Ductility of reinforced masonry shear walls with C-shaped boundary elements

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ABSTRACT

Reinforced masonry shear walls have been proved, through testing, to be able to provide the required strength and ductility to be considered as an efficient seismic force resisting system (SFRS) for mid-rise buildings. One way of increasing reinforced masonry shear walls ductility and overall seismic performance is by adding confined boundary elements to the walls' end zones to enhance the ultimate compressive strain and wall curvature ductility. Boundary elements were typically constructed using regular stretcher blocks which results in some limitations due to the geometry restrictions of the stretcher units. In this study, six half-scale reinforced masonry shear walls with boundary elements specimens, flexural dominated, were constructed in two phases and tested under a reversed cyclic moment and lateral loading. In this paper, phase two walls are presented. These walls represent the plastic hinge zone located in lower story panel of 12-story reinforced masonry shear wall building. C-shape masonry units were used to construct the boundary elements instead of the stretcher units. The wall's boundary elements are varied in size and vertical and transverse reinforcement ratios. The results showed that using C-shape masonry units overcome the limitations arise from using stretcher units to construct the boundary elements. Also, it showed that the reinforced masonry shear walls with C-shape boundary elements are capable of providing a high level of ductility with small strength degradation when subjected to quasi-static reversed cyclic loading.

Keywords: Ductility, Shear wall, Boundary element, Masonry, C-shaped.

INTRODUCTION

Reinforced masonry shear walls (RMSW) form the lateral force resisting system for multistory masonry buildings. 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 characterized by its favourable ductile behaviour, due to vertical reinforcement yielding, the formation of plastic hinge and crushing of masonry and grout[1]. Several research studies were conducted to understand the seismic response of RMSW better [2-7]. These studies showed that the flexure mode of failure provides high levels of ductility and small strength degradation at large drift levels. To enhance the ductility and the overall seismic response of RMSW there was a need to confine the toe zones in the wall to delay the buckling of vertical reinforcement and increase the grouted masonry ultimate compressive strain which will lead in an increase in the ultimate curvature capacity. Typical rectangular reinforced RMSW has a geometry restriction of having one layer of vertical reinforcement which will not allow for adding confining hoops to the end zone. Many confinement methods were proposed by researchers such as confinement plates, confinement comb and spiral ties. The other condiment method alternative is to add boundary elements to wall's end zones. Boundary elements provide the required space to have two layers of vertical reinforcement which allows to add confinement hoops.

Shedid et al. [6] 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. Banting 2013 [8] 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 to 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 the 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].

Previously tested RMSW with boundary elements are limited in the literature. The boundary elements in these tested walls were made from regular stretcher blocks, except one wall tested by Shedid et al. (2010)[6]. Due to the geometry restrictions of the stretcher units, the spacing between the transverse reinforcement hoops spacing is limited and does not provide the required vertical reinforcement buckling prevention spacing. Also, using stretcher blocks restricts the boundary elements shape to the square and restricts the number of vertical reinforcement bars. Moreover, the confined core in the boundary elements made by using stretches units is a mix of three materials; grout, stretcher block, and mortar which makes it a non-homogeneous material, which make it hard to control its properties in the practical applications.

In this study, a new boundary element block (i.e. C-shaped blocks) were utilized to form the boundary elements in the tested walls. That allows designers to decrease the spacing between hoops in the boundary elements and eliminates the limitations associated with regular concrete blocks (i.e. stretchers) utilized in previous studies [1][2]. The configuration of the new boundary was achieved in collaboration with the masonry industry in Canada [CCMPA, CMDC] to ensure its practicality for future manufacturing and use in the construction industry. This study was conducted to check the RMSW with boundary elements formed with C-shaped blocks capabilities to provide the required strength and ductility to resist earthquake events and to understand its nonlinear response,

PROPOSED BOUNDARY ELEMENT CONFIGURATION

Currently, the boundary elements are made from regular stretcher units as shown in Figure 1. These boundary elements are restricted in size and vertical and transverse reinforcement ratio. Also, it has many constructability issues, for example, masonry units and hoops should be laid in a sequence which consumes lots of time and workforce. Also, to have hoops spacing less than the block unit height lots of cutting operations need to be done. The proposed C-shaped boundary element units are shown in Figure 1. Here the boundary element is formed using two C-shape masonry units facing each other and the steel cage is installed as one peace. C-shaped BE has the advantage of providing more homogenous grouted core, flexibility in selecting boundary element size and amount of vertical and transverse reinforcement.

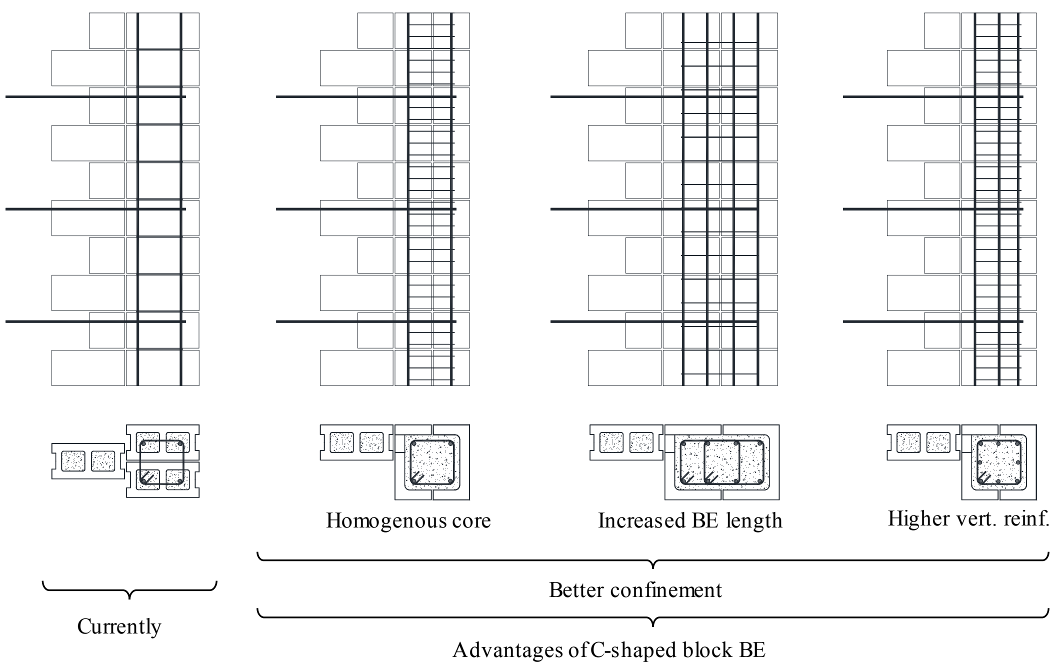

Figure 1. Advantages of C-shaped block boundary elements

EXPERIMENTAL PROGRAM

Six half-scale fully grouted reinforced masonry shear walls were built and tested under reversed cyclic lateral load and top moment in two phases. The specimens represent the plastic hinge zone located in lower story panel of 12-story reinforced masonry shear wall building. C-shape masonry units were used to construct the boundary elements instead of the stretcher units. The wall's boundary elements are varied in size and vertical and transverse reinforcement ratios. All walls were designed to be flexure dominated. Shear walls were designed to provide shear and sliding resistance with a safe margin to avoid undesirable shear failure. Deformed wires shear reinforcement D8 (diameter = 8.11 mm) with 90°/180° hook spaced at 285 mm along the height of the wall were placed alternatively [9]. Also, D8 horizontal reinforcement bars with 180° hooks 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.

Test specimens

In this paper, phase two walls are presented. This phase includes wall 4, 5 and 6. Table 1 shows the summary of the walls' details. l_b and b_b are the length and the width of the boundary elements. ρ_v is the vertical reinforcement ratio in the boundary elements. l_w and b_w are the length and the thickness of the web, respectively. Walls reinforcement typical details are shown in Figure 2. Wall 4 is considered as the reference wall for this group. Comparing Wall 4 and 5 would determine the effect of changing the boundary element length when keeping the same amount of vertical reinforcement on the wall's behaviour, whereas comparing Wall 5 and 6 would investigate the effect of boundary element vertical reinforcement ratio on the wall's response. All walls were subjected to 1.5 MPa vertical stress.

Table 1. wall's reinforcement details.

Wall	Boundary Element					Web			
	L_b (mm)	b_b (mm)	ρ_v (%)	Vert. Reinf.	Hoops size@spacing	L_w (mm)	b_w (mm)	Vert. Reinf.	Hori. Reinf.
Wall 4	190	190	1.57	8#3	D4@60 mm	1335	90	4#3	D8@190 mm
Wall 5	290	190	1.03	8#3	D4@60 mm	1145	90	4#3	D8@190 mm
Wall 6	290	190	0.77	6#3	D4@60 mm	1145	90	4#3	D8@190 mm

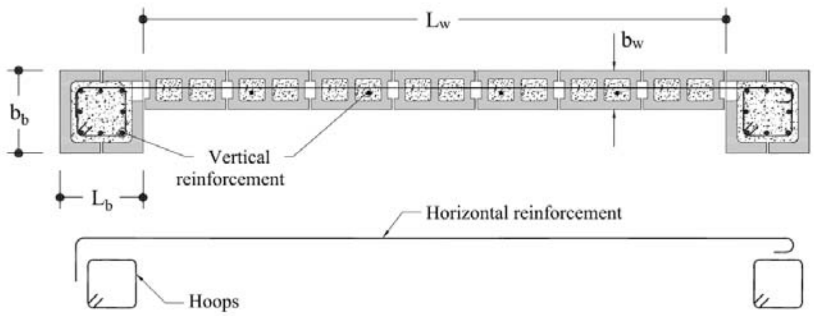

Figure 2. wall's reinforcement details

Instrumentation

Six string potentiometers were attached to rigid support from one side, and the other side they were attached to the specimen to measure the lateral displacement and the sliding of the wall. Twelve LVDT's were mounted on the wall ends to measure wall curvature. Relative displacement between the web and boundary elements; and web and top and bottom footings also were measured by LVDT's. Finally, shear deformation was tracked by two potentiometers mounted in a cross shape along the panel height. Twenty strain gauges were installed on the outermost bars in each wall to capture the yield initiation and propagation over the loading history.

Test setup

The reaction frame shown in Figure 3 was used to conduct the test. The test setup allows the application of displacement increments in a quasi-static pattern to observe the walls' full lateral behaviour. The test setup allows testing shear wall's plastic hinge zone panels when subjected to constant axial load along with synchronized cyclic top moment. Two vertical ±750 kN actuators are attached to the reaction frame to apply the service and cyclic top moment loads. The horizontal actuator was used to apply the lateral displacement in a reversed cyclic pattern.

Load-displacement sequence

The horizontal excitation was applied in a reversed cyclic pattern. Every two cycles are meant to achieve a specific target displacement, following the recommended loading protocol of ASTM E2126. 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 were applied as multiple of the actual yield displacement ($2\Delta_{y,}$ $3\Delta_{y\ldots}$) and repeated twice at each displacement level. The test was carried in sequential stages starting by applying the axial load by the two vertical actuators then the horizontal actuator moves until it reaches the required target displacement. Following that, the top moment was introduced through the vertical actuators according to the horizontal actuator load cell readings.

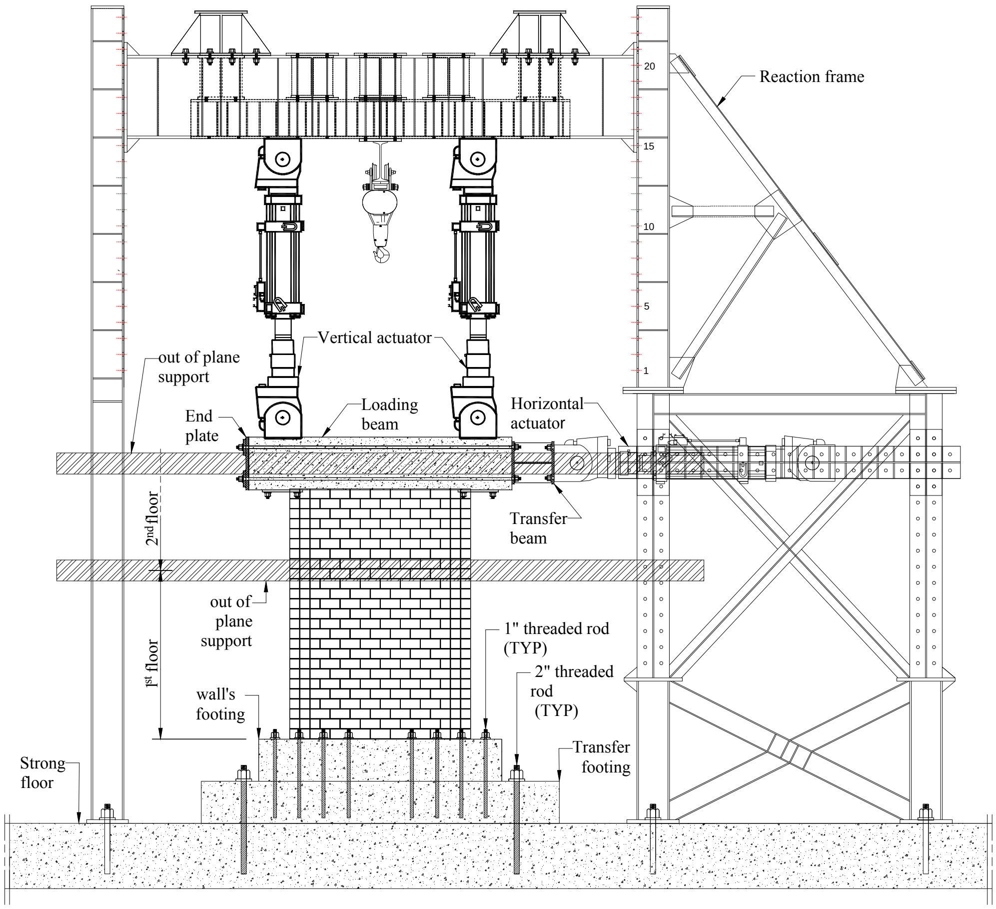

Figure 3. Test set-up

EXPERIMENTAL RESULTS

In general, walls were dominated by a flexural failure mode characterized by yielding of vertical reinforcement, horizontal cracks, and toe-crushing. Vertical splitting cracks appeared in the boundary elements and spalling accrued to uncover the intact grouted core when increasing the applied loads. Increasing the lateral displacement led to toe crushing of the confined core and buckling/rupture of the vertical bars in the boundary elements.

Observed behaviour and failure mechanism

For all walls, hair cracks appeared in the bed joints at $1\Delta_y$. The first visible cracks extended along the first storey height spaced at every two courses were observed at $3\Delta_y$ as horizontal flexural cracks in the bed joints at the boundary elements and web areas. By increasing the applied loads more horizontal crack developed at the bed joint in the boundary elements and the web area and in the zone between the bed joints, in the masonry block and the grouted core, in the boundary elements.

For wall 4, vertical crack was observed between the grouted core and C-shape masonry unit in the toe area in the left boundary element along with crushing in the C-shape masonry unit face shell at $7\Delta_y$. The failure occurred at the second cycle of $13\Delta_y$ when buckling of vertical reinforcement and crushing of the grouted core took place as shown in Figure 4a.

For wall 5, vertical cracks and crushing of boundary elements face shell at the toe zone took place at $9\Delta_y$. Vertical cracks in the boundary elements propagated till the 3rd course at $11\Delta_y$. The failure occurred at the first push of $14\Delta_y$ when buckling of vertical reinforcement and crushing of the grouted core took place.

For wall6, vertical cracks and crushing of boundary elements face shell at the toe zone took place at $8\Delta_y$ as shown in Figure 4b. Vertical cracks in the boundary elements propagated till the 9th course at $10\Delta_y$. Boundary elements face shell spalling started at the toe zones at $11\Delta_y$. At $14\Delta_y$, buckling of vertical reinforcement occurred at the 7th boundary element course and the wall resistance dropped.

(a)

(b)

Figure 4. wall failure: (a) bar buckling and grout crushing in wall 4 at 13Δy, (b) vertical cracks in the boundary element in wall 6 at 8Δy.

Load-deformation relationship

In this test, the positive lateral force and displacement were measured in the push direction when the horizontal actuator pushes the wall to the west direction and vice versa. The wall's capacities are shown in Table 2 where Q_y is the measured yield lateral force and Q_u is the measured ultimate lateral force. The walls have a similar response in push and pull directions except for wall 6 it has 8.47 kN difference in the measured yield strength due to a small cavity found the web next to the east boundary element. However, this cavity did not affect the ultimate capacity of the wall or its ductility ratio as will be explained later in this paper.

Table 2. Wall's lateral strength.

Wall	Q_y		Q_u		Q_u/Q_y	
	Push (kN)	Pull (kN)	Push (kN)	Pull (kN)	Push (%)	Pull (%)
Wall 4	56.69	-54.23	74.56	-74.09	131.52%	136.61%
Wall 5	56.37	-56.82	77.96	-74.95	138.30%	131.91%
Wall 6	53.61	-45.13	67.76	-66.34	126.41%	147.00%

The effect of changing the boundary element length and vertical reinforcement ratio on the response of the walls are shown in Figure 5. changing the boundary element length has almost no effect on the lateral resistance of the wall, however, wall 5 with longer boundary element has a ductility ratio of 14 compared with 13 for wall with shorter boundary element, wall 4. This increase in the ductility could be explained as a result of increasing the compressive strain in the long boundary elements wall. This increase is due to vertical reinforcement and hoop detailing in the boundary element were arrange as shown in Figure 6. in the long boundary element every bar was tied to confinement hoop counter to short boundary element only four bars out of eight bars were tied to confinement hoop. Tying every vertical bar has the effect of increasing the strength and the ductility of the boundary elements[10]. Increasing the compressive strain will reduce the compression zone depth to the wall length ratio ($\frac{c}{l}$) which will lead to a more ductile section. Wall 5 and 6 showed that increasing the vertical reinforcement increased the lateral capacity of the wall and it affected the ductility which will be discussed in the ductility section in this paper.

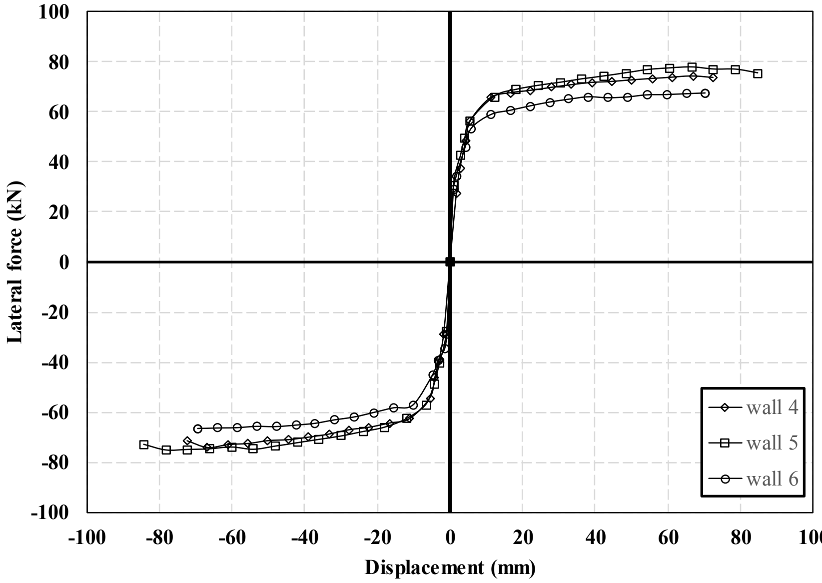

Figure 5. Effect of changing boundary element length and vertical reinforcement ratio.

(a) (b)

Figure 6. reinforcement arrangement in boundary elements: (a) 190 x290 boundary element, (b) 190x190 boundary element.

Ductility

Ductility ratio μ_Δ represents the ratio between ultimate displacement Δ_u and the yield displacement Δ_y as shown in Eq. 1. Equation 1 best describes the ductility ratio for an elastic-perfectly plastic system. However, masonry walls have different yield mechanisms due to its geometry, details and material properties[11]. From the literature, there are many methods to idealize the force-displacement relationship[12]. None of these methods is preferable on another[13], however, the most common method is equal energy concept where considering that the area under the real face deformation curve is equal to the area under the Idealized curve. The objective of this paper is to present the seismic response and in particular the ductility of the proposed RMSW system. Thus, no idealization for the force-deformation relationship will be considered in this stage.

$$\mu_\Delta = \frac{\Delta_u}{\Delta_y} \tag{1}$$

The yield displacement will be taken as the displacement at the onset of yielding of the vertical reinforcement bars at the end of the wall. Since no force degradation was observed, the ultimate displacement will be considered as the maximum displacement recorded for the wall. Table 3 shows the measured yield and ultimate displacement and the displacement ductility ratio. From walls 4 and 5, increasing the boundary element length increased the yield displacement by 7.14% and the ultimate displacement by 15.38%. Also, increasing the boundary element length provided more ductility ratio.

Table 3. Measured yield and ultimate displacement.

Wall	Δ_y (mm)	Δ_u (mm)	μ_Δ
Wall 4	5.6	72.8	13
Wall 5	6	84	14
Wall 6	5.35	74.9	14

It can be shown from walls 4 and 6 that the wall can reach almost the same ultimate displacement and more ductility ratio when increasing the boundary element length and use less amount of the vertical reinforcement. From walls 5 and 6, reducing the vertical reinforcement ratio in the boundary elements reduced the yield and ultimate displacement by 12.14%.

CONCLUSIONS

The presented work is a part of an ongoing research program at Concordia University. The objective is to investigate the seismic response of reinforced masonry shear walls with C-shape boundary elements. The presented test matrix investigates the effect of changing the confinement ratio, the boundary element size and vertical reinforcement ratio in the wall's boundary elements on the seismic response of RMSW. New C-shape boundary element blocks were utilized in wall's boundary elements allowing various lateral reinforcement spacing. The test setup is adequate and can simulate the test for the lower panel of RMSW in 12 storey building. In general, test results showed that the proposed system can provide the lateral strength and ductility required to resist earthquake events. Walls were dominated by a flexural failure mode characterized by yielding of vertical reinforcement, horizontal cracks, and toe-crushing. Vertical splitting cracks appeared in the boundary elements and spalling accrued to uncover the intact grouted core when increasing the applied loads. Increasing the lateral displacement led to toe crushing of the confined core and buckling/rupture of the vertical bars in the boundary elements. Increasing the boundary element length has the effect of increasing the ductility ratio and increasing the yield and ultimate displacement. Increasing the boundary elements vertical reinforcement increases the lateral strength and the yield and ultimate displacement, but it has a minor effect on the ductility ratio.

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