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OUT-OF-PLANE CYCLIC RESPONSE OF SLENDER REINFORCED MASONRY WALLS SUBJECTED TO INCREASING AXIAL LOAD

Sparling, Adrien[1] and Palermo, Dan[2]

ABSTRACT

Modern reinforced concrete masonry unit construction allows for the efficient use of resilient materials for the construction of large buildings. In Canada, the CSA S304 Design of Masonry Structures standard governs all aspects of practical design. The current standard was developed based on pioneering research and testing of masonry assemblies; however, the legacy of traditional assumptions and rules of thumb is still evident in certain sections. The clauses related to the design of slender reinforced masonry (RM) walls contain seemingly arbitrary prescriptive constraints. This paper is focused to inform the current understanding of the response of slender RM walls under service loading conditions including axial and out-of-plane loading. Simply supported 8m-high hollow RM walls are subjected to out-of-plane 4-point bending, while a sustained axial load is applied. Through cyclic out-of-plane loading under increasing axial load, the flexural response is characterized under axial load increments up to 150kN. The test series will compare the behaviour of walls with conventional embedded reinforcement to those reinforced with vertically oriented Near-Surface Mounted (NSM) steel reinforcement. Conventionally reinforced slender concrete unit masonry walls have limited out-of-plane stiffness due to the location of the reinforcing steel near the centre of the wall's cross-section; conversely, NSM reinforcement is located near the extreme tension fibres of the wall, thereby greatly improving stiffness. The benefits of the NSM reinforcement system (i.e.: reduced cracking and reduced moment magnification through improved stiffness) will become apparent through this full-scale test series on slender RM walls.

KEYWORDS: *reinforced masonry; slender wall; out-of-plane flexure; near-surface mounted reinforcement; moment magnification*

[1] PhD Candidate, Department of Civil Engineering, York University, 4700 Keele St., Toronto, ON, Canada, adriensp@yorku.ca
[2] Professor, Department of Civil Engineering, York University, 4700 Keele St., Toronto, ON, Canada, dan.palermo@lassonde.yorku.ca

INTRODUCTION

Modern structural masonry construction allows for the efficient use of resilient materials for the construction of large buildings, and is accompanied, in Canada, by a comprehensive standard, CSA S304-14 (R2019) *Design of Masonry Structures* [1], governing all aspects of practical design. The current standard was developed based on cutting-edge research and testing of masonry assemblies; however, the influence of its empirically-based predecessors is still evident in certain sections. The clauses related to the design of very slender reinforced masonry (RM) walls still contain restrictive constraints; for walls with a slenderness ratio $kh/t > 30$, where kh is the effective height, and t is the wall stiffness, the maximum allowable axial load is limited to 10% of the section capacity, regardless of the flexural stiffness.

The focus of this research is to provide a better understanding of the response of very slender RM walls under service loading conditions including axial and out-of-plane forces. The research complements a previously conducted preliminary testing program [2] [3], which compared the behaviour of conventionally reinforced walls (containing embedded grouted reinforcement) and walls with Near-Surface Mounted (NSM) reinforcement. It supplements existing formative data from tests conducted in the 1970s-80s and introduces a novel approach to reinforcing new masonry construction. This paper includes a review of the literature that led to current provisions in design standards. It also includes preliminary results from a response assessment of a partially grouted 8m-tall RM wall. The results presented are part of a series of four, full-scale slender wall tests comparing the behaviour of conventionally reinforced partially grouted walls to hollow masonry walls with NSM steel reinforcement.

LITERATURE REVIEW

A review of the current literature revealed few accounts of full-scale tests under combined axial and out-of-plane loading for slender RM walls. Although the large number of walls tested by Yokel et al. [4] and Hatzinikolas et al. [5] were critical in the transition, from empirical to rational design approaches in North American structural standards, developments in construction techniques and understanding of the structural mechanics of RM justify the need to revisit some of the conclusions drawn during that time. In 1970, Yokel et al. [4] suggested a rational method for calculating the capacity of a slender masonry wall based on elastic buckling theory and the reduced stiffness, EI, of a cracked RM wall (where EI represents the product of the Young's modulus, E, and the moment of inertia, I). In this method, the applied moment is magnified by a factor accounting for the ratio of the applied axial load to the critical elastic buckling load, and the estimated cracked stiffness of the walls was taken as 40% of the effective uncracked value.

Hatzinikolas et al. [5] describe the transition from empirical design standards to more rational approaches which took place in the 1960s to 70s in masonry design. Accompanying the results of their series of experimental tests on slender RM walls is a discussion of theory surrounding the buckling behaviour of slender RM walls following a similar approach to that described by Yokel et al. [4]; however, more detailed equations are presented for the determination of the cracked moment of inertia. These equations are based on the line of thrust and the deformed shape of the walls; they do not, however, consider the stiffness of the transformed cracked section. Testing and analysis by Simpson [6] introduced the use of the cracked moment of inertia to determine the stiffness for the assessment of moment magnification effects in slender RM walls. More recently, da Porto et al. [7] tested a series of slender cantilever RM walls in out-of-plane bending. The walls had an effective slenderness of $kh/t=30$, and that testing illustrated significant moment resistance and predictable behaviour under large deflections (5% drift) and significant axial surcharge loading (25kN/m). Donà et al. [8] discuss the impact these tests may have on design using the Eurocode 6 [9], however the walls were constructed from perforated clay brick and some included tied rebar cages; a construction technique not commonly used in Canada. Nevertheless, the tests did highlight that properly constructed and detailed slender RM walls behave in a manner conducive to rational analysis. Another recent investigation by Robazza et al. [10] was based on the out-of-plane behaviour of slender RM shear walls under reversed cyclic in-plane loading. The slender walls tested ($h/t=27$), which failed in in-plane shear, did not exhibit signs of out-of-plane instability. These studies suggest that the assumption that very slender walls are inherently unstable and require special restrictive design provisions should be re-evaluated.

Design of a slender structural member subjected to axial load is fundamentally an exercise in design for out-of-plane stiffness. Several techniques have been proposed to increase the out-of-plane stiffness of RM walls to reduce the influence of P-Δ effects (product of axial load and wall deflection). The simplest of these was proposed by Abboud et al. [11], where the reinforcing bars within the cells were located as near to the inner side of the face shell as practicable. Other methods to restrict the out-of-plane bending include post-tensioning of the main vertical reinforcement [12], NSM steel reinforcement [3], or a tied rebar cage [7] [13].

To date, the application of NSM reinforcement has been limited to the retrofitting of existing structures to increase the resistance to changing loading conditions, or to improve seismic resilience; the state of practice is well documented by de Lorenzis and Teng [14]. Existing examples of practical application of NSM reinforcement have mostly incorporated fibre-reinforced polymer bars or tapes to avoid changing the stiffness of the existing structural members; however, the current study aims to take advantage of the increased stiffness afforded by NSM steel reinforcement to benefit the construction of slender masonry walls.

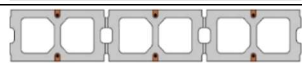
EXPERIMENTAL PROGRAM

The current testing program involves four slender RM walls. The goal is to assess the flexural strength and stiffness response of the walls, and to compare the performance of walls with conventionally embedded and grouted reinforcement to walls with NSM reinforcement.

Test walls

The length of the walls was set at 1.2m to conform to and to provide a consistent comparison to other wall tests in the literature (e.g., [4] [6] [11]). Furthermore, this length permits a variety of other reinforcement layouts for future tests. Two layouts were selected for the walls in this test series, both having a gross reinforcement ratio of 0.26%. One of the layouts included reinforcement applied using conventional means, by placing reinforcing bars centrally within the cells of the Concrete Masonry Units (CMU), and positioning them using masonry grout; walls S1 and S2 were reinforced with two deformed reinforcing steel bars. The two cells containing the reinforcing bars were grouted, while the remaining four cells remained hollow. The remaining walls S3 and S4 were reinforced by applying six deformed reinforcing steel bars within continuous grooves along the height of the wall (three on the tension side and three on the compression side). The bars were bonded to the CMUs with epoxy following the NSM technique. A summary of the reinforcement layout and grouting of the four walls is presented in Table 1.

Table 1: Wall reinforcement layouts

Wall ID	Conceptual Layout	Bar Size (quantity)	Grouting	Reinforcement Type
S1, S2		20M (2)	Partial	Conventional
S3, S4		10M (6)	None	NSM

The walls were constructed in three stages by a certified mason. The main longitudinal reinforcing bars for the conventionally reinforced walls (20M bars) were lap-spliced over a length of 800mm and located centrally within the thickness of the walls. The NSM reinforcing bars (10M bars) were continuous along the full height of the wall. The top and bottom courses of each wall were grouted solid and reinforced with a hooked 10M reinforcing bar, as shown in Figure 1. The constructed walls measured 7.8m in height (slenderness ratio *kh/t=42*).

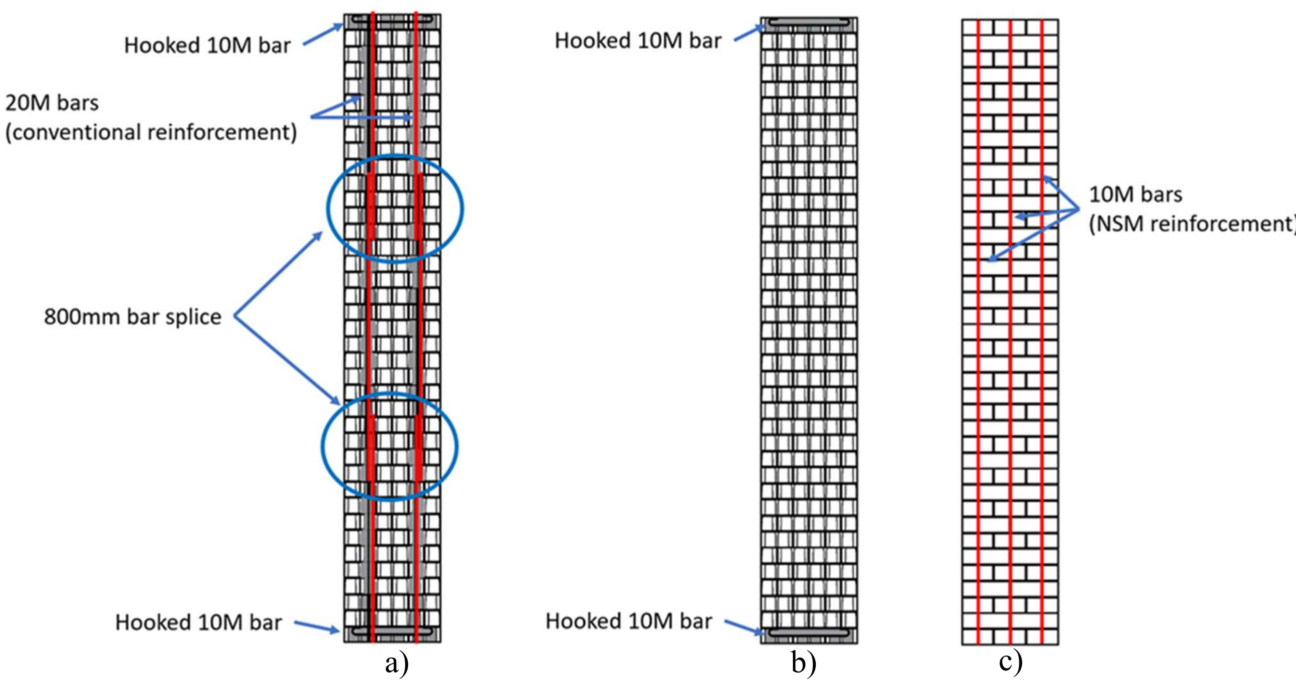


Figure 1: Wall details: a) reinforcement placement in walls S1 and S2; b) grouted reinforcement in walls S3 and S4; and c) NSM reinforcement in the walls S3 and S4

Materials

The materials used in construction of the walls include 190mm x 190mm x 390mm CMUs with a nominal compressive strength of 15MPa. The conventionally reinforced walls were constructed from hollow stretcher units with alternating courses of three full units and two full units with two saw-cut half units (running bond pattern). The half units were cut from stretcher units to 190mm in length. The walls with NSM reinforcement were similarly constructed in running bond from specially fabricated grooved units that were cast using the same equipment and concrete mix as the conventional stretcher units. These units, as described by Sparling et al. [3], differ from the conventional units in that they include a central 20mm x 30mm central groove on both exterior faces, and partial grooves at the block ends as shown in Figure 2.

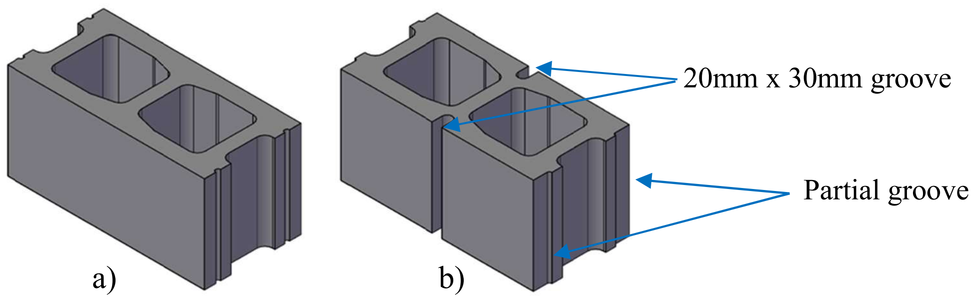


Figure 2: CMU types: a) conventional; and b) grooved

The mortar used was produced from a pre-blended, bagged Type S mortar mix, and the grout was a proportion-specified coarse grout conforming to CSA A179 (cement:aggregate:sand ratio of 1:2:3 by volume) mixed on site. The average 28-day compressive strength of the mortar and grout were 27.3MPa and 14.5MPa, respectively. Longitudinal reinforcement for the conventional block walls was provided by 20M deformed steel bars; 10M deformed reinforcing bars were used for the NSM reinforcement. The properties of the reinforcing steel bars are listed in Table 2. A low sag doweling epoxy, with a manufacturer reported 7-day tensile strength of 24.8MPa and a modulus of elasticity of 4.5GPa, was used to apply the NSM reinforcing bars.

Table 2: Mechanical properties of reinforcing steel bars (ASTM E8, average of 3 bars)

Steel Bar Type	Effective Area (mm^2)	Young's Modulus (MPa)	Yield Stress (MPa)
10M	100	194 000	530
20M	300	190 000	440

TESTING

The following sections focus on the first slender wall test of a conventional block wall reinforced longitudinally with 20M deformed steel bars (wall S1). The wall was subjected to cyclic out-of-plane loading under increasing axial load.

Instrumentation
The reinforcing bars were fitted with twenty, 120ohm strain gauges. These gauges were located to be aligned with the mortar joints of the constructed wall, thereby capturing the locations most likely to exhibit the largest strain. [Horizontal flexural cracking is typically initiated at the mortar joints.] The layout of the strain gauges within the wall S1 is illustrated in Figure 3 a); a strain gauge was placed at every mortar joint within the central 2m of the wall (maximum moment zone) and were spread farther apart near the supports where the resulting moments were significantly lower.

Surface strain was measured near the midspan and at 1.5m from the bottom of the wall using four linear displacement transducers (potentiometers) with a gauge length of 400mm. These transducers were located symmetrically on the front and back of the wall, at the locations illustrated Figure 3 b), to record the strain profile through the thickness of the wall.

Out of plane displacements of the wall were recoded using string transducers at 1m intervals along the height of the wall, including at the top and bottom pin/roller supports as shown in Figure 3 c). Displacements were recorded at two points along the length of the wall at the mid span and at the supports to record any out-of-plane twisting of the wall or supports.

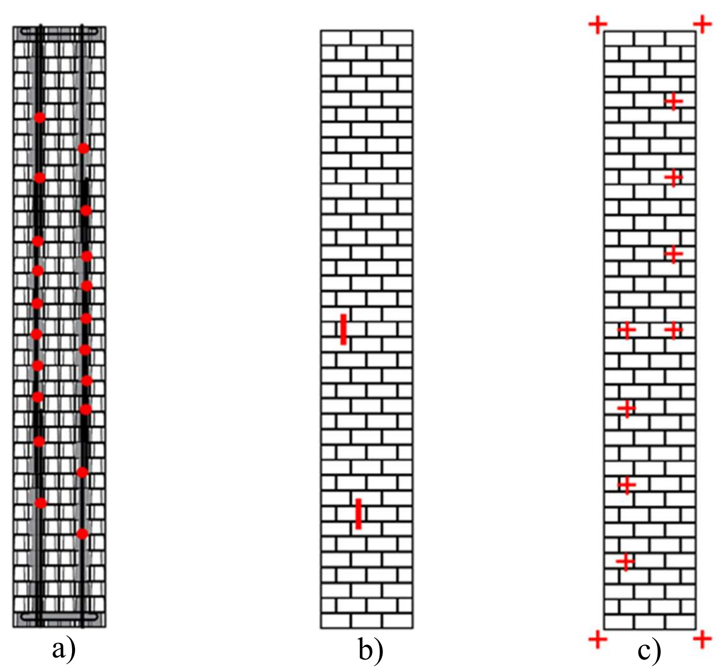


Figure 3: Location of instrumentation: a) strain gauges; b) linear displacement transducers; c) string transducers

The applied loads were recorded using the actuators' load cells. The horizontal actuator's load cell recorded the out-of-plane load and the vertical actuator's load cell recorded a value proportional to the applied axial load at the top of the wall. Additional data collected during testing included the vertical elongation/contraction of the wall (measuring from the centre of the bottom course to the centre of the top course), and time lapse photographic imagery near the linear displacement transducers to be used for Digital Image Correlation (DIC) analysis of surface strains and crack growth.

Test Method

The testing setup, shown in Figure 4, was composed of a structural steel support frame, with axial and out-of-plane loading applied using hydraulic actuators. The wall was simply supported in the loading frame. The wall was supported at the base using a steel channel connected to a 35mm-diameter steel rod running through a series of pillow-block mounted bearings. The top of the wall was fitted with a steel capping channel connected to a roller assembly consisting of the same type of steel rod and bearing as the base. The top cap channel also included a steel fulcrum, aligned with the roller assembly, on which the axial load was applied. The unsupported length of the wall (from centre to centre of the support pin and roller) was 8m.

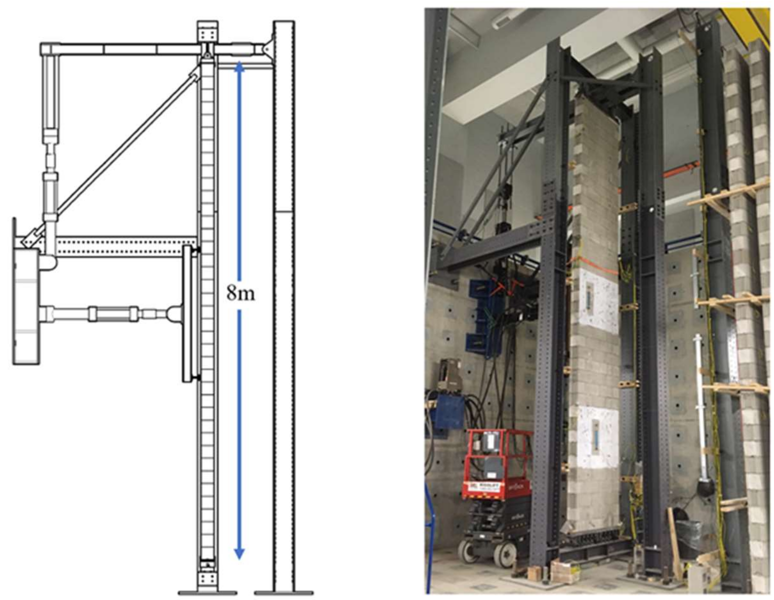


Figure 4: Loading frame for combined axial and out-of-plane loading

Out-of-plane loading was applied using a horizontally-mounted hydraulic actuator fitted with a spreader beam assembly to apply two equal line loads to the wall 2m apart (1m above and below the midspan point). Axial loading was applied using a lever arm connected at one end to a vertically oriented hydraulic actuator and pinned at the other end to a column that was anchored to the laboratory floor. Axial loading was thereby applied at the fulcrum of the lever arm (at the top of the wall) by retracting the head of the vertical actuator.

Testing was conducted in stages with incrementally increasing applied axial load. For each loading cycle, a pre-determined level of axial load was maintained while the wall was loaded out of plane under displacement control until a maximum strain reading of 0.18% was experienced (90% of the nominal yield strain of the reinforcing bars) at any of the strain gauge locations. The out-of-plane load was then removed, followed by the axial load, prior to the next loading cycle. Through this loading protocol, the wall was loaded in its elastic response range with superimposed axial loading ranging from 0 to 140kN (up to 13.7% of the effective section capacity $f'_m A_e$). A loading cycle with an applied axial load of 150kN was halted prior to the target reinforcing bar strain being achieved due to moment magnification effects causing a reduction in the out-of-plane load response with increasing displacement (elastic buckling). Following the elastic testing, a final loading cycle was completed with an applied axial load of 60kN (5.9% of $f'_m A_e$), during which the wall was displaced to twice the yield displacement.

Results

The maximum load, moment, and displacement response of wall S1, as the reinforcing bars reached 0.18% in tensile strain, is presented in Table 3 for various axial load levels.

Table 3: Response summary at 0.18% reinforcement strain at various axial load levels

Axial Load (kN)	Out-of-Plane Load (kN)	Total Moment (kNm)	Maximum Displacement (mm)
0	9.0	15.3	138
60	7.1	21.2	143
100	5.7	24.8	144

With increasing axial load, the wall exhibited increasing initial stiffness response but decreased out-of-plane resistance (at the target maximum strain), as shown in Figure 5 a). The total moment resistance response of the wall was calculated by adding the applied moment from the horizontal actuator to the moment induced by the axial load (including self-weight). The total moment-average displacement response of the wall, as shown in Figure 5 b), illustrates an increase in flexural strength with increasing applied axial load. In the responses, the height, H, over which the deflection ratio Δ/H is provided is the distance between supports (8m).

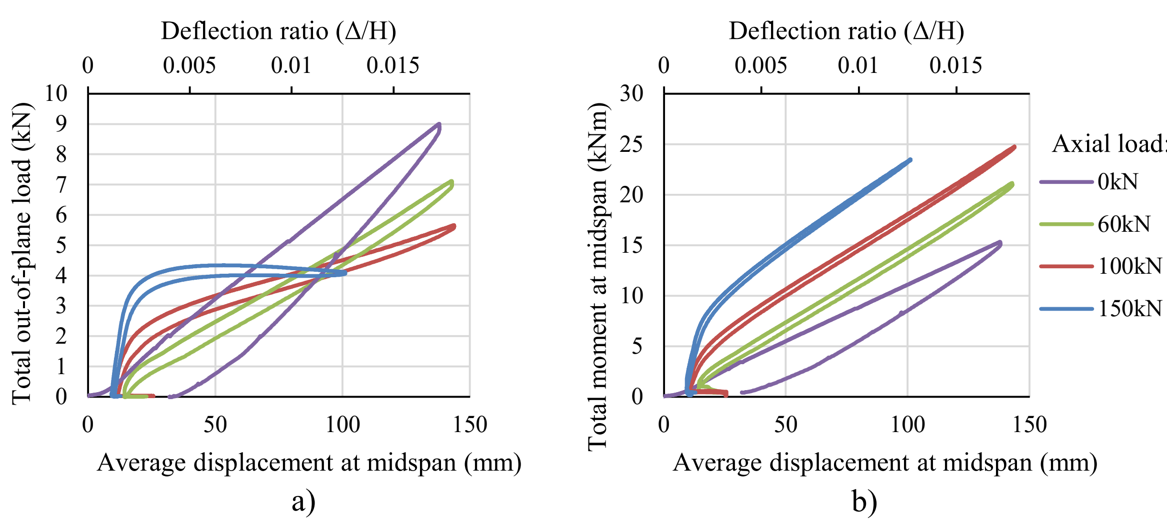


Figure 5: Test results of Wall S1 at various axial loads: a) load-displacement; and b) moment-displacement

As the wall was loaded out-of-plane under displacement control, both the out-of-plane moment and out-of-plane load increased; however, when the axial load of 150kN was applied, the out-of-plane load began to decrease after a midspan displacement of approximately 60mm. This behaviour was due to the incremental increase in applied moment due to P-Δ effects being larger than the incremental increase in moment resistance due to elastic curvature (elastic buckling). The onset of this behaviour coincided with the displacement of the wall approaching twice the kern eccentricity.

When the wall was loaded beyond its yield point under an applied axial load of 60kN, the out-of-plane resistance began to decrease after the onset of yielding in the reinforcing bars, as demonstrated in Figure 6 a). However, the total moment resistance continued to increase until the test was halted when the out-of-plane displacement exceeded twice the yield displacement, as shown in Figure 6 b). This increase in moment resistance was most likely due to strain hardening in the reinforcing bars.

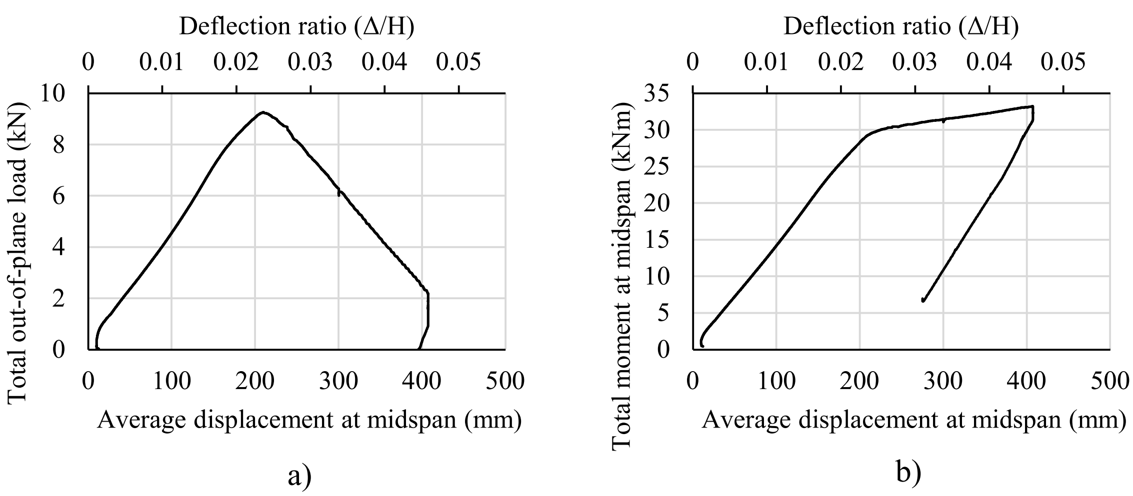


Figure 6: Response of Wall S1 at 60kN of axial load: a) load-displacement; and b) moment-displacement

DISCUSSION

Although the wall did not recover completely between loading cycles in the elastic range (the out-of-plane displacements did not return to the starting location), the strain in the reinforcing bars followed a linear path on the loading and recovery branches. Visible damage to the wall during testing was restricted to horizontal cracks which developed along the horizontal mortar joints near the midspan as the wall was displaced. These cracks opened to approximately 5mm in width as the wall reached its maximum displacement, as shown in Figure 7. The wall maintained sufficient structural integrity and was removed from the test frame in one piece following the test.

Figure 7: Wall S1 at maximum displacement with mortar joint cracking at midspan

CONCLUSIONS

A loading frame was designed and constructed to test 8m-tall, reinforced masonry walls in combined axial and out-of-plane loading conditions. Cyclic testing on a partially grouted reinforced masonry wall exhibited increasing moment resistance and decreasing out-of-plane load resistance with increasing axial loads. When no axial load was applied, the total out-of-plane load resistance reached 9.2kN. The out-of-plane elastic flexural response of the wall was recorded under superimposed axial loading up to 150kN (14.7% of $f'_m A_e$). The maximum moment resistance was achieved when the wall was loaded beyond its yielding point, while 60kN of axial load was applied; at a maximum deflection ratio of 4.6%, the total moment resistance of the wall was 33kNm. The results from this test series will be used to assess the performance of current Canadian masonry design standards for slender masonry walls, and to compare the behaviour of walls with conventional embedded reinforcement and NSM reinforcement.

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