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SEISMIC PERFORMANCE OF MASONRY WALLS USING INTERLOCKING UNITS

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SUMMARY

This paper presents a method for improving the seismic performance of unreinforced masonry (URM) walls using interlocking masonry units. Two new URM wall specimens, consisting of brittle and ductile interlocking units (Wall-BI and Wall-DI, respectively), were designed and tested. Brittle units were made of brick, and ductile units were made of fiber-reinforced cement composite, which was specially produced for Wall-DI. The seismic performances of Wall-BI and Wall-DI were compared with that of another conventional URM wall specimen (Wall-C) consisting of typical bricks. Although Wall-C failed in shear at a small drift level, flexural behavior was observed in Wall-BI and Wall-DI. As a result, the lateral strengths of Wall-BI and Wall-DI were much higher than that of Wall-C. In Wall-BI, however, strength degradation was observed at a large deformation. This was caused by the lateral force-resisting characteristics of URM walls using brittle interlocking units. On the contrary, no degradation was observed up to the 1/50 drift level in Wall-DI. Therefore, it was experimentally verified that URM walls can be effectively strengthened using interlocking masonry units. Moreover, ductile interlocking units can improve the ductility as well as the strength of URM walls.

1. INTRODUCTION

Recent serious earthquakes, such as the 1999 Kocaeli, Turkey earthquake [EERI, 2000], the 1999 Chi-Chi, Taiwan earthquake [EERI, 2001], the 2003 Boumerdes, Algeria earthquake [EERI, 2003], and the 2003 Bam, Iran earthquake [IIEES, 2004], destroyed a lot of vulnerable structures, in particular unreinforced masonry (URM) houses, and killed huge numbers of people. Although URM structures cannot adequately resist seismic loads, they have been used in high seismic risk areas of the world due to their several advantages, such as economy, ease of construction, and environmental efficiency. Therefore, URM structures have played important roles in spite of their vulnerability to earthquakes.

On the other hand, URM structures are not common in Japan, due to lessons learned from past earthquake disasters. In recent years, however, the seismic performance of this type of structure has been investigated to support developing countries technically [Mayorca and Meguro, 2004, Kiyono and Kalantari, 2004, and Choi et al., 2005]. This study also presents a method for improving the seismic performance of URM structures using interlocking masonry units. A series of static loading tests conducted to investigate the seismic performance of URM walls consisting of interlocking units is reported herein.

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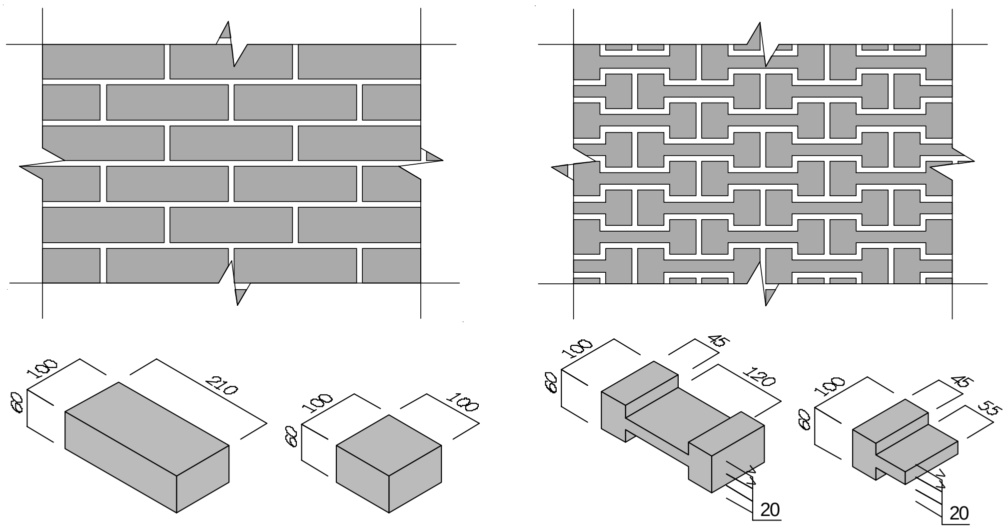
2. TEST PROGRAM

2.1 Theme Structures

Different kinds of infinite plane URM wall were assumed as the theme structures in this study, as shown in Figure 1. They consisted of conventional parallelepiped units and new detailing interlocking units, respectively. Figure 1 also shows details of the masonry units.



Unit: mm

(a) Conventional type **(b) Interlocking type**

Figure 1: Theme structures

2.2 Test Specimens

Three URM wall specimens that were taken from the theme structures in Figure 1 were designed and manufactured to compare seismic performance. They can be summarized as follows:

Wall-C

A conventional URM wall specimen, Wall-C, consisted of typical parallelepiped bricks, as shown in Figure 2 (a). The bricks were laid up with cement mortar. The mortar joint thickness was 10 mm.

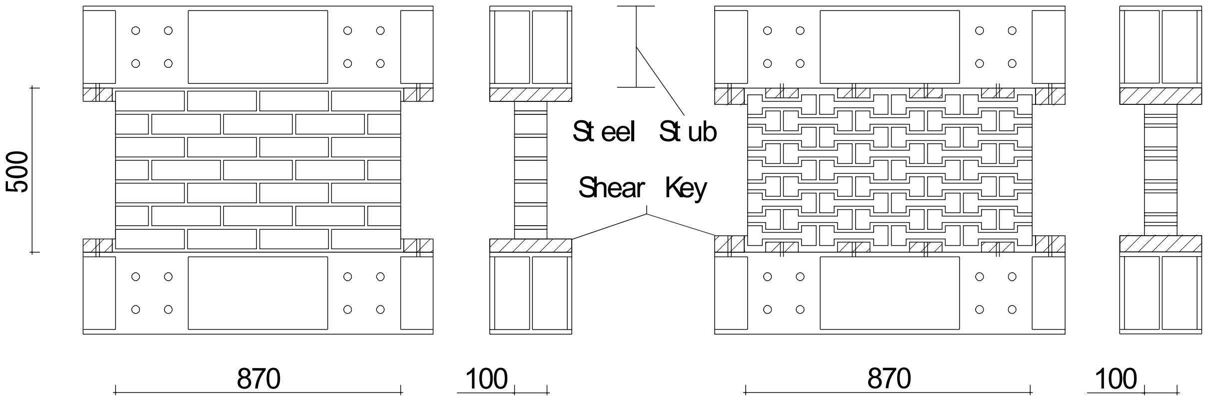
Wall-BI

New interlocking masonry units were used for Wall-BI, as shown in Figure 2 (b). The units were cut out from typical bricks. Although this specimen was manufactured in the similar manner as Wall-C, the mortar joint thickness of only the top and bottom layers was 20 mm to keep its height the same as that of Wall-C.

Wall-DI

Ductile interlocking units made of fiber-reinforced cement composite (FRCC) were applied for Wall-DI, instead of brittle bricks. The dimensions of Wall-DI were the same as those of Wall-BI.

The shear keys were fixed on steel stubs, as shown by the hatching in Figure 2 to prevent the URM walls from sliding. The joint mortar was specially produced with 125% water/cement ratio and 849% sand/cement ratio to simulate the low-quality mortar generally used in developing countries [Mayorca and Meguro, 2004]. Table 1 shows the tensile strengths of joint mortar, brick, and FRCC. 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 material [Suwada et al., 2001] and preliminary material tests. As a result, the expected tensile strength of the FRCC was obtained as shown in Table 1.



Unit: mm

(a) Wall-C (b) Wall-BI and Wall-DI

Figure 2: Elevations of the specimens

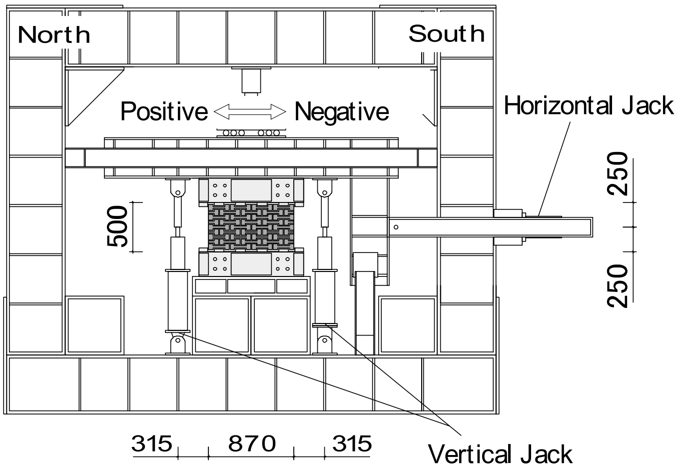
Table 1: Tensile strengths of materials

Specimen	Mortar		Brick	FRCC	
	Age (days)	Strength (N/mm^2)	Strength (N/mm^2)	Age (days)	Strength (N/mm^2)
Wall-C	7	0.91	7.62		
Wall-BI	7	1.08			
Wall-DI	7	1.28		18	7.48

2.3 Test System and Loading Program

The tests were carried out at a testing facility of Niigata University. Figure 3 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 4.

Figure 5 shows the set-up of transducers to measure the horizontal and vertical relative displacements of the specimens. Crack width was also measured at every peak drift in Figure 4.



Unit: mm

Figure 3: Loading system

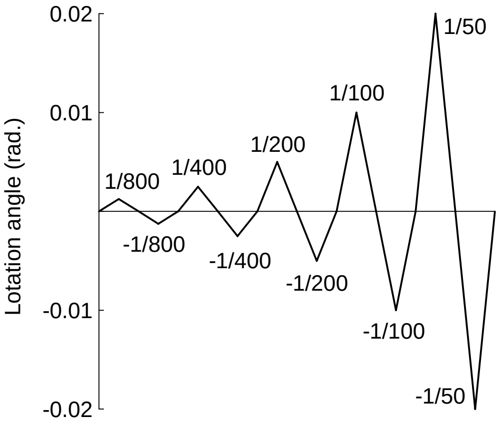


Figure 4: Loading history

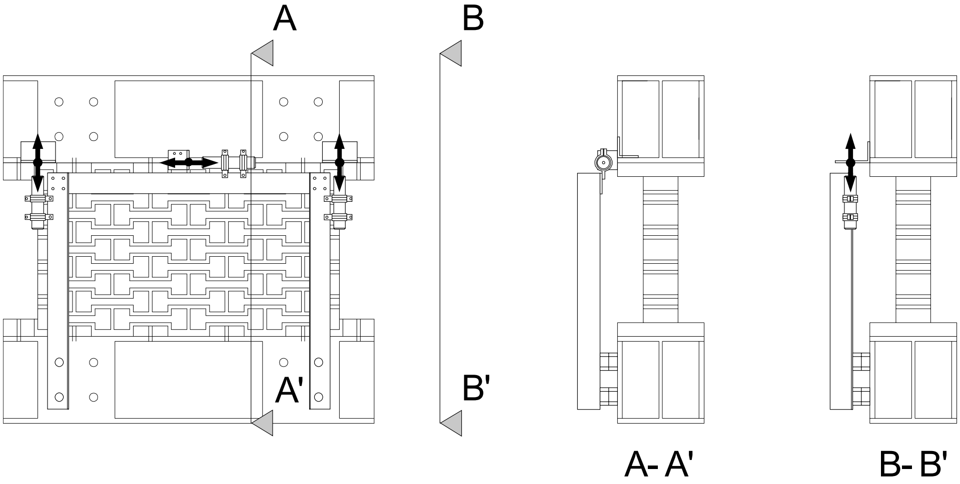


Figure 5: Transducers set-up

3. TEST RESULTS

3.1 Failure Process

Wall-C

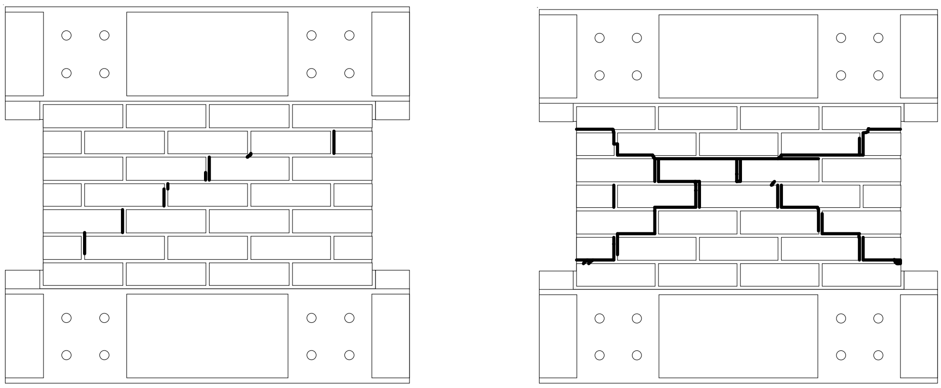
Initial shear cracks occurred along the vertical mortar joints during the cycles to ±1/800. Although the maximum strength of 17.2 kN was also recorded, strength degradation was not exhibited subsequently. A stair step crack pattern had formed at the peak drift of +1/800, as shown in Figure 6 (a). The lateral deformation of the specimen increased with the opening of vertical cracks in the following cycles. Figure 6 (a) also shows the final crack pattern of Wall-C. A typical stair step crack pattern can be observed on the wall surface in each direction.

Wall-BI

Initial flexural cracks were observed at the top and the bottom of the specimen during the cycles to ±1/800. Although several tensile cracks also occurred in the masonry units, no stair step crack patterns had formed during these cycles, as shown in Figure 6 (b). 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 suggests 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 as shown in Figure 6 (b), and the strength of the wall was noticeably degraded.

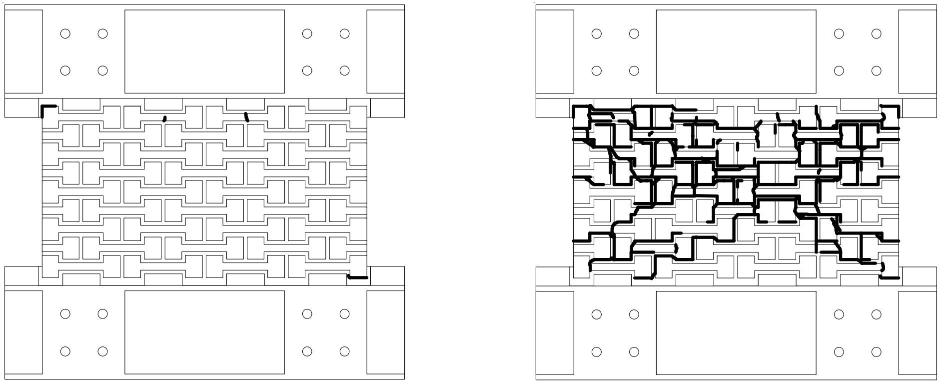
Wall-DI

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 cycles to ±1/100; nevertheless, no stair step crack patterns had formed by the end of the test, as shown in Figure 6 (c). Compared to Wall-BI, the cracks spread over a wider area in the case of Wall-DI, which means that internal stress was more evenly distributed in this case. This was due to ductile units not experiencing brittle failure. Consequently, no FRCC units were split due to their fiber contents.



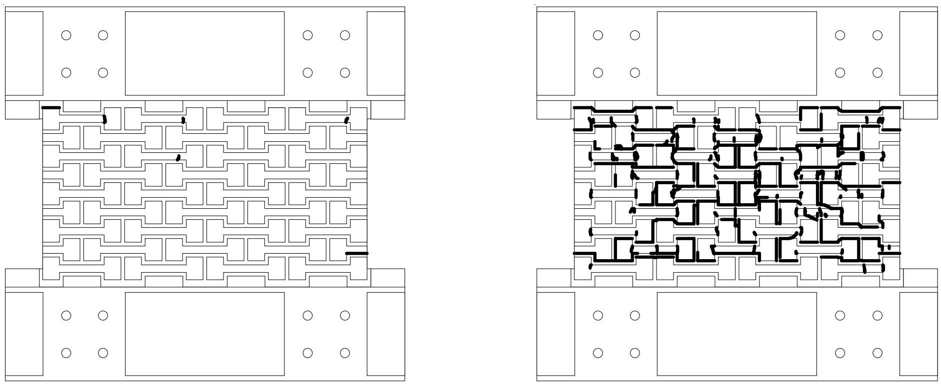
At the +1/800 drift level **After testing**

(a) Wall-C



At the +1/800 drift level **After testing**

(b) Wall-BI



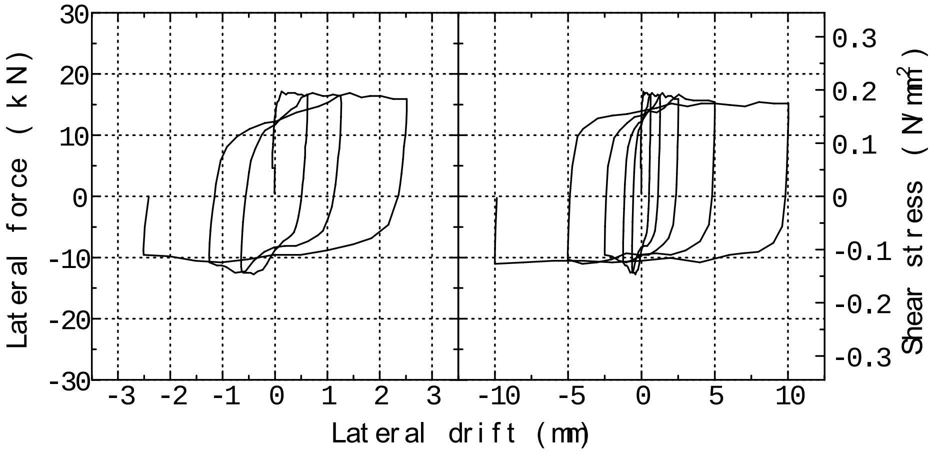
At the +1/800 drift level **After testing**

(c) Wall-DI

Figure 6: Crack patterns

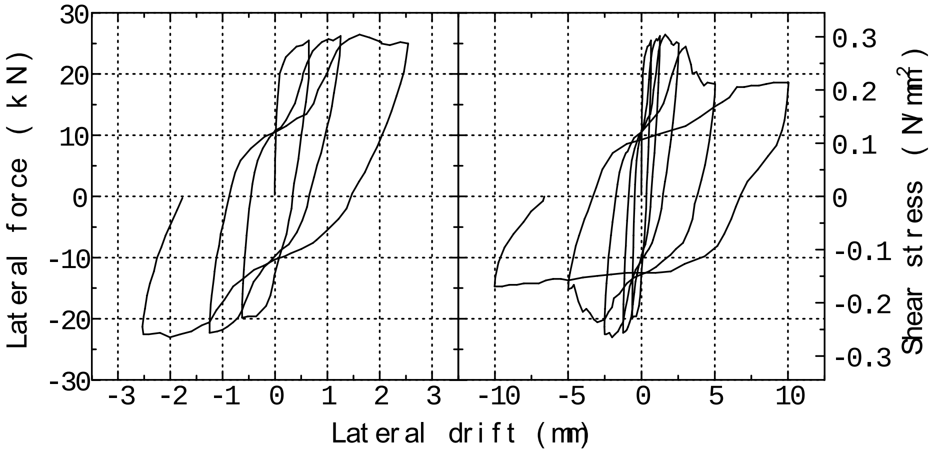
3.2 Seismic Performance

Figures 7 and 8 show lateral force-top drift relationships and relationships between the maximum width of flexural and shear cracks and the lateral drift at every peak drift for all specimens. Wall-C exhibited bilinear hysteresis loops as shown in Figure 7 (a). This specimen was considered to resist lateral loads due to static friction between masonry units in the horizontal direction because lateral deformation increased as soon as its strength recovered in each loading cycle. Lateral strength could be approximately evaluated from the estimate of 11.6 kN (= 0.58 x Axial loading of 20 kN), based on the average friction factor of 0.58 from another element test described below. Figure 8 (a) indicates not only that shear dominant behavior was observed throughout the test, but also that the maximum crack width was almost identical to the peak lateral drift, or was a little larger than that due to residual drifts.



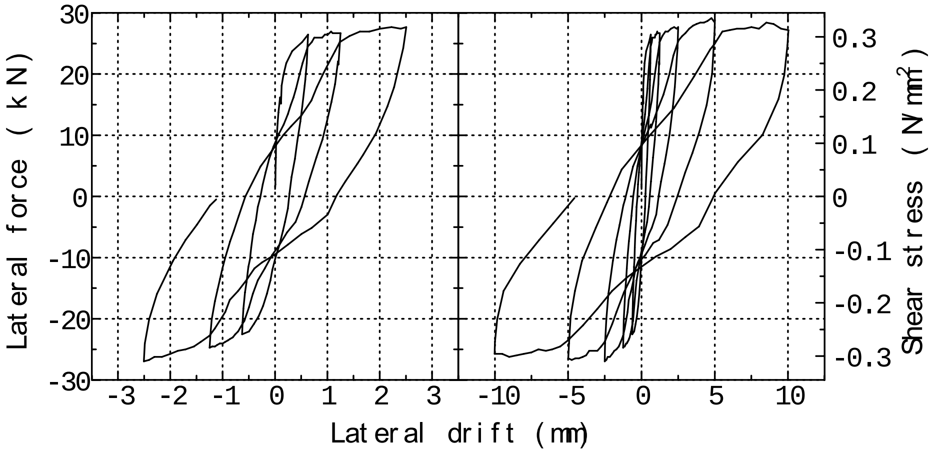
+1/800 → -1/200 **+1/800 → -1/50**

(a) Wall-C



+1/800 → -1/200 **+1/800 → -1/50**

(b) Wall-BI



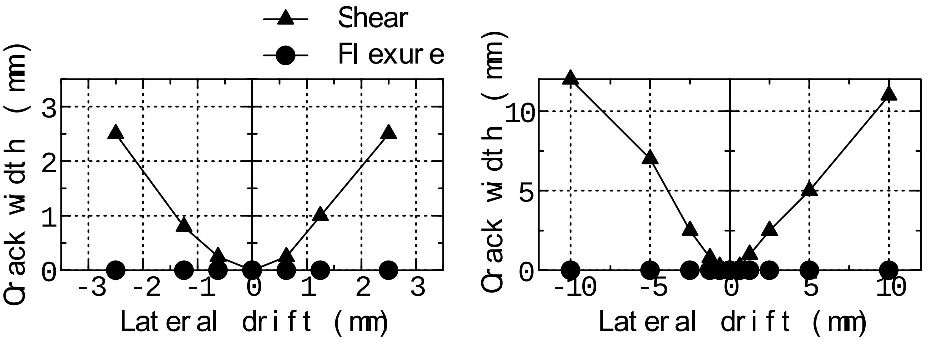
+1/800 → -1/200 **+1/800 → -1/50**

(c) Wall-DI

Figure 7: Lateral force-top drift relationships

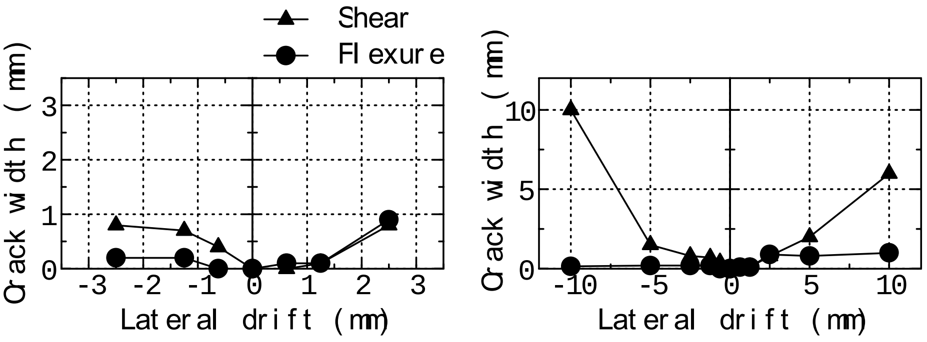
On the other hand, the maximum strength of Wall-BI, recorded during the cycle to +1/200 was 26.5 kN, which was more than 1.5 times higher than that of Wall-C, as shown in Figure 7 (a) and (b). This specimen deteriorated with tensile failures of the units during the cycles to ±1/100. Strength was decreased by about half of the peak strength, but then was maintained. The lateral force-resisting mechanism might have changed from an interlocking mechanism to a frictional mechanism, because strength after degradation was as high as that of Wall-C. Figure 8 (b) also shows the shear dominant behavior of the specimen after its strength degradation. These results mean that masonry walls can be strengthened using interlocking bricks, but they finally fail in shear because of brittle failures of the units.

In the case of Wall-DI, the maximum strength of 29.2 kN was recorded, which was about 1.1 times higher than that of Wall-BI. Stable spindle-shaped hysteresis loops with no strength degradation were observed as shown in Figure 7 (c). This specimen exhibited its peak strength due to 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 (c).



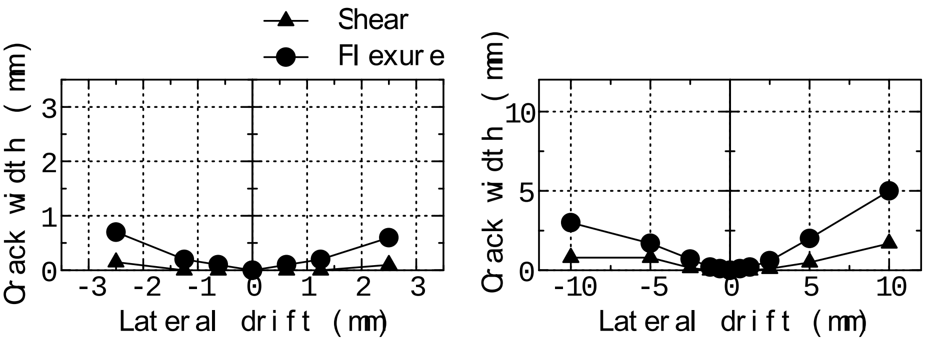
+1/800 → -1/200 **+1/800 → -1/50**

(a) Wall-C



+1/800 → -1/200 **+1/800 → -1/50**

(b) Wall-BI



+1/800 → -1/200 **+1/800 → -1/50**

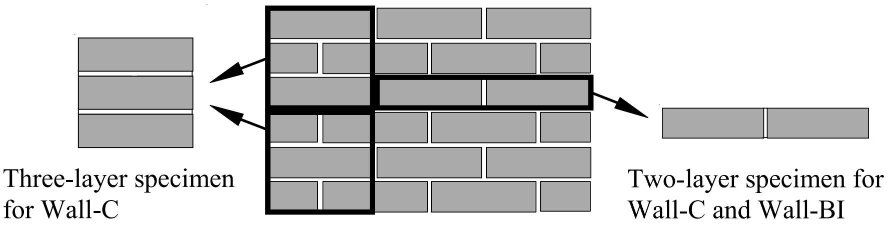
(c) Wall-DI

Figure 8: Maximum crack width-lateral drift relationships

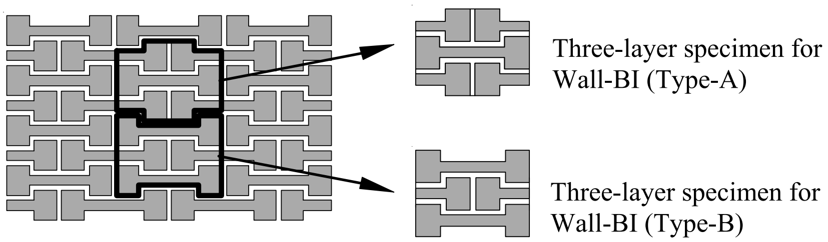
4. ELEMENT TESTS

4.1 Test Program

Three kinds of element test were conducted to investigate shear strength, bond strength, and friction factor between masonry units. Specimens for the element tests were picked out from the theme structures in Figure 1, as illustrated in Figure 9. Three-layer and two-layer specimens were manufactured for evaluating shear and bond strengths, respectively. Three specimens were used for each test. The loading set-up of each test is shown in Figure 10. Shear and bond strengths were evaluated for Wall-C and Wall-BI, and the friction factor was evaluated for only Wall-C using the three-layer specimens after testing for shear strength. Although element tests for Wall-DI were also conducted, the test results are not reported in this paper because appropriate results could not obtained due to an unexpected error when manufacturing the specimens.

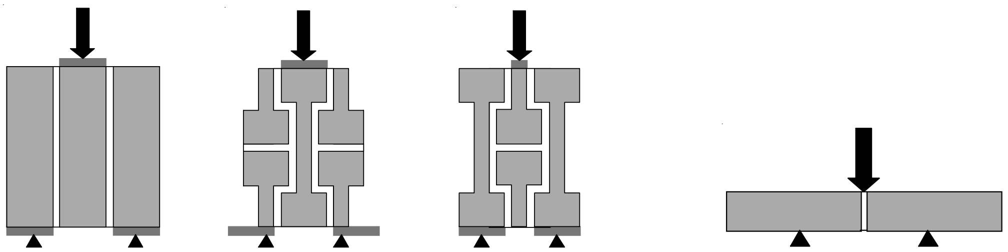


Conventional type

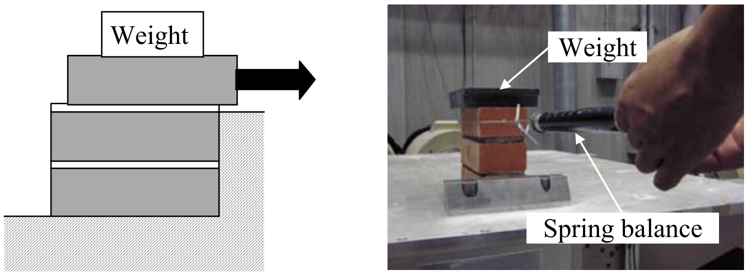


Interlocking type

Figure 9: Specimens for the element tests



(a) Test for evaluating shear strength (b) Test for evaluating bond strength



(c) Test for evaluating friction factor

Figure 10: Loading set-up for the element tests

4.2 Test Results

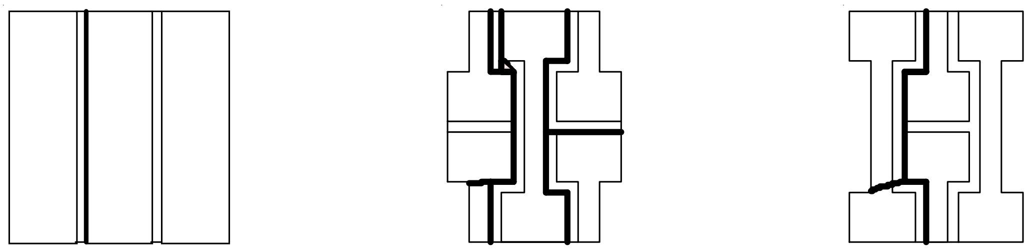
Averaged strengths and friction factor obtained from the element tests are shown in Table 2. The evaluated shear strength for Wall-BI was about 0.3 N/mm^2, which was about three times higher than that for Wall-C. From the wall test, however, the lateral strength of Wall-BI was about 1.5 times higher than that of Wall-C, as described above. This result indicates that a flexural yielding mechanism might be formed in Wall-BI in the similar manner as Wall-DI. Figure 11 shows the typical failure pattern of each specimen. It can be found that the specimens consisting of interlocking units resisted shear forces due to their interlocking mechanisms.

On the other hand, it was found that the bond strength was extremely low. This result is consistent with the test results of Wall-C, with no damage observed in the masonry units.

The friction factor was evaluated as the average of 27 test results, which were obtained through tests on three specimens with three patterns of vertical loading, repeated three times. Although the calculated average was 0.58, this was obtained from 27 samples with a 47% margin of error.

Table 2: Results of the element tests

Specimen	Shear strength (N/mm^2)		Bond strength (N/mm^2)	Friction factor
Wall-C	0.090		0.19	0.58
Wall-BI	Type-A	0.31	0.17	
	Type-B	0.26		



(a) Conventional type **(b) Interlocking type (Type-A)** **(c) Interlocking type (Type-B)**

Figure 11: Typical failures of the specimens

5. CONCLUSIONS

A method for improving the seismic performance of URM structures using interlocking masonry units was proposed, and its potential was investigated experimentally. Seismic loading tests on three URM wall specimens consisting of typical parallelepiped bricks, new detailing interlocking bricks, and ductile interlocking blocks were carried out in this study. Major findings of the tests are summarized below:

1 The strength of Wall-BI, consisting of interlocking bricks, was much higher than that of the conventional URM wall, Wall-C. Therefore, masonry walls can be effectively strengthened using interlocking bricks. In the case of Wall-C, however, brittle failure finally occurred because of tensile failures of the units.

2 The ductility and the strength of Wall-DI, consisting of ductile FRCC interlocking units, were superior to those of Wall-BI. No strength degradation was observed up to the 1/50 drift level. Therefore, URM walls consisting of ductile interlocking units might be an effective structural element for improving vulnerable URM structures.

3 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.

The in-plane behavior of different kinds of URM wall was investigated in this study. Although further studies on their out-of-plane behavior are indispensable for application to actual structures, interlocking masonry units are also expected to be effective for out-of-plane performance.

6. ACKNOWLEDGMENTS

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