A NEW RETROFIT TECHNIQUE TO IMPROVE SEISMIC RESISTANCE OF MASONRY WALLS UNDER OUT-OF-PLANE LOADS

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ABSTRACT

Unreinforced Masonry (URM) walls are commonly used as interior partitions and/or exterior perimeters in building structures throughout the world. One of the most critical deficiencies of URM walls is the out-of-plane brittleness. This study proposes a new retrofit technique for improving the seismic performance of masonry walls in the out-of-plane direction. Geometric axial elongation of masonry walls under lateral deformation is focused and utilized as a source of passive compression in the proposed method. Applying tension rods to masonry walls to restrain the axial elongation, compression can be applied to wall cross-sections under lateral deformation and therefore increases the flexural strengths. The mechanism of retrofit technique above is summarized in the paper. Application tests were conducted using brick wall specimens which were actually placed in an earthquake-damaged building in Indonesia. The wall specimens strengthened/un-strengthened by the proposed method were subjected to uniform out-of-plane loads using a new loading system developed in this study. Although shaking tables are usually implemented to investigate out-of-plane performance of URM walls subjected to inertial forces normal to the surfaces, it is occasionally difficult to observe failure behavior by optical inspections in dynamic tests. Therefore, in this study, a new static loading system was also developed using a rubber airbag which was adopted as a generator of uniform distribution loads, and implemented for evaluating out-of-plane performance of the specimens. As a result of the tests, it was found that the proposed retrofit technique improved the out-of-plane performance, namely deformation capacity as well as flexural strength of the brick wall specimen.

Keywords: Brick masonry, deformation capacity, flexural strength, seismic strengthening, structural test.

1. INTRODUCTION

Masonry is one of the oldest structural systems and has been widely used over the world even after engineering materials such as concrete and steel had been introduced in construction. 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.

Therefore, there have been numerous efforts to upgrade the out-of-plane performance of masonry walls and to develop strengthening schemes. El Gawady et al. [1] reviewed typical techniques for retrofitting existing unreinforced masonry (URM) buildings. One of the retrofit techniques is post-tensioning, which can effectively provide structural stability for URM walls, as reported by e.g. Ismail et al. [2]. This system is particularly valuable when strengthening historical buildings because it can maintain exterior appearances. However, it generally requires high construction cost, high skills in construction, and maintenance even after construction, which is 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, as mentioned in the paper.

The major objectives of this study are to introduce the strengthening mechanism and to verify the proposed system through a series of laboratory tests of URM wall specimens strengthened/un-strengthened by the system.

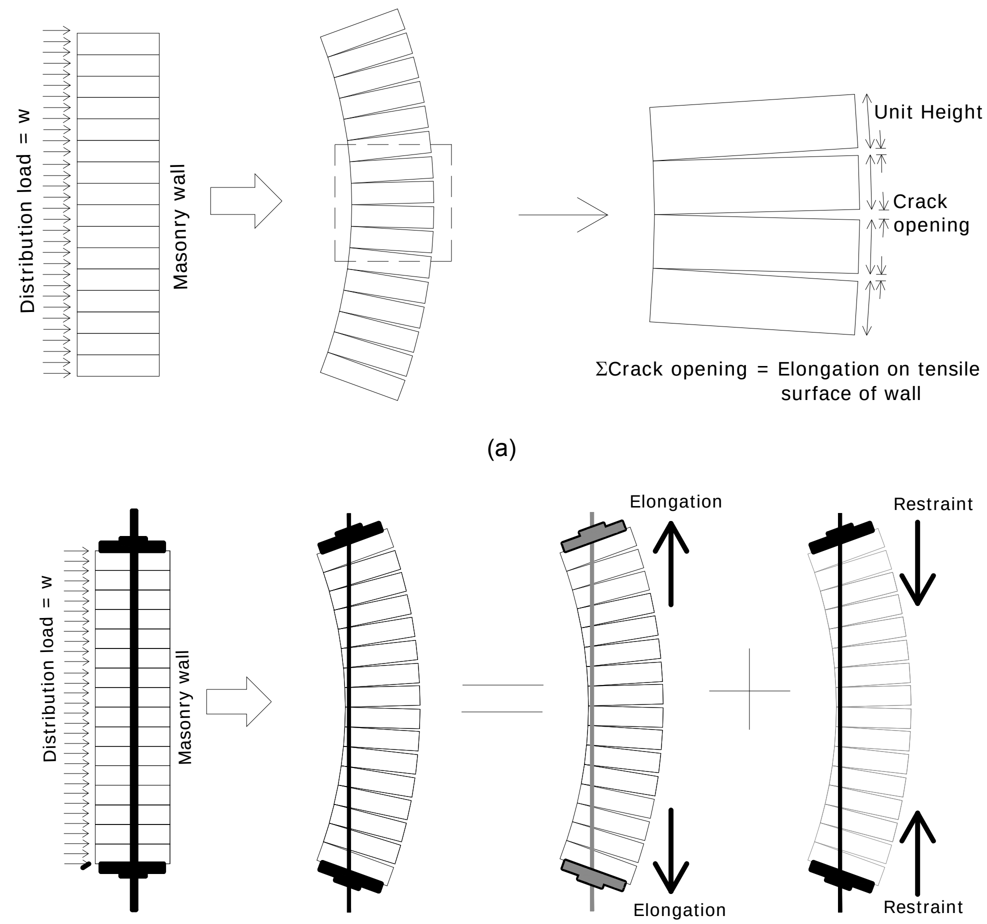
On the other hand, although shaking tables are usually implemented to investigate out-of-plane performance of URM walls subjected to inertial forces normal to the surfaces, it is occasionally difficult to observe failure behavior by optical inspections in dynamic tests. Therefore, in this study, a new static loading system was also developed with a rubber airbag, and implemented for evaluating out-of-plane performance of the specimens.

2. PROPOSAL OF A NEW OUT-OF-PLANE STRENGTHENING SYSTEM

Masonry walls are commonly fragile in the out-of-plane direction when subjected to lateral loads caused by earthquake, wind, or blast. This is because of low tensile/bond strength of masonry units/adhesive. Therefore, applying compression e.g. due to pre-stressing or post-tensioning is effective to improve the out-of-plane performance, as reported by e.g. Ismail et al. [2]. On the other hand, masonry units and typical adhesive of cement mortar can resist high compression. Such characteristics of masonry materials cause geometric axial elongation of walls with lateral deformation under out-of-plane loads, as illustrated in Figure 1(a).

Focusing on the specific characteristics of masonry 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 of wall and passively generate axial compression on the wall cross-section as a reaction of restraint, as shown in Figure 1(b). Therefore, no previous stress is necessarily provided for the wall cross-section as well as restraint rods in the proposed system, which results in preventing/reducing complexity in construction, long-term pre-stress loss, and maintenance after construction.

A series of feasibility tests was conducted to verify the effectiveness of the proposed strengthening system using typical brick walls in Indonesia in the following.



(b)

Figure 1. Concept of strengthening

3. EXPERIMENTAL SPECIMENS AND METHODS

The proposed strengthening method was applied to brick wall specimens which were extracted from an earthquake-damaged building in Indonesia [3], as shown in Photo 1.

Three brick wall specimens were prepared with the dimensions of 190 mm x 140 mm x 900 mm in width x thickness x height, as shown in Photo 2 and Table 1. One of them was the control specimen, N-1. 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.

M8 steel rods were used for restraining the wall elongation, as shown in Figure 1(b). The 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, as shown in Table 1. Two of the specimens, R-1 and R-2, were strengthened by the rods which were placed along the wall height and fixed at the end plates provided at the wall ends, as shown in Photo 3 and Figure 2. An initial tensile strain of 400μ was applied only to the rods of R-2 specimen to induce an initial compression on the cross-section.

Photo 1. Earthquake-damaged building and brick walls for test

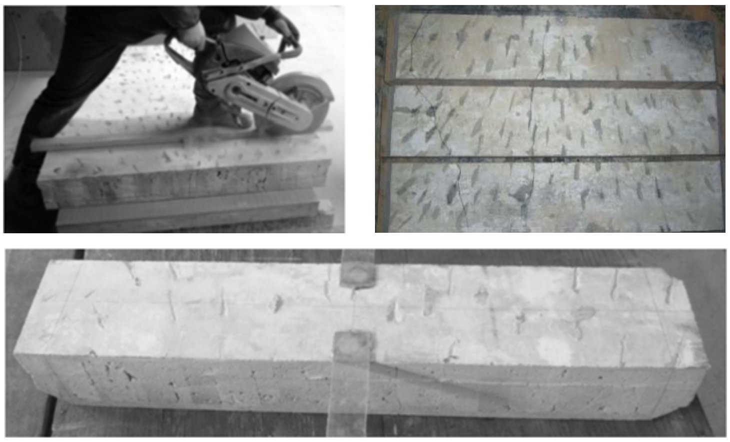


Photo 2. Conditioned brick wall specimens

Table 1. Material properties of specimens

Specimen	N-1	R-1	R-2
Brick wall			
Young's modulus (N/mm^2)	634	634	634
Compressive strength (N/mm^2)	2.91	2.91	2.91
Steel rods			
Cross-sectional area (mm^2)	-	36.6	36.6
Young's modulus (N/mm^2)	-	2.29 x 10^5	2.29 x 10^5
Yield stress (N/mm^2)	-	560	560
Tensile strength (N/mm^2)	-	838	838
Initial strain/stress* (μ / N/mm^2)	-	0 / 0	400 / 0.40

* compressive stress on wall cross-section.

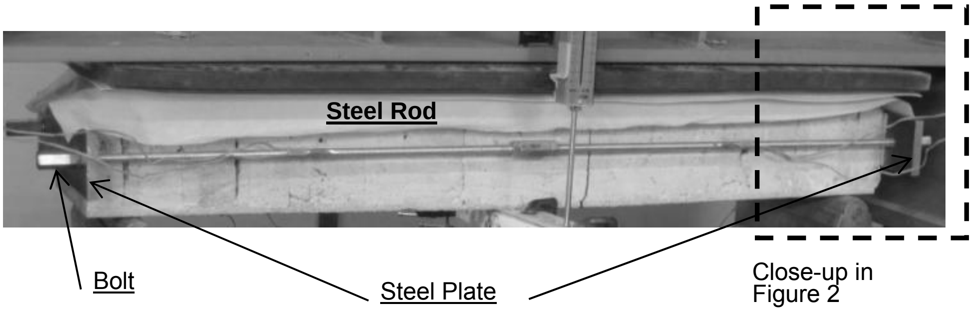


Photo 3. Brick wall specimen strengthened by steel rods

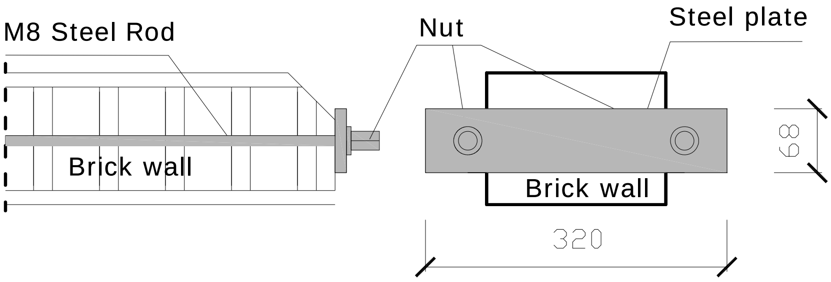


Figure 2. Details of end plate

Photo 4 shows an out-of-plane loading system for masonry walls developed in this study. Design details of the system can be referred to Figure 3. A rubber bag jack (airbag), as shown in Photo 5, 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 4 and Figure 3. The specimens were inserted below the airbag and simply supported in the system. Applied loads to the specimens which resulted from the airbag were measured by load cells implemented under the roller supports. Set-up of two displacement transducers for the test can be seen in Figure 4. They were located to measure the vertical displacements at the middle span of the specimen. This figure also shows locations of strain gauges on the steel rods of the strengthened specimens, which were installed to measure tension of strengthening rods and compression acted on the cross-section of specimens. Initiated cracks were also observed to identify the failure mechanism of specimens.

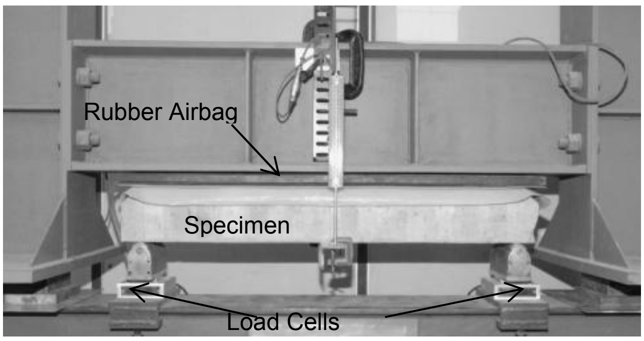


Photo 4. Front view of out-of-plane loading system

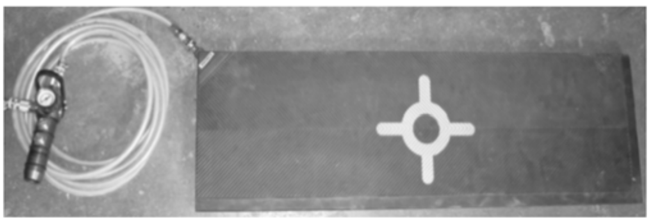


Photo 5. Implemented airbag

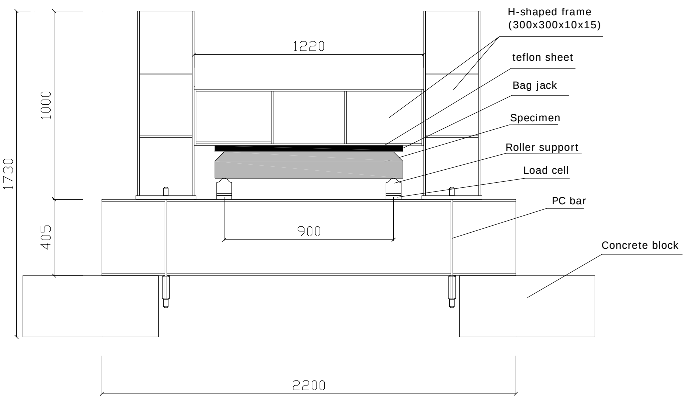


Figure 3. Design details of out-of-plane loading system

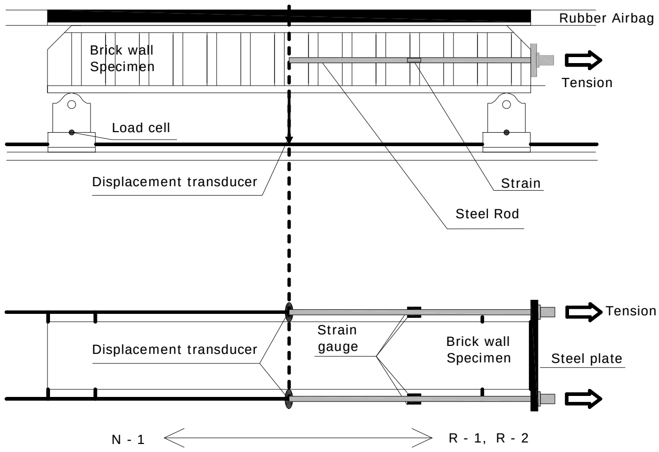


Figure 4. Test set-up

4. EXPERIMENTAL RESULTS

Figure 5 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 in Figure 4, by half of the wall height. Although the N-1 specimen failed under a small moment of 158 Nm at an initial cracking, 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%. Photo 6 shows the R-2 specimen at a large drift of 5% rad. Figure 6 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 higher resistances of R-1 and R-2 could be obtained by the proposed strengthening system.

Photo 6. R-2 specimen at a drift angle of 5% rad.

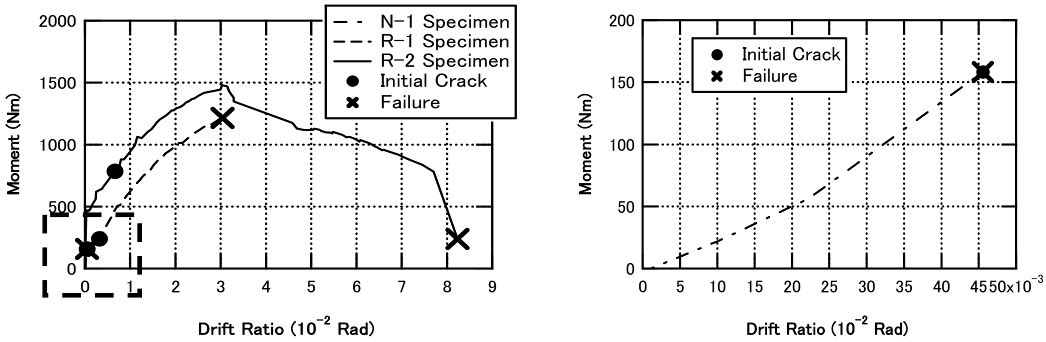


Figure 5. Moment-drift angle relationships of specimens

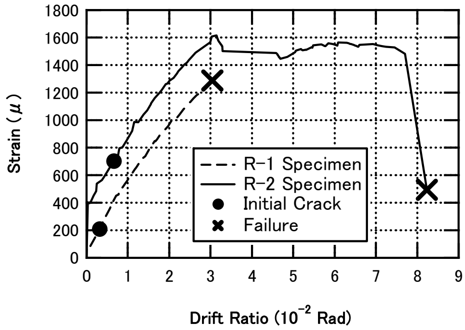


Figure 6. Strain-drift angle relationships of strengthened specimens

5. CONCLUDING REMARKS

A new strengthening method, which utilized geometric deformation characteristics of masonry itself as well as restraint by steel rods, was proposed and verified to enhance the out-of-plane performance of masonry walls. The following conclusions were obtained from the experimental study.

Mechanism of the proposed strengthening was introduced. Out-of-plane performance of masonry walls are enhanced by passive compression applied to wall cross-sections, which is caused by restraint of axial elongation of walls with their out-of-plane deformation.

The test results indicated that both of the retrofitted specimens exhibited much higher strengths and deformation capacities even after cracking of walls, nevertheless the unretrofitted specimen brittlely failed with an initial cracking. The proposed system can effectively improve the out-of-plane performance of masonry walls.

6. REFERENCES

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