcement detailing at the wall ends and thus optimising the wall design. Moreover, the walls presented in the current study have a high aspect ratio (i.e. 11) which meet the recent need of increasing the heights of RMSW systems. This paper present the test matrix, details of walls, construction steps, and loading protocol. The RMSWs load-displacement response was predicted analytically, whereas, increasing the confining ratio in the boundary elements slightly increase the wall capacity and enhance the wall ductility significantly.

ACKNOWLEDGEMENTS

The authors acknowledge the support from the Natural Science and Engineering Research Council of Canada (NSERC), l'Association des Entrepreneurs en Maçonnerie du Québec (AEMQ), the Canadian Concrete Masonry Producers Association (CCMPA) and Canada Masonry Design Centre (CMDC).

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