A FEASIBILITY STUDY ON RETROFIT METHOD USING MASONRY WALLS CONSISTING OF DUCTILE INTERLOCKING BLOCKS

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ABSTRACT: This paper presents a retrofit method for existing structures using masonry walls consisting of ductile interlocking blocks. Several advantages of this method, such as application of easy-to-install interlocking units, no reinforcement work, and no construction noise and vibration, decrease construction costs and allow buildings to remain occupied during retrofitting. In this feasibility study, two unreinforced masonry (URM) wall specimens, consisting of brittle and ductile interlocking units (Wall-BI and Wall-DI, respectively), were designed and tested. Although the brittle units were made of brick, the ductile units were made of fiber-reinforced cement composite, which was specially produced for Wall-DI. Although both specimens behaved in a similar manner under low-amplitude cyclic loads, strength degradation was observed during the cycles to ±1/100 in Wall-BI. This was caused by the lateral force-resisting characteristics of URM walls using brittle interlocking units. As a result, the lateral strength of Wall-DI was higher than that of Wall-BI. Moreover, no degradation was observed up to a 1/50 drift level in Wall-DI. Therefore, it was experimentally verified that the ductile interlocking units improve ductility as well as strength of URM walls. The masonry wall using ductile interlocking blocks (Wall-DI) can be an effective structural element for retrofitting existing buildings.

KEYWORDS: brick, fiber-reinforced cement composite, seismic retrofit, static loading test, unreinforced masonry.

1 INTRODUCTION

Interlocking blocks have been used mainly for accelerating masonry construction and/or improving structural performance in various countries [1]. The authors have also investigated the seismic performance of masonry walls, consisting of interlocking bricks, for application to vulnerable structures in developing countries [2]. As a result, it was experimentally verified that masonry walls can be effectively strengthened using interlocking bricks.

On the other hand, masonry structures are not common in Japan, based on lessons from past earthquake disasters. When retrofitting existing buildings, however, they have several advantages such as utilization of easy-to-handle masonry units, and no noise and vibration during construction work. Therefore, a new retrofit method using masonry walls is proposed in this study. This method aims to improve not only the strength but also the ductility of existing structures using ductile interlocking blocks, and to simplify construction work without reinforcements. This paper reports on a series of tests conducted to investigate the seismic performance of additional walls consisting of brittle and ductile interlocking units.

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2 PROPOSAL FOR A NEW RETROFIT METHOD

Figure 1 shows the infinite plane masonry wall using interlocking blocks assumed as the theme structure in this study. This figure also shows details of the masonry unit. Fiber-reinforced cement composite (FRCC) and brick were assumed as the brittle and ductile materials of the unit, respectively.

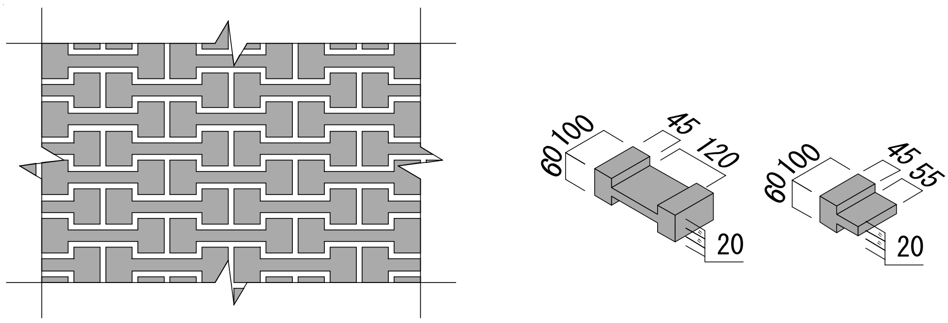


Figure 1. Investigated masonry wall and its unit

Figure 2 illustrates an ideal retrofit method using the masonry wall shown above. Additional walls are expected to be simply constructed laying masonry units without reinforcements after adhesively bonding reaction elements. Compared to conventional methods installing steel braces or reinforced concrete shear walls, several advantages of this method, such as application of easy-to-install interlocking units, no reinforcement work, and no construction noise and vibration, decrease construction costs and allow buildings to remain occupied during retrofitting.

Although only in-plane behavior of installed panels is discussed in this paper, interlocking blocks are also expected to be effective for out-of-plane behavior, which will be investigated in a subsequent study.

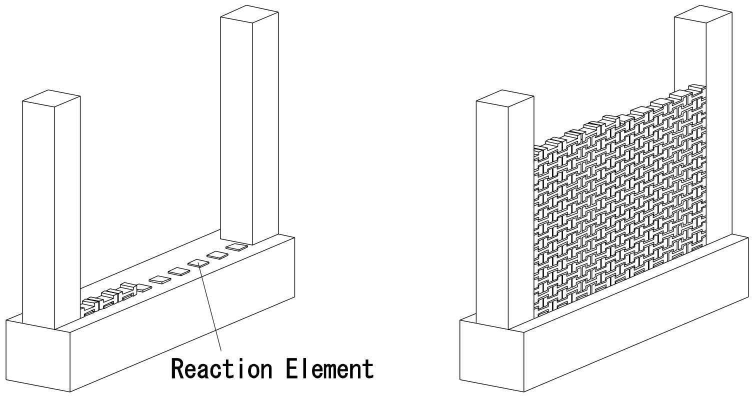


Figure 2. Ideal retrofit method

3 TEST PROGRAM

3.1 SPECIMENS

Two URM wall specimens, representing the installed panels in Figure 2 were designed and tested. One specimen was Wall-BI consisting of brittle interlocking units made of brick, the other was Wall-DI consisting of FRCC. The elevations of specimens are shown in Figure 3. The shear keys were fixed on the steel stubs, as shown by hatching in the figure, to prevent the URM walls from sliding. The mortar joint thickness was 10 mm, except for the top and bottom layers, which was 20 mm, as derived from the dimensions of the loading system described below. Table 1 shows the tensile strength of brick, FRCC, and joint mortar. The tensile strength of FRCC was expected to be as low as that of brick, because only the effects of the ductility of masonry units should be clarified in this study. Therefore, the FRCC was produced with a 1.0% fiber content by volume, 60% water/cement ratio, and 40% sand/cement ratio, based on reference 3) and preliminary material tests. As a result, the expected tensile strength of the FRCC could be obtained as shown in Table 1.

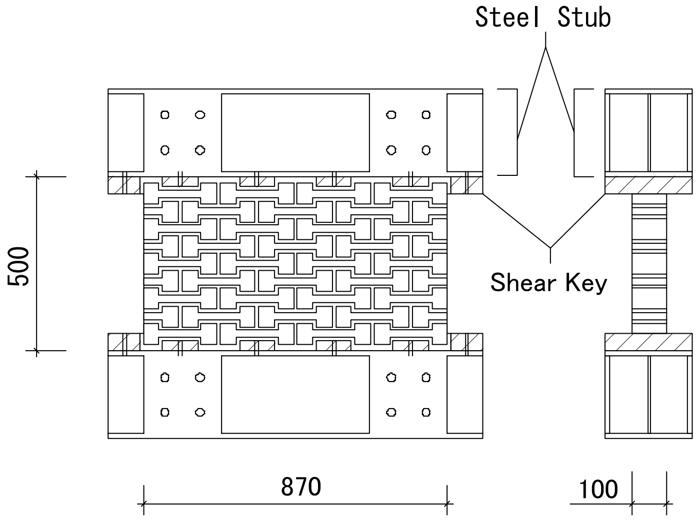


Figure 3. Elevations of the specimens

Table 1. Tensile strength of materials

Specimen	Brick	FRCC		Mortar	
	Strength (N/mm^2)	Age (days)	Strength (N/mm^2)	Age (days)	Strength (N/mm^2)
Wall-BI	7.62			7	1.08
Wall-DI		18	7.48	7	1.28

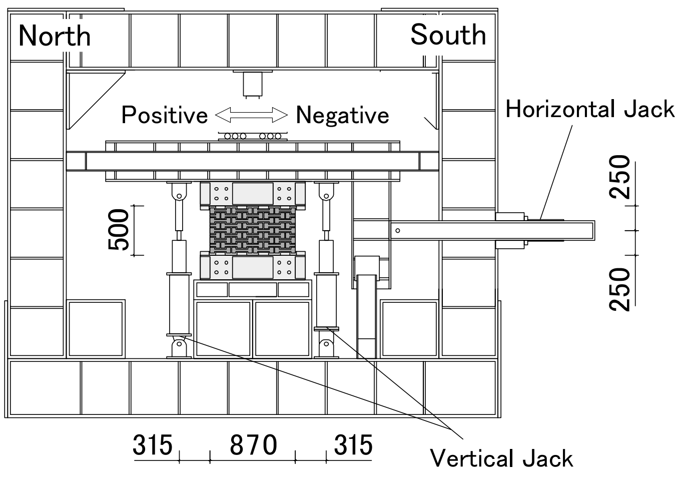


Figure 4. Loading system

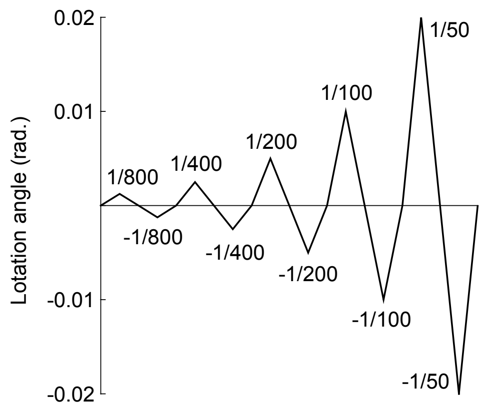


Figure 5. Loading history

3.2 LOADING SYSTEM AND PROGRAM

The tests were carried out at a testing facility of Niigata University. Figure 4 shows the loading system used for the tests. The specimens were subjected to cyclic antisymmetric bending and shear under constant axial loading of 20 kN (≈0.23 N/mm^2). The applied loading history in the lateral direction is illustrated in Figure 5.

4 TEST RESULTS

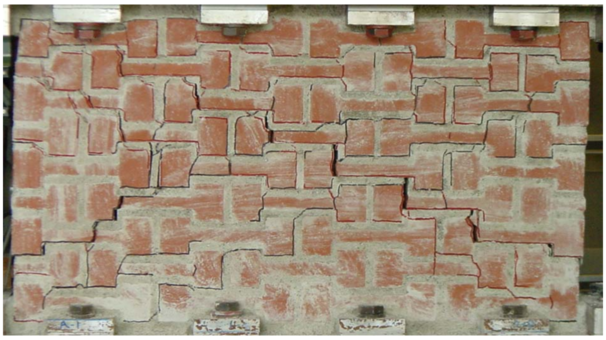
4.1 FAILURE PROCESS

<u>Wall-BI</u>

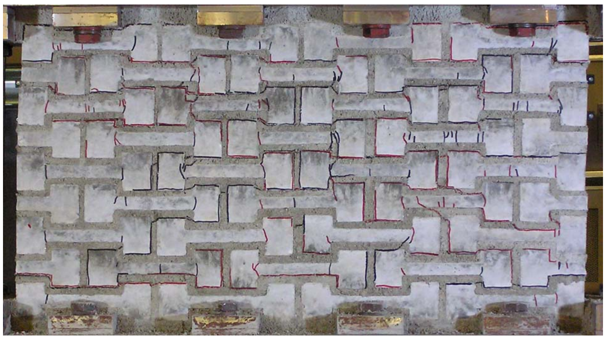
Initial flexural cracks were observed at the top and the bottom of the specimen during the cycles to ±1/800. Several tensile cracks also occurred in the masonry units. Horizontal and vertical cracks began to appear along the mortar joints during the cycles to ±1/400. They extended across the masonry units after the following cycle. Crack appearance in each unit means the lack of an interlocking mechanism between units. Therefore, it was found that each interlocking mechanism could not act simultaneously in Wall-BI because of brittle failures of brick units following local stress concentration in the panel. As a result, the cracks in the joints and the units formed stair step crack patterns on the wall surface, and the strength of the wall was noticeably degraded. Picture 1(a) and Figure 6(a) show the specimen after testing and its final crack pattern. In Figure 6(a), however, the stair step cracks are accented with thick lines.

<u>Wall-DI</u>

Although a lot of slight tensile cracks occurred in the masonry units, few visible cracks were observed at the mortar joints up to the cycles to ±1/200. Damage to the joints increased after the cycles to ±1/100, nevertheless no stair step crack patterns had formed by the end of the test, as shown in Picture 1(b) and Figure 6(b). Compared to Wall-BI, the cracks spread over a wider area in the case of Wall-DI, which means that the internal stress was more evenly distributed in this case. This was due to the ductile units without brittle failure. Consequently, no FRCC units were split due to their fiber contents.

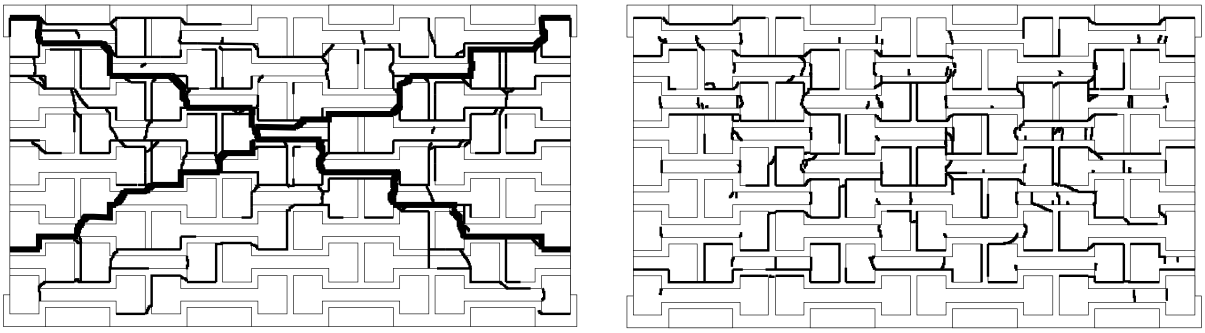


(a) Wall-BI



(b) Wall-DI

Picture 1. Specimens after testing



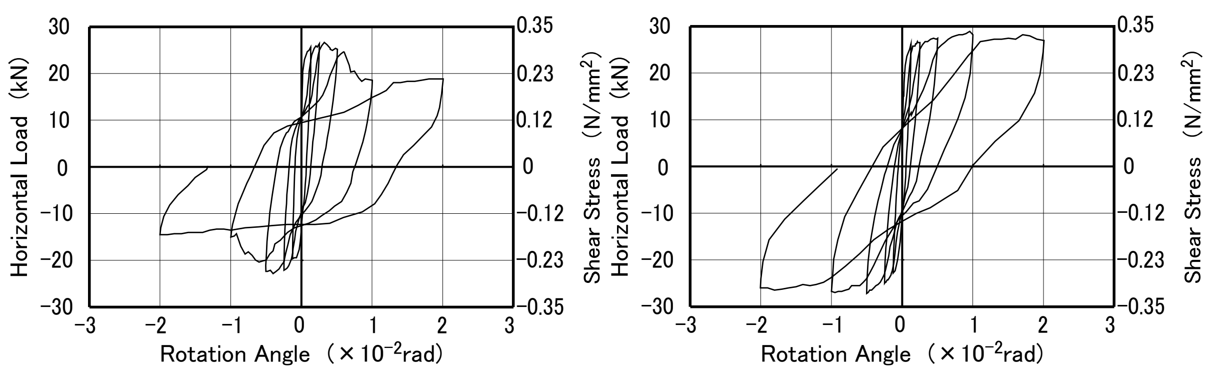
(a) Wall-BI **(b) Wall-DI**

Figure 6. Final crack patterns

4.2 SEISMIC PERFORMANCE

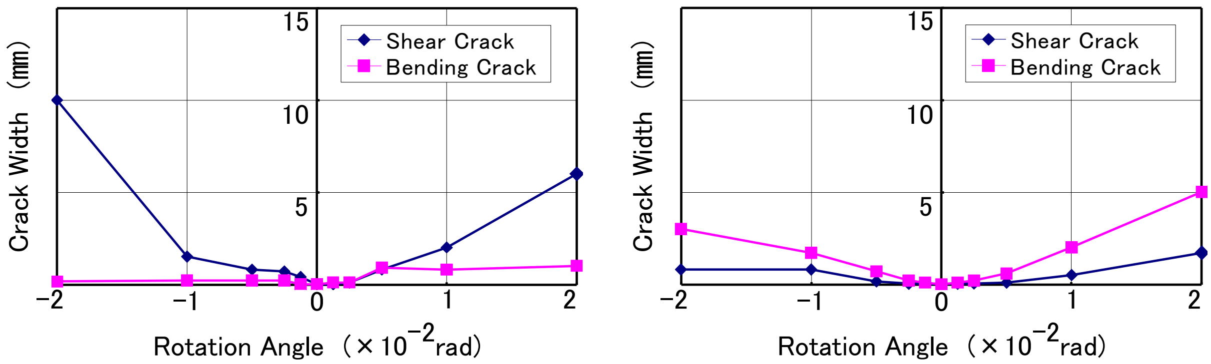
The lateral force-drift ratio relationships of both specimens are shown in Figure 7. The maximum strength of Wall-BI was 26.5 kN, which was recorded during the cycle to +1/200. This specimen deteriorated with tensile failures of the units during the cycles to ±1/100. Strength was decreased by about half of the peak strength, but then was maintained. The lateral force-resisting mechanism might change from an interlocking mechanism to a frictional mechanism, because strength after degradation was as high as the estimate of 11.6 kN (= 0.58 x Axial loading of 20 kN), based on the averaged friction factor of 0.58 from another element tests. Figure 8(a) shows the relationships between the maximum width of flexural and shear cracks and the lateral drift at every peak drift. This figure also indicates the shear dominant behavior of the specimen after its strength degradation. These results mean that masonry walls can be strengthened using brittle interlocking blocks, but they finally fail in shear.

On the other hand, the maximum strength of 29.2 kN was recorded for Wall-DI, which was about 1.1 times higher than Wall-BI. Stable spindle shape hysteresis loops with no degradation were observed as shown in Figure 7(b). This specimen exhibited its peak strength due to a flexural yielding. Although the theoretical flexural strength of 34.8 kN was a little higher than the test result, flexural crack openings were obviously observed throughout the test as shown in Figure 8(b). Therefore, the maximum strength of this specimen might be higher, assuming that it was subjected to shear deformation due to the surrounding frame shown in Figure 2.



(a) Wall-BI **(b) Wall-DI**

Picture 7. Lateral force-drift ratio relationships



(a) Wall-BI **(b) Wall-DI**

Picture 8. Maximum crack width-drift ratio relationships

5 CONCLUDING REMARKS

A retrofit method using masonry walls consisting of ductile interlocking blocks was presented and two installed panel specimens with brittle and ductile units were tested in this study. Major findings of the tests are summarized below.

1. The ductility and the strength of Wall-DI, consisting of ductile FRCC interlocking units were superior to those of Wall-BI, consisting of brittle brick ones.

2. Each interlocking mechanism between units could not act simultaneously in Wall-BI because of brittle failures of brick units following local stress concentration in the panel. In the case of Wall-DI, however, the internal stress was more evenly distributed due to its ductile units. Consequently, no FRCC units were split due to their fiber contents.

3. No strength degradation was observed in Wall-DI up to a 1/50 drift level. Therefore, URM walls consisting of ductile interlocking units might be an effective structural element for retrofitting.

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