Finite element analysis of post-tensioned brick masonry walls

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1. Introduction

Many studies reported that unreinforced masonry structures have experienced severe damage due to moderate to large earthquake ground motions. Recent research has shown that using *unbonded post-tensioning* as a retrofitting measure for a structural element can enhance the performance of the retrofitted element. Unbonded post-tensioning structural element demonstrates rocking and self-centering behavior provided by the restoring force of the post-tensioning force. This self-centering reduces residual displacement of the rocking element.

Rosenboom and Kowalsky (2003) tested *clay brick* post-tensioned masonry walls and developed a monotonic force-displacement analysis procedure. However, cyclic behavior of masonry material was not considered. Wight and Ingham (2008) carried out finite-element (FE) analysis using ABAQUS to verify the current MSJC (2008) code equations for unbonded post-tensioned *concrete masonry* walls. The FE model predicted maximum strength of the wall accurately but, failed to capture the post-peak behavior due to shortcomings in the stability of the FE model.

The objective of the present study is to propose a numerical model able to capture the behavior of a post-tensioned wall under *in-plane cyclic load.* The model was developed using the software platform LS-DYNA. The numerical results were validated with experiments from the literature. The model was then used to assess the effect of the post-tensioning tendon spacing on the behavior of a typical post-tensioned wall.

2. Finite-element modeling

For the post-tensioned masonry shear wall, masonry was modeled as a homogenous material. The important details of the unbonded post-tensioned masonry wall were considered, including vertical holes where the tendons would be placed and placing of the tendons. The interface joints between the masonry wall and the reinforced concrete (RC) foundation as well as between the masonry wall and the RC cap beam were a) allowed to open under tensile forces, b) not allowed to penetrate under compression, and c) had a horizontal coefficient of friction of 0.5.

3. Validation of the model

An unbonded post-tensioned brick masonry wall (1.2 m x 2.1 m x 0.3 m) tested by Rosenboom and Kowalsky (2003) was used for validation of the FE model. Ewing and Kowalsky (2004) experimentally determined the characteristics of the material used for the construction of this wall. *CONCRETE_ DAMAGE_REL3* model was used for material model of masonry. Properties of grouted double wythes masonry prism tested were used for the material model of masonry (Table 1). The elastic modulus of masonry E_m is calculated from $E_m = 700 f'_m$, where f'_m is compressive strength of masonry prism (MSJC 2008).

Table 1 Properties of double wythes masonry prism.

f'_m (MPa)	$\varepsilon_{f'm}$	$\varepsilon_{0.5f'm}$	$\varepsilon_{0.2f'm}$
25.90	0.0017	0.0050	0.0087

Table 2 Properties of post-tensioning steel.

E_{ps} (GPa)	A_{ps} (mm^2)	f_{py} (MPa)	ε_{py}	f_{pu} (MPa)	ε_{pu}
205.0	550.0	890.0	0.0043	1030.0	0.05

PLASTIC_KINEMATIC model was used for the post-tensioning steel and the properties of the post-tensioning steel are given in Table 2.

The proposed finite-element model predicted maximum force response of the wall with sufficient accuracy and captured the behavior of the wall well under cyclic load, even after strength degradation occurs. Damage to the wall was restricted to the toe regions of the wall, similar to the experiment. Recorded maximum force response of the wall was 330 kN in the test and the analysis result was 326 kN. Fig. 1 shows force-displacement histories from the experiment and analysis.

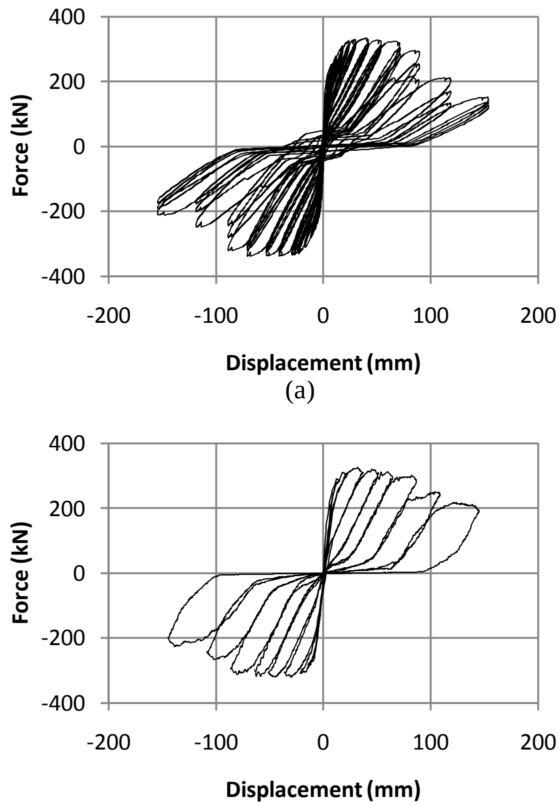

Fig. 1 Force-displacement history: (a) experiment; (b) FEM.

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4. Configuration of wall and spacing

To evaluate the effects of post-tensioning tendon spacing on the behavior of the wall, a large wall (6 m x 7.98 m x 0.3 m) was considered. Double wythes clay brick masonry wall with a grouted cavity was considered (Fig. 2). Four tendons were used for each group since the tendon diameter required for using one tendon was too large. The post-tensioning force ratio f_m/f'_m was 0.1 in all cases and corresponding total post-tensioning force P was calculated as 6,224 kN. To keep this P, diameters of post-tensioning tendons were adjusted for different cases of spacing. The post-tensioning stress was decided as 67% of yield stress of the post-tensioning steel f'_y. Table 3 shows the details of walls with different tendon spacing.

Table 3 Spacing and diameter of tendons.

Wall	No. of tendons	Spacing d (m)	PT tendons φ (mm)
W1-T3	12	3.81	33.2
W1-T4	16	2.54	28.6
W1-T5	20	1.9	25.6
W1-T7	28	1.27	21.7
W1-T9	36	0.95	19.1

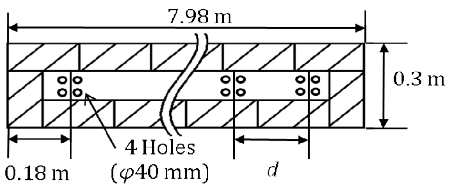

Fig. 2 Double wythes clay brick masonry wall with grouted cavity (not to scale).

5. Effects of tendon spacing

Before performing analysis, nominal strength V_f of each wall was calculated using MSJC (2008). The average nominal strength of the walls was 5277 kN. The calculated nominal strengths of the walls using MSJC showed that wall strengths are slightly dependent on the spacing between the tendons. However, the results of the FE model showed that for tendon spacing greater than 1.9 m, the strength of the walls increased with decreasing the tendon spacing. For tendon spacing smaller than 1.9 m, the strength of the walls changed slightly. Force response versus displacement for each wall under push over load is presented in Fig. 3. In addition, the average prediction using MSJC (2008) is presented on the same figure. Behavior of W1-T3 which has the largest tendon spacing was undesirable. Failure of the masonry was observed at the top of the wall near post-tensioning tendon location due to the stress concentration. W1-T4 to W1-T9 showed similar behavior in developing vertical cracks along the tendons and uplifting. After vertical splitting reached the bottom of the wall, walls started to uplift and vertical cracks along the tendons were developed from bottom to top of the wall. To improve the undesirable behavior of W1-T3 which has the largest tendon spacing, horizontal steel reinforcement rebar were placed (E_s = 200 GPa, A_s = 198 mm^2 and f_s = 420 MPa). The maximum force response and ductility of the wall increased when the horizontal reinforcement ratio was increased from 0% to 0.1% and 0.5%.

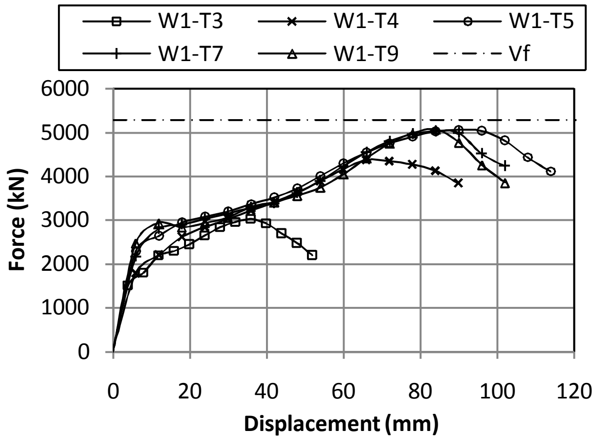

Fig. 3 Force-displacement curves for different tendon spacing.

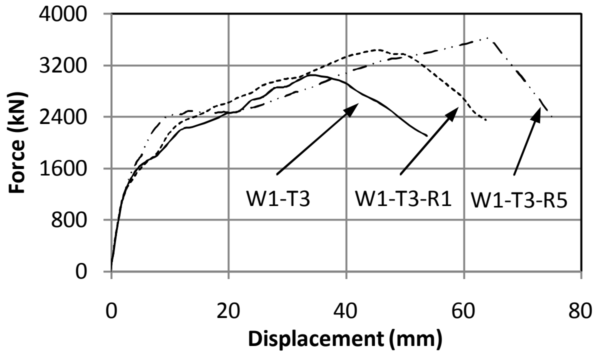

Fig. 4 Force-displacement curves for W1-T3 with different reinforcement ratios.

By increasing the horizontal reinforcement ratio from 0% to 0.5%, the strength of the wall increased by 18.8% as shown in Fig. 4.

6. Summary and Conclusions

In this study, the behavior of unbonded post-tensioned clay brick masonry walls and the effects of post-tensioning tendon spacing were studied using finite-element analyses. Walls with different tendon spacing were configured and analyzed by the proposed FE model. Responses of the walls were predicted using the equation provided by MSJC (2008). From the results of the finite element analyses, for tendon spacing greater than 1.9 m, the strength of the wall increased when the tendon spacing were decreased. For smaller tendon spacing, there was no significant effect on the strength of the wall. Placing horizontal reinforcement rebar increased both the strength and ductility of the specimens.

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