OUT-OF-PLANE LOADING TESTS ON MASONRY WALLS STRENGTHENED WITH RESTRAINING AXIAL ELONGATION

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ABSTRACT

This paper proposes a new out-of-plane strengthening method for masonry walls with passive compression, which is applied to wall cross-section by restraining axial deformation with steel rods. The strengthening mechanism was introduced and implemented to verify its availability. In this study, a new out-of-plane loading system was also developed to apply uniform distributed loads to masonry walls by a rubber airbag. The test system was developed aiming at obtaining basic mechanical characteristics of simply supported masonry walls in the out-of-plane direction. Three kinds of structural tests were conducted (a) to verify the developed loading system by using an aluminum plate specimen, (b) to evaluate the out-of-plane performance of a brick wall specimen which was cut off from an earthquake-damaged building in Indonesia, and (c) to compare the performance of brick wall specimens with/without the proposed strengthening. Consequently, the test results clarified (a) good agreements between the experimental measurements and theoretical estimations, (b) vulnerability of the brick wall, and (c) significant improvements of the out-of-plane performance of walls by the proposed method.

Keywords: Brick wall, Performance evaluation, Retrofit, Rubber airbag, Uniform distributed load.

1. INTRODUCTION

Unreinforced masonry (URM) structures are commonly used in building construction throughout the world. Brick masonry is still the most popular building component in developing countries due to its easy handling and cost-effectiveness. Unfortunately, however, no reinforcement is provided in old existing masonry buildings and non-structural masonry components such as exterior/partition walls in developing countries. Such walls are significantly vulnerable to out-of-plane loads which may be caused by seismic action, high speed wind, or blast explosion.

In this study, a new static loading system was developed with a rubber airbag, and implemented for evaluating out-of-plane performance of URM walls. This kind of test system has been adopted in

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the past studies (Paulopereira et al. 2011 and Ismail et al. 2009). However, verification for appropriate loading was not provided in those studies. Therefore, in this study, a verification test of the developed system was conducted to obtain more reliable experimental data. Then, an application test was conducted to evaluate the out-of-plane performance of a brick wall specimen which was actually placed in an earthquake-damaged building in Indonesia.

There have been numerous efforts to upgrade the out-of-plane performance of URM walls and to develop strengthening schemes. Typical techniques for retrofitting existing URM buildings were categorized into five methods: surface treatment, grout and epoxy injection, external reinforcement, confining by R/C tie columns, and post-tensioning (ElGawady et al. 2004). The study focuses on the post-tensioning which can effectively provide structural stability for URM walls (Ismail et al. 2009). However, it generally requires high construction cost, high skills in construction, and maintenance even after constructions, which are not suitable for application in developing countries. Therefore, this study proposes a new post-tensioning system which can reduce specific difficulties in the conventional system.

2. PROPOSAL OF STRENGTHENING METHOD

URM walls are fragile in the out-of-plane direction because of low tensile/bond strength of masonry units/adhesive. Therefore, pre-stressing or post-tensioning is effective to improve the out-of-plane performance (Ismail et al. 2009). On the other hand, masonry units and typical adhesive of cement mortar can resist high compression. Such characteristics cause geometric axial elongation of walls with lateral deformation under out-of-plane loads, as illustrated in Figure 1(a).

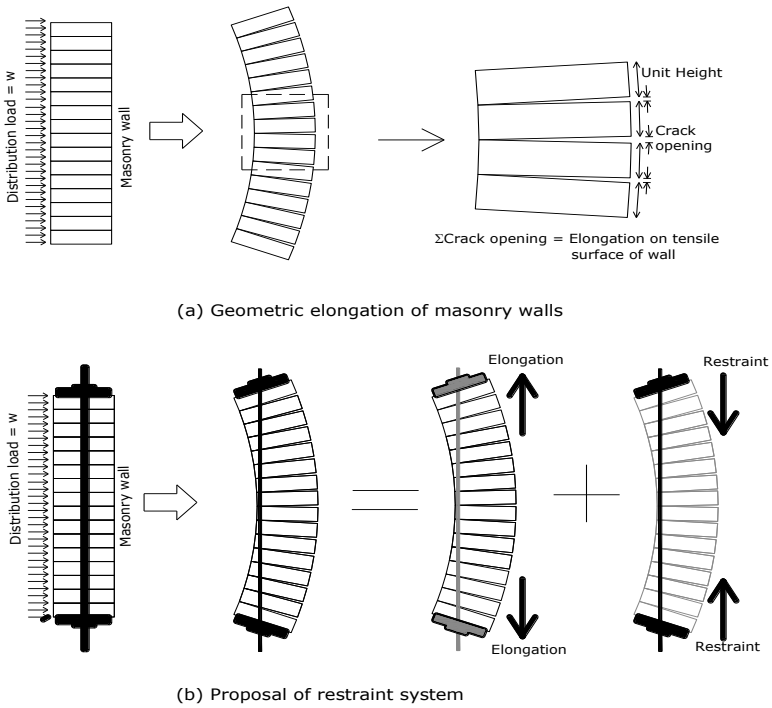
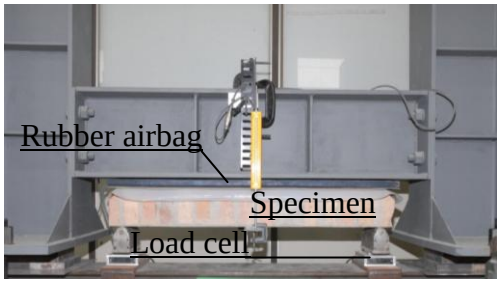


Figure 1: Concept of retrofitting.

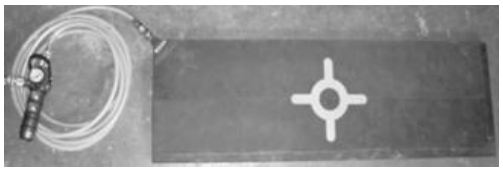
Focusing on such specific characteristics of URM walls, this study proposes a new strengthening system which utilizes the geometric axial elongation above. The strengthening is implemented by providing outer steel rods which restrain the geometric elongation and passively generate axial compression on the wall cross-section, as shown in Figure 1(b). Therefore, no previous stress is necessarily provided for the wall cross-section as well as restraint rods, which results in preventing/reducing complexity in construction, long-term pre-stress loss, and maintenance after construction.

3. DEVELOPMENT OF LOADING SYSTEM

Photo 1 shows an out-of-plane loading system for URM walls developed in this study. Design details of the system can be referred to Figure 2. A rubber bag jack (airbag), as shown in Photo 1, was adopted as a generator for uniform distributed loads normal to wall surfaces. Internal pressure in the airbag was generated by a widely used air compressor. The airbag was placed between the reaction frame, which consisted of H-shaped steel and was anchored on a reaction floor, and prospective specimens, as shown in Photo 1 and Figure 2. Specimens were inserted below the airbag and simply supported in the system. Applied loads to specimens which resulted from the airbag were measured by load cells implemented under the roller supports.



a) Front view



b) Implemented airbag

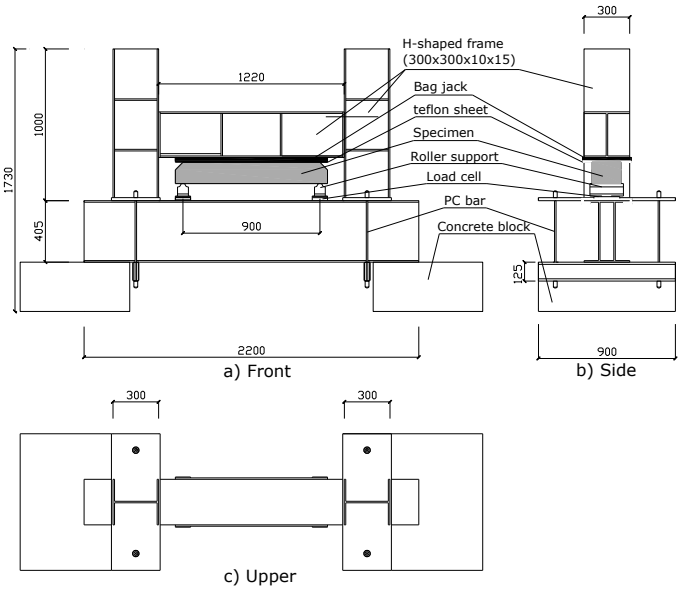


Photo 1: Out-of-plane loading system. **Figure 2: Details of out-of-plane loading system.**

4. VERIFICATION TEST OF LOADING SYSTEM

4.1. Specimen

An aluminum plate specimen was prepared for a verification test of out-of-plane loading system. In particular, appropriate action of uniform distributed loads was verified through comparing

experimental results with theoretical calculations. The dimensions of specimen were 190 mm x 10 mm for a cross section with a length of 900 mm. The yield strength and Young's modulus of aluminum used for the specimen were 98.0 N/mm^2 and 6.26 x 10^4 N/mm^2, respectively. Figure 3 illustrates locations of strain gauges/displacement transducers installed on the bottom surface/side faces of the specimen. In particular, output of each strain gauge means an extreme fiber strain on the tension side when loads were applied by the airbag.

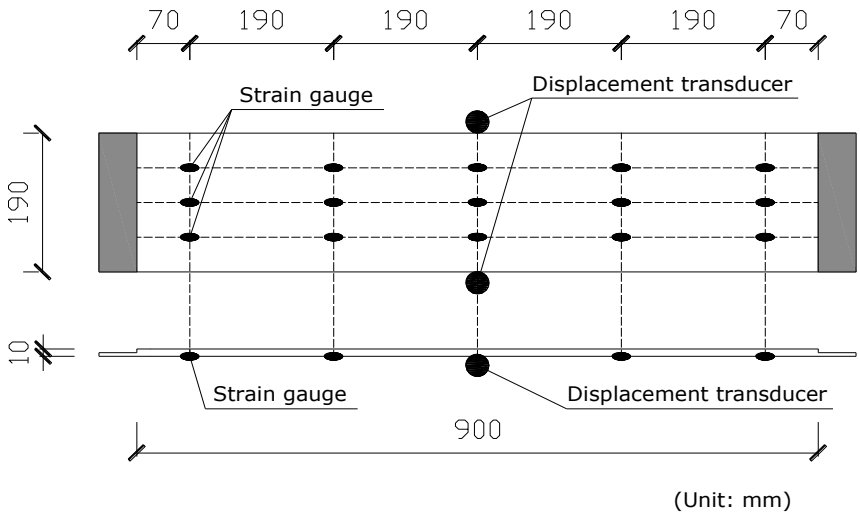


Figure 3: Measurements location on/beside the elastic specimen.

4.2. Experimental results and discussions

Static monotonic loading was applied to the elastic specimen to compare the experimental results with theoretical calculations. In the following comparisons, a theoretical vertical deformation δ at the middle span and strain ε_x along the x-axis were obtained by:

[δ at the middle span]

$$\delta = \frac{5 \cdot w \cdot l^4}{384 \cdot E \cdot I} = \frac{5 \cdot P \cdot l^3}{384 \cdot E \cdot I} \tag{1}$$

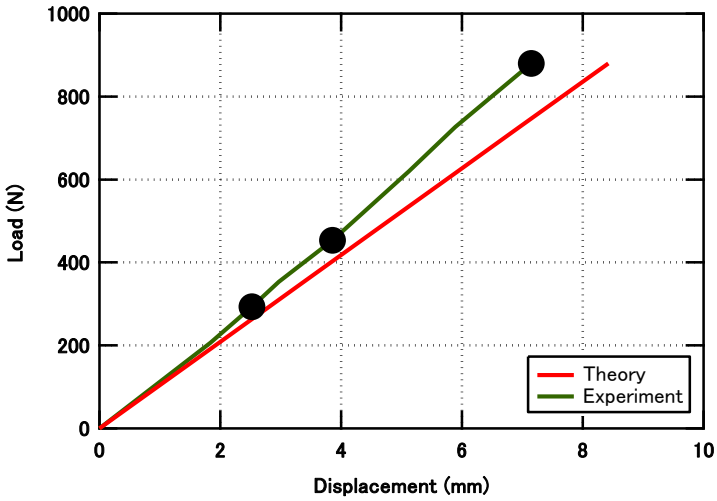
where, w: distribution load, l: span length, E: Young's modulus, I: moment of inertia, P: total vertical load (= wl)

[ε_x along the x-axis]

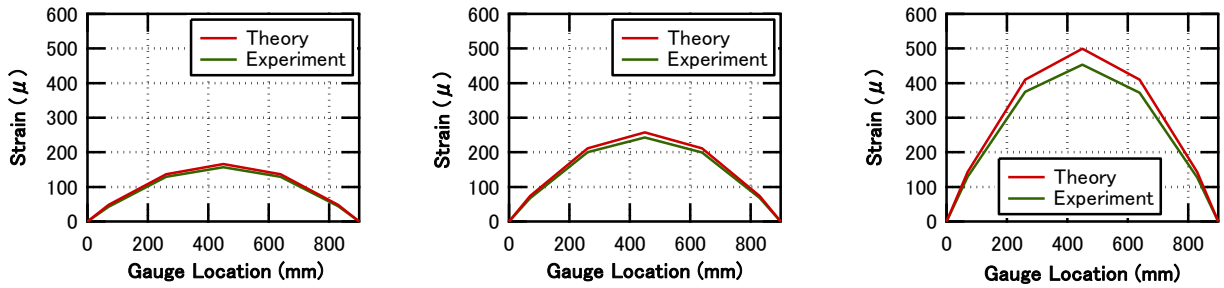
$$\varepsilon_x = \frac{M_x}{ZE}, \quad where \quad M_x = \frac{wl}{2}x - wx\frac{x}{2} = \frac{1}{2}\left(wlx - wx^2\right)$$
$$So, \quad \varepsilon_x = \frac{\left(wlx - wx^2\right)}{2ZE} = \frac{\left(Px - \frac{P}{l}x^2\right)}{2ZE} \tag{2}$$

where, M_x: moment along the x-axis, Z: modulus of section.

Figure 4a shows the relationship between applied load and vertical deformation at the middle span, where the experimental deformation is the averaged value of outputs from two transducers shown in Figure 3. Figure 4b shows a transition of the distributions of experimental strains, which represent the moment distributions, along the plate length under several loads indicated in Figure 4a. However, the experimental strain at each location means the averaged value of three measurements along the width of specimen, as shown in Figure 3. It was found that symmetric distributions were observed throughout the test. Moreover, in these figures, theoretical calculations are compared to the experimental results. Good agreements were observed between the experimental and theoretical values, which mean that the proposed out-of-plane loading system successfully subjected the specimen to uniform distributed loads.



(a) Comparison of load-deformation relationship



a) Load of 0.29 kN b) Load of 0.45 kN c) Load of 0.88 kN

(b) Comparison of strain distribution

Figure 4: Comparisons between experimental and theoretical results.

5. APPLICATION TO BRICK WALL

5.1. Specimens

An investigation was conducted on two reinforced concrete buildings in Padang, Indonesia, after the 2007 Sumatera earthquakes (Maidiawati and Sanada 2008). Brick walls were extracted from one

of the buildings and transported to Japan from Indonesia. Photo 2 shows an overall view of the building after the earthquakes, and photographs in extracting and cutting walls for the following experiment.

Three types of brick wall specimens: N-1 as a control specimen, and R-1 and R-2 as strengthened specimens, were prepared with the same dimensions of 190 mm x 140 mm x 900 mm in width x thickness x length, as shown in photo 3. Young's modulus and compressive strength in the longitudinal direction of the specimens were 634 N/mm^2 and 2.91 N/mm^2, respectively.

Photo 2: Damaged building and preparing specimens.

Photo 3: Brick wall specimens.

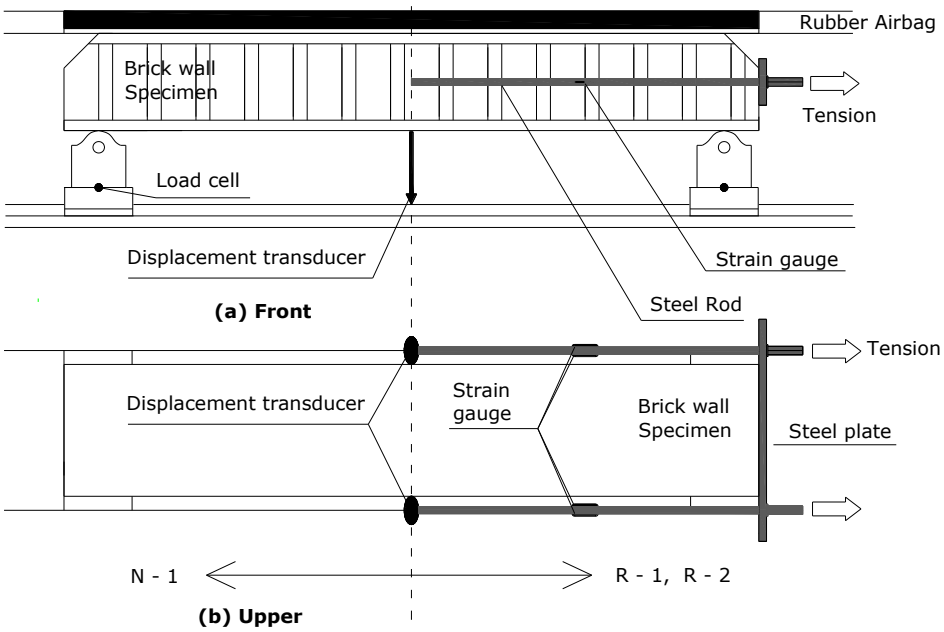
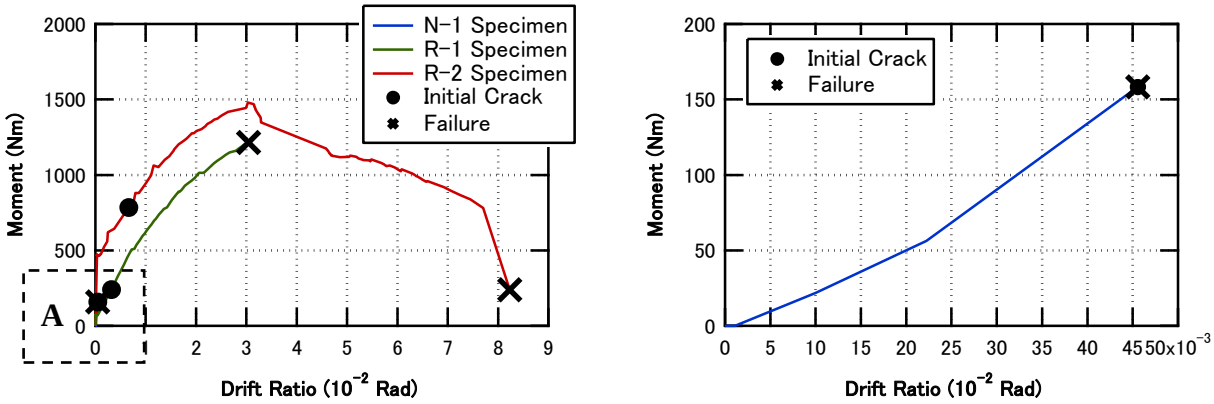


Figure 5: Brick wall test set-up.

M8 steel rods were used for restraining the wall elongation. Cross-sectional area, Young's modulus, and yield strength of the rods were 36.6 mm^2, 2.29 x 10^5 N/mm^2, and 560 N/mm^2, respectively. Steel rods were placed along the wall and fixed at the end plates which were also provided at the wall ends, as shown in Figure 5. However, an initial tensile strain of 400μ was applied only to the tensioning rods for R-2 specimen to induce an initial compression on the cross section of wall.

5.2. Experimental results and discussions

Figure 6 compares the relationships between moment and drift angle at the middle span among three specimens. However, the drift angle was evaluated dividing the vertical deformation, which was the averaged value from two transducers as shown in Figure 5, by half of the wall height. It is indicates that the N-1 specimen failed under a small moment of 158 Nm at an intial cracking, otherwise the R-1 and R-2 specimens exhibited much higher resistances even after cracking. The maximum moments of R-1 and R-2 specimens were 1.22 kNm and 1.48 kNm, respectively. Moreover, the drift angles at the maximum moments were 3.0% rad. for both of the strengthened specimens, nevertheless N-1 failed at a small drift angle of 0.05%.



(a) Comparisons among three specimens (b) Close-up of area A for N-1 specimen

Figure 6: Moment – drift angle relationship results.

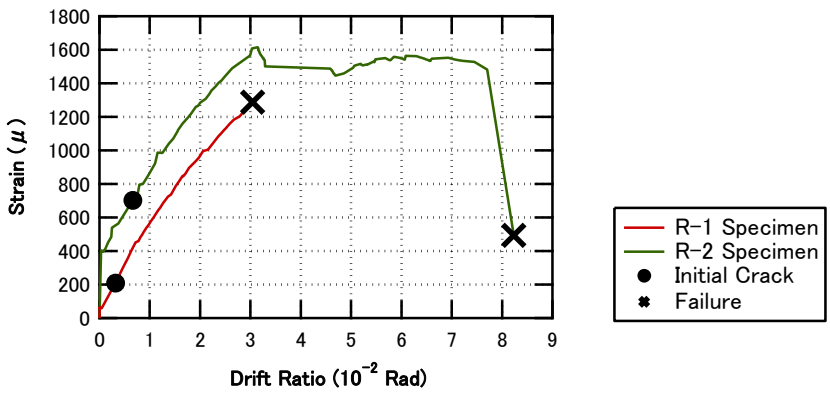


Figure 7: Strain – drift angle relationships of strengthened specimens.

Figure 7 gives the averaged strain from gauges, which were pasted on the rods of the strengthened specimens, versus drift angle relationships. Each tensile strain increased according to an increase of drift angle, which means that a higher compression acted on the cross-section under a larger drift angle. As a result, the larger resitances of R-1 and R-2 could be obtained by the proposed simple retrofit system.

6. CONCLUSIONS

- A new out-of-plane loading system was developed by using a rubber airbag for evaluating structural performance of URM walls in the out-of-plane direction.
- Uniformly distributed loads could be applied to an elastic plate, which was verified through comparing the experimental measurements and theoretical caluculations.
- A new out-of-plane strengthening method was proposed for URM walls and its strengthening mechanism was introduced.
- Effectiveness of the proposed strengthening method was verified through out-of-plane loading tests of brick wall specimens with/without strengthening.

ACKNOWLEDGMENTS

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