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Novel Panel System for Concrete Masonry Walls

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ABSTRACT

Masonry is one of the oldest materials that humans use for construction. It is durable, as seen on ancient structures built thousands of years ago, yet still in excellent shape. Recently, masonry walls have struggled to be competitive among other construction materials such as precast concrete, tilt-up walls, timber, etc. This is mainly due to construction practices and the lack of a standardized modular masonry system that prevents offsite construction. In this paper, new construction methods for concrete masonry walls are proposed. These methods are based on building partially grouted masonry panels that can be built onsite or offsite, then transported and assembled on the site. The methods commonly use a restrained unbonded post-tensioned (UPT) threaded bar to join panels. A full-scale experimental program campaign at the University of Alberta (UOA) is currently undergoing to test the proposed methods. Numerical models were developed before the experimental investigation to assess the behaviour of such techniques under out-of-plane loading. Bare joints, connecting panels reinforcement, and grouting joints are the three types of panel connections proposed here. The influences of the magnitude of prestressing and lateral restraints stiffness are also studied. The results show that the proposed approaches are comparable to traditionally constructed walls with improved serviceability. Also, because of the relative ease of construction and improved post-cracking behaviour, connecting panel reinforcement is the preferred method. Whereas the increasing level of prestressing enhances service conditions but leads to premature failure. Also, lateral restraints with high stiffness, such as grout or steel, are essential to enhance post-cracking behaviour.

KEYWORDS

Masonry Walls; Concrete Masonry Panels; Post-tensioning and Panels connection

INTRODUCTION

Masonry is one of the oldest building materials known to humanity. It has proven to be a long-lasting material, as seen by ancient constructions still in use today. The ancient use of masonry was not in a specific region only but worldwide. For example, The Great Pyramids of Egypt, the Great Wall of China, and the Colosseum in Rome were built 4600, 2300, and 1952 years ago, respectively. These facts prove the ability of masonry structures to survive through decades without losing their structural or architectural nature. However, masonry did not evolve rapidly enough to compete with other, more recent materials such as precast concrete, timber, etc. Masonry construction requires certified masons to lay blocks in a specific pattern using mortar and grout, consuming more construction time than other alternatives. Also, this repetitive procedure, in addition to blocks' weight, causes masons fatigue and may lead to serious injury. Mortar and grout quality is subjected to masons without much supervision from engineers.

The proposed new construction methods for masonry walls facilitate and accelerate the construction process. The goal of this study is to discretize masonry walls into prefabricated panels that can be built offsite (factories, yards) or onsite and then assembled on the site. This is beneficial for projects with tight schedules and sites with small spaces that cannot store materials. Since the prefabricated masonry panels can be built in closed areas, the work can continue under severe weather conditions for 24 hours. Furthermore, the panelization of masonry walls facilitates using automation and robotics to get the work done and reduce masons' efforts and potential injuries. In addition, working in a factory provides a safer working environment for masons and allows for the construction of panels in a more controlled manner, resulting in high-quality panels. To make it easy for contractors to adopt the proposed methods in this study, the panels are built using available commercial concrete masonry units in a running bond pattern. The main challenge is to assemble these segments on top of each other, forming the whole wall as if it was built conventionally.

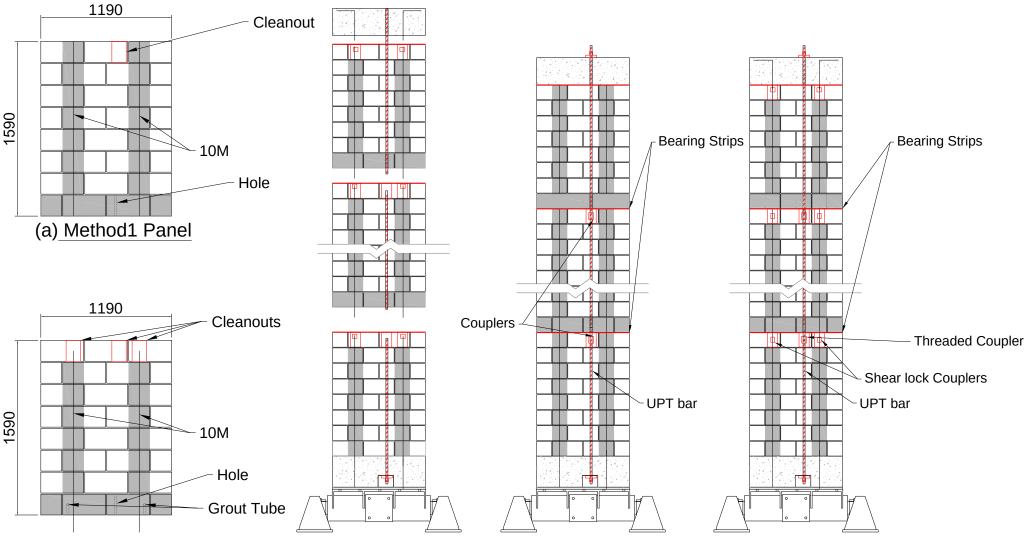
This paper has eight sections: 1) the introduction part which is discussed in previous paragraphs, 2) a brief literature review, 3) a detailed explanation of the proposed methods, 4) a description of the experimental setup, 5) details of the numerical models and verification, 6) results and discussion, 7) conclusion, and finally 8) the acknowledgement part.

LITERATURE REVIEW

Few studies have been conducted on prefabricated masonry. Braun et al. (2010) proposed two footing connections for prefabricated masonry panels and tested them experimentally for in-plane loading. Zhang et al.(2020) conducted a lateral loading experimental study on prefabricated masonry panels with vertical connections that consist of in-place grouting for a reinforcement cage placed between panels. Results showed that this system has greater ductility than conventional walls. Xu et al. (2018) proposed hollow concrete masonry panels connected to the site footings using dowels and grouting. The in-plane lateral load testing showed very similar results to conventionally built walls. Some studies have been conducted on post-tensioned ungrouted masonry walls (Bean Popehn et al., 2007; Souza & Parsekian, 2009; Ota, 2011; Miranda et al., 2018). These studies reported the feasibility of using such systems as it increases the wall's elastic range with reasonable ductility. There is a noticeable gap in research regarding testing out the plane response of masonry walls consisting of multiple panels. This paper introduces a preliminary numerical analysis of such systems prior to the full-scale experimental test.

NEW CONSTRUCTION METHODS

The new construction methods are illustrated in Fig. 1. To keep the running bond pattern in all rows, an even number of courses should be chosen. The height of the panels was set to be eight courses to allow for construction without the use of scaffolding. The panels could be built in any width depending on the feasibility of transportation. This width also could be chosen to represent vertical construction joints between panels. An 1190 mm width is chosen in this study to fit the experimental setup, which will be briefly discussed in the next section. The panels have two reinforced grouted cells to maintain panels integrity during transportation and assembling. Two 10M bars were selected for this purpose since this is the smallest bar size available in the market, and it may be only needed for segment handling. Bond beams are used at the beginning of each segment to facilitate segment lifting. Also, besides the original purpose of using bond beams in conventional construction, they are also used to restrain the UPT bars. Restraining the UPT bars from moving is essential to have stable post-cracking behaviour (Bean Popehn et al., 2007). Three connections were proposed: bare joints (M1), connecting panels' reinforcement (M2), and grouting joints(M3). In M1 the panels are built by grouting the first inner cells in the eight courses, as shown in Fig. 1a while leaving the last course ungrouted for M2 and M3 methods, as depicted in Fig. 1b. In all methods, panels are assembled on top of each other, and a threaded UPT bar is inserted at a segmental level and connected using couplers through the cleanouts openings. Since the UPT bars are unbonded, rotating them to install the couplers is sufficient. The reason for using additional cleanouts in M2 and M3, as shown in Fig. 1b, is that these cleanouts are used to install couplers to connect panels' reinforcement. Since the panels' reinforcement is bonded to the panels and can not be rotated to install couplers, shear locking couplers could be used. M3 uses in-place casting grout for the connection zone to ensure the continuity of both grout and panels' reinforcement. Since it would be challenging to have a mortar layer between various segments, bearing strips could be used to avoid uneven surfaces and stress concentration due to projecting parts of the blocks, as shown in Fig. 1d,c. The difficulty of panel assembling is increasing from M1 to M3, so these methods are modelled to see if it is worthy of increasing installation difficulty or not.



(a) Method1 Panel

(b) Method 2 & 3 Panel (c) Panels Assembling (d) Method 1 Wall (e) Method 2 & 3 Wall

Figure 1. Panels details and assembling procedure

EXPERIMENTAL SETUP

The new construction methods will be tested in the current undergoing campaign at UOA. The test setup is similar to the one used by the ACI-SEASC Task Committee on Slender Walls (American Concrete Institute, 1982). It consists of a steel frame that acts as a rigid system for applying load. The out-of-plane load is applied by inflating an airbag between the steel frame and the wall, as shown in Fig. 2. A constant eccentric (170 mm) axial load of 15 kN is applied on the top of the wall using a water tank hanging on a cantilever arm. The bottom support was designed to simulate either a pinned, partially fixed, or fixed base condition. While the upper one was designed to represent a roller support condition as found in steel-joist roof systems. The control wall which was built conventionally has been tested, and its results are used here for verification purposes of the numerical models. More information on the test setup and the control wall can be found in (Alonso et al., 2022)

Figure 2. Experimental setup

NUMERICAL MODELS

Two-dimensional (2D) models were developed using The Open System for Earthquake Engineering Simulation (McKenna et al., 2009) software. The 2D models adopted a macro modelling approach where the masonry walls were modelled using BeamColumn elements with fiber sections. This element is a distributed plasticity element that can capture material nonlinearity along the wall height and cross-section.

Due to the lack of experimental studies conducted on the proposed method, two related experimental studies were used to verify the numerical models. The first is the control wall (Ex1) used in the current campaign at UOA (Alonso et al., 2022). While the second one (Ex2) is an ungrouted post-tensioned masonry wall which is referred as PC4-35-R in the study of (Bean Popehn et al., 2007). Since the nature of these studies was different, two numerical approaches were used for modelling. Ex1 was a partially grouted reinforced concrete masonry wall with an effective height of 8.83 m and a width of 1.190 m, built using 20 cm concrete blocks. Ex2 walls were constructed using ungrouted 10 cm concrete blocks with an effective height of 3.54 m and 0.8 m wide. Figure 3 depicts the details of the walls.

The equivalent section for the wall cross-section was used in the model, as shown in Fig. 3. For Ex1, reinforcing bars were defined as a fiber with bars properties in the equivalent fiber section.

While for Ex2, the cross-section was defined using only two face shells since they are the only mortared part, and the UPT bars were defined as inelastic truss elements. Since UPT bars exert lateral and vertical forces on masonry units during deformation (Miranda et al., 2018), two node-link elements were used to define the lateral restraint for the UPT bars. These elements have lateral, vertical, and rotational springs. The stiffness of the lateral and vertical springs was chosen based on model calibration, while the rotational spring stiffness was defined with a negligible value. Rigid elements were used to model anchorage zones for unbonded bars in Ex2. Material properties were used as reported in the experimental studies. The Concrete06 material model was selected to define the stress-strain curve of masonry, and Steel02 was adopted for bars. The prestressing force was applied using the initial strain material model combined with Steel02.

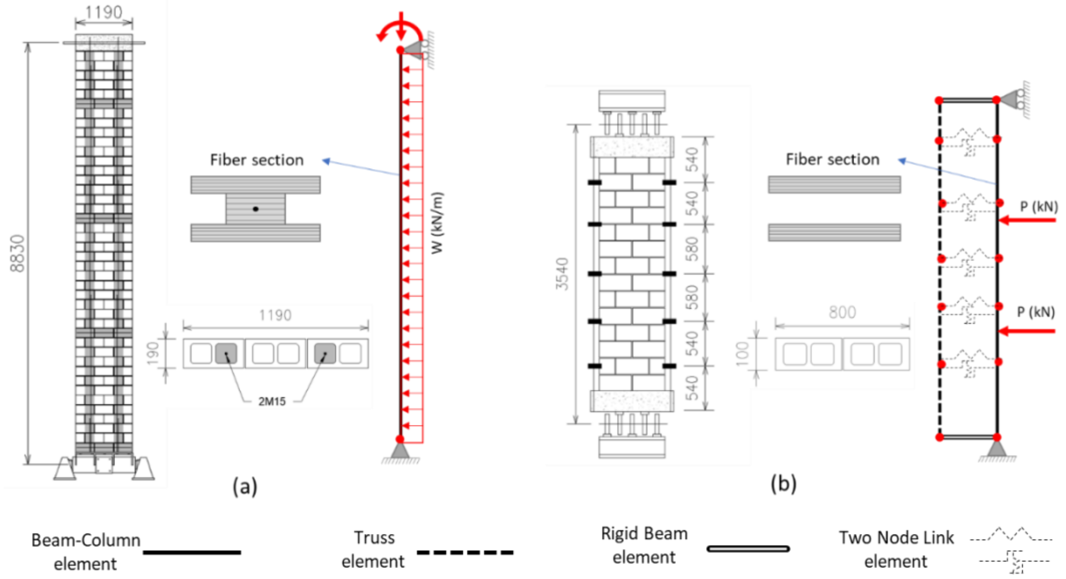
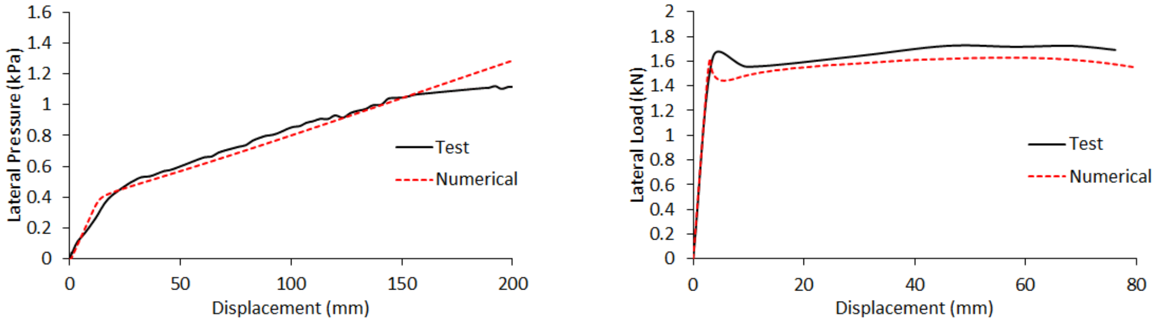


Figure 3. Details of the numerical model and experimental specimens. a) Ex1 (Alonso et al., 2022), b) Ex2 (Bean Popehn et al., 2007) (all dimensions in mm)

Figure 4 shows the results of the numerical models compared to the experimental. The models can capture the walls' overall behaviour, including the elastic and post-cracking stages. Therefore the concepts discussed in the development of these models were combined to develop models for the proposed construction methods mentioned in this paper. An additional element was needed to model the interface between panels. The sectional zerolength element was used between segments. In M1, this section was unreinforced with zero tensile strength for masonry. While for M2, this section was modified by adding reinforcements. Since in M3 both grout and reinforcement are continuous, the wall was modelled like the Ex1 model in addition to adding the prestressed truss elements. All details of the models are shown in Fig. 5. Since this type of wall has not been experimentally tested in previous studies, it is worth noting that this modelling approach may not be completely accurate. So, it will be modified and calibrated when the experimental test results are ready. The material properties and wall dimensions were like the Ex1 specimen, so the model consists of 5 panels. The UPT bar was selected to be 20 mm in diameter with 900 MPa for yield strength. Models matrix are shown in table 1. The reference lateral stiffness value was selected to be 175 kN/m^2, which was recommended by (Bean Popehn et al., 2011) for masonry or grout restraints, while five times (5k) of this value and its half (0.5k) represent steel plates and wood restrainers, respectively.



(a) (b)

Figure 4. Numerical models validation a) Ex1 , b) Ex2

Table 1. Models designation

Model	Construction Method	Stiffness (k)	Presstressing Level (% Fy)
M1-K-P30	1	1	30
M2-K-P30	2	1	30
M3-K-P30	3	1	30
M2-K-P40	2	1	40
M2-K-P50	2	1	50
M2-K-P60	2	1	60
M2-K-P70	2	1	70
M2-0.5K-P30	2	0.5	30
M2-2K-P70	2	2	30
M2-5K-P70	2	5	30

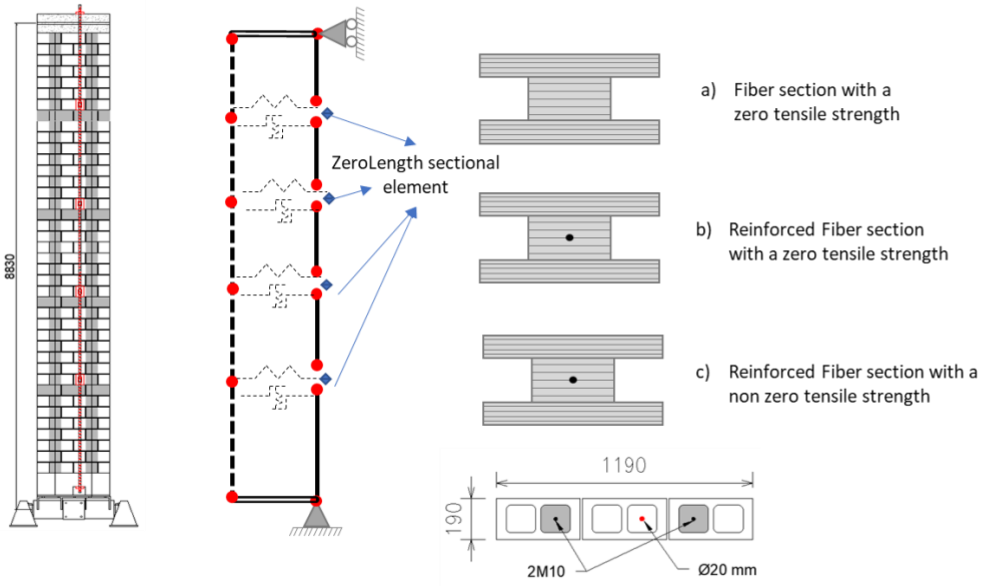
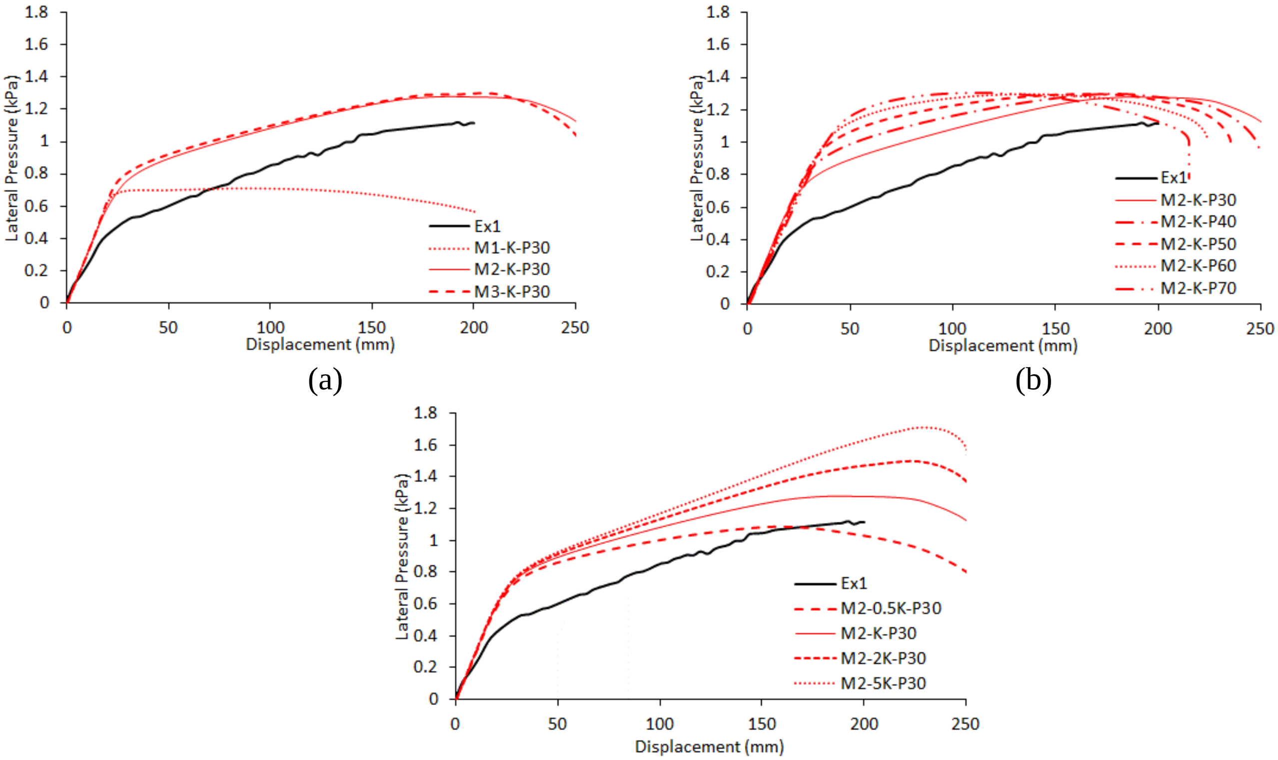


Figure 5. Details of the numerical model for the proposed construction methods. a) M1, b) M2, c) M3

RESULTS AND DISCUSSION

The control wall (Ex1) results were used to compare with the proposed methods. Post-tensioning increased elastic range and enhanced serviceability conditions regardless of the proposed construction method. The serviceability limit associated with Ex1 is 48 mm *(h/180)* as according to the Candian Standards Association (CSA) (2019). The proposed methods increased the pressure associated with the service displacement by 16% for M1, and 50 % for both M2 and M3 as shown in Fig. 6a. M2 seems to be the best option as it maintained pressure increasing after cracking. Moreover, failure occurred at a relatively high drift ratio (Δ/h=2.27%) with an increase of peak pressure by 18% of the Ex1. This is attributed to the contribution of panels' reinforcement to resist the out-of-plane moments. On the other hand, grouting in the M3 case has a negligible effect on the behaviour since grouting has low tensile strength. Based on these results, M2 was adopted for studying the other parameters.

As indicated in Fig. 6b, increasing prestressing levels improves serviceability conditions. Applying prestressing levels ranging from 30% to 70% of bar yielding stress increases pressures associated with the serviceability limit from 50% to 103%. However, there was no gain with the increasing prestressing level after the elastic limit, as the ultimate capacity did not change. These results agreed with the findings of (Graham & Page, 1994). In contrast, failure occurs earlier for higher post-tensioning levels due to increased compressive strains on masonry. So increasing post-tensioning level is recommended only in buildings with expensive finishes that require very low deformations under higher pressures. Otherwise, using lower values is recommended to prevent sudden failures. Figure 6c shows that lateral restraints stiffness is a critical parameter. The use of weak restrainers such as wood decreases peak capacity even more than the non-post-tensioned walls. In contrast, using grout or steel restrainers increases capacity due to maintaining the depth of the post-tensioning bar to the maximum compression fiber.



(a) (b)

(c)

Figure 6. Effect of variable parameters: a) Construction Methods, b) Lateral stiffness, c) Post-tensioning level

CONCLUSION

New construction methods for concrete masonry walls were proposed in this paper. The new methods adopt a construction of masonry panels and then assemble them on the site on top of each other using an unbonded threaded post-tensioning (UPT) bar. Three connections were proposed: bare joints, connecting panels' reinforcement, and grouting joints. Numerical models were developed to assess these proposals. Based on the preliminary numerical analysis, connecting panels' reinforcement is recommended since it does not require much site work. At the same time, it enhances both pre and post-cracking behaviour. Also, using bond beams as restrainers for the UPT bar is essential for maintaining UPT bar depth to the maximum compression fiber and enhancing post-cracking behaviour. Finally, Increasing the post-tensioning level is recommended for buildings with expensive finishes requiring minimal deflection. Still, care must be taken since it causes failure under lower displacement without gaining peak capacity. The numerical model results indicate improved masonry wall performance using the proposed methods. In addition to that, building the panels in a more controlled environment like factories without using scaffolds will enhance the quality of the panels, reduce fatigue and injuries to masons, increase productivity, and speed up the construction process. Some of the limitations of the proposed methods are that no previous experimental studies were done to validate the numerical models. Also, there is no direct way to calculate how gain in the construction time will be. Some issues may appear during assembling the panels such as misalignment and the need for bracing for all panels until the construction completion. So, as a future research, a full-scale experimental study on these methods will be conducted to tackle all aspects of the proposed methods.

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