INTERLOCKING BLOCK INFILL CAPABLE OF RESISTING OUT-OF-PLANE LOADS

Y. Sanada[1], N. Yamauchi[2], E. Takahashi[3], Y. Nakano[4] and Y. Nakamura[5]

[1] *Associate Professor, Dept. of Arch. and Civil Eng., Toyohashi University of Technology, Toyohashi, Japan*
[2] *Technical Associate, Institute of Industrial Science, The University of Tokyo, Tokyo, Japan*
[3] *Graduate Student, Graduate School of Engineering, The University of Tokyo, Tokyo, Japan*
[4] *Professor, Institute of Industrial Science, The University of Tokyo, Tokyo, Japan*
[4] *Lecturer, Faculty of Engineering, Niigata University, Niigata, Japan*
Email: sanada@tutrp.tut.ac.jp

ABSTRACT :

This paper proposes new masonry infill walls using ductile interlocking blocks, and describes their availability for retrofitting existing structures. Although no reinforcement is provided in the proposed infills, they can resist out-of-plane loads by the interlocking mechanism between blocks. Three reinforced concrete frames were prepared, and two of them were retrofitted by installing the proposed infills, which were constructed in different bond patterns. Quasi-static loading tests of the specimens were carried out in the in-plane and out-of-plane directions, to compare their seismic performance. As a result, it was found that the installed infills significantly affected and enhanced the seismic performance of the existing frames. Although the proposed infills were designed so that the interlocking mechanism was effective only for out-of-plane loads, the infills also contributed to increase the in-plane strength of the frames, which can be explained based on the lateral force-resisting mechanism of this kind of structures. Focusing on the behavior in the large deformations, the un-retrofitted frame axially collapsed as soon as the columns failed in shear. In the case of the retrofitted ones, however, the installed infills supported axial loads instead of the collapsed columns. Moreover, one of the proposed infills also exhibited not only a substantial lateral resistance in the in-plane direction, which was caused by friction between the blocks under axial loads transferred from the collapsed columns, but also a sufficient deformation capacity in the out-of-plane direction.

KEYWORDS: experimental study, masonry, reinforced concrete, seismic performance, seismic retrofit

1. INTRODUCTION

Seismically vulnerable masonry structures are not common in Japan, based on lessons learned 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. On the other hand, interlocking blocks have been used not only for paving streets but also for accelerating masonry construction and/or improving structural performance in various countries [Ramamurthy and Kunhanandan, 2004]. Focusing on past studies, several papers discussed on structural performance for interlocking block walls using differently shaped blocks [e.g. Hatzinikolas et al., 1986, and Anand and Ramamurthy, 2000], few studies have been reported on their applicability for retrofitting seismically vulnerable structures. Therefore, a new retrofit method using masonry walls, consisting of ductile interlocking blocks, is proposed in this study. This paper introduces the development concept of the proposed method, and discusses on its availability through laboratory testing.

2. DEVELOPMENT CONCEPT

Our previous study [Sanada et al., 2006] concluded that masonry structures could be seismically enhanced using interlocking blocks. In this study, although the interlocking mechanism was applied only to improve the in-plane performance of masonry walls, it seemed to be effective for out-of-plane performance. Therefore, in this study, a new interlocking block, capable of resisting out-of-plane loads, was designed as a prototype, as shown in Figure 1.

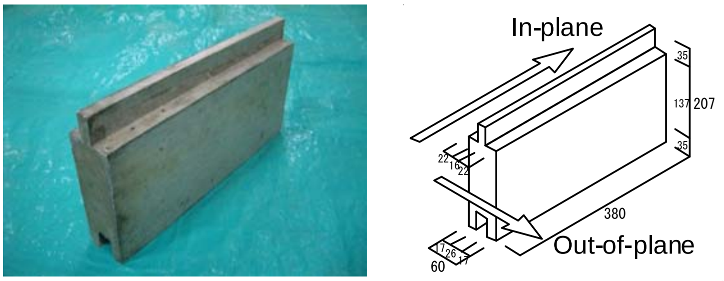


Figure 1 Prototype of interlocking block capable of resisting out-of-plane loads

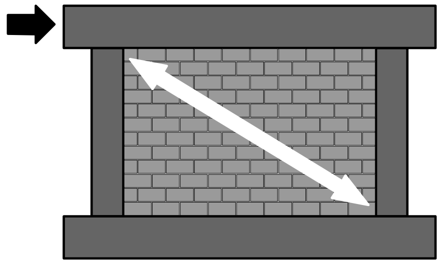


Figure 2 Lateral force-resisting mechanism of infilled frames

2.1. Demand for Blocks

The interlocking mechanism was particularly effective to strengthen masonry structures, which means that higher stresses act between masonry blocks in interlocking walls. Therefore, ductile materials should be used to produce interlocking blocks because tensile failure of brittle materials causes a loss of the interlocking action between blocks. In this study, a fiber-reinforced cement composite (FRCC) was applied to interlocking blocks to prevent walls from brittle failures.

2.2. Advantages in Construction

The masonry walls presented herein do not necessarily need reinforcements inserted to prevent overturning in the out-of-plane direction and losing structural integrity during quakes. Compared to conventional constructions, several advantages can be pointed out as follows. 1) Construction work can be simplified. When retrofitting existing buildings, 2) light and small construction materials are easily conveyed into construction sites, and 3) buildings can be used during construction because main assembly work does not generate noise and vibration.

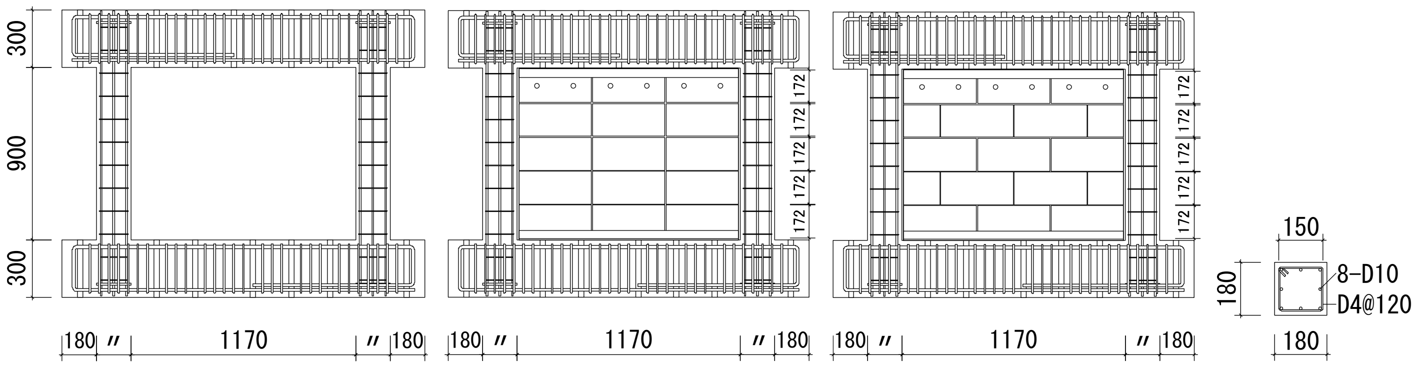
2.3. Expected Seismic Performances

The interlocking mechanism between blocks illustrated in Figure 1 is effective only for out-of-plane loads. On the other hand, bond and friction between blocks contribute as lateral resistance for in-plane loads. Therefore, the in-plane lateral strength of a stand-alone wall made of this block is expected to be very low, in particular, under low axial loads. According to our past study [Choi et al., 2005], however, unreinforced concrete block infills, installed into reinforced concrete frames, could contribute to enhance in-plane strength of frames, although axial loads hardly acted on post-installed infills. This was due to an inclined compression strut forming in the panel when the infill was subjected to shear deformation by the surrounding frame, as illustrated in Figure 2. In this study, focusing on this interaction effect, the blocks presented were planned to apply to post-installed infills so that the structures could exhibit relatively high in-plane lateral strength. Moreover, they were also expected to support axial loads after their surrounding frames failed.

3. EXPERIMENTAL PROGRAM

3.1. Specimens

Three 3/10 scale reinforced concrete one-bay frame specimens, which represent two columns in the first story of typical school buildings designed according to Japanese standards before 1971, were prepared. Two of them were retrofitted by constructing block infills in different bond patterns, as described below. Figure 3 gives details of each specimen (B-Frame: un-retrofitted specimen, I-Frame (S) and (R): retrofitted specimens). The RC columns were expected to fail in shear prior to flexural yielding because of insufficient shear reinforcements. The material properties used for each specimen are shown in Tables 1 to 4. Although the specified compressive strength of concrete was 18 N/mm^2, the actual strength was much higher for all specimens. As a result, the columns did not fail in shear up to the relatively large drift levels in the tests. FRCC used for interlocking blocks was produced with a 1% fiber content by volume, 45% water/cement ratio, and 40% sand/cement ratio, based on the past study [Suwada et al., 2001]. The joint mortar was produced with 67% water/cement ratio and 200% sand/cement ratio, as used for conventional masonry constructions in Japan.



(a) B-Frame (b) I-Frame (S) (c) I-Frame (R)

Figure 3 Details of specimens

Table 1 Concrete properties of specimens

Specimen	E_c (GPa)	f_c (MPa)	f_{cr} (MPa)
B-Frame	21.4	25.3	2.4
I-Frame (S)	23.8	26.8	2.5
I-Frame (R)	24.1	30.4	2.8

where, E_c: initial modulus of concrete, f_c: peak compressive strength of concrete cylinder, f_{cr}: cracking stress of concrete in tension.

Table 2 Steel properties of specimens

Bar no.	Type	E_s (GPa)	f_y (MPa)	f_t (MPa)
D10	Deformed	189	364	489
D4	Deformed	197	382	575

where, E_s: initial modulus of reinforcement, f_y: yield stress of reinforcement, f_t: peak strength of reinforcement.

Table 3 Properties of FRCC of interlocking blocks

Specimen	${}_{cc}E_c$ (GPa)	${}_{cc}f_c$ (MPa)	${}_{cc}f_{cr}$ (MPa)
I-Frame (S)	14.0	45.3	
I-Frame (R)	11.2	39.3	1.6

where, ${}_{cc}E_c$: initial modulus of FRCC, ${}_{cc}f_c$: peak compressive strength of FRCC, ${}_{cc}f_{cr}$: cracking stress of FRCC in tension.

Table 4 Properties of joint mortar for masonry construction

Specimen	${}_{jm}f_c$ (MPa)	${}_{jm}f_{cr}$ (MPa)
I-Frame (S)	37.9	8.7
I-Frame (R)	38.9	9.3

where, ${}_{jm}f_c$: peak compressive strength of joint mortar, ${}_{jm}f_{cr}$: cracking stress of joint mortar in tension.

3.2. Process of Installing the Infills

The proposed masonry blocks were installed in the I-Frame (S) and (R) as shown in Figure 3 (b) and (c). Figure 4 illustrates a process of installing an infill. The vertical cross-section of the retrofitted specimens is also illustrated in Figure 5. The mortar joint thickness was 5 mm except for the surrounding layers of 10 mm. Although interlocking blocks were laid up to the interior clear height of the specimens, only blocks at the top were produced as two pieces divided in half, placed from both sides, and fixed by steel bolts which penetrated blocks, because normal blocks, used for lower layers, could not be physically inserted due to the existence of interlocking shear keys. A stack and running bond patterns were adopted for the I-Frame (S) and (R), respectively. After assembling the blocks, L-shaped steel angles were provided at every corner to prevent the infills from overturning in the out-of-plane direction.

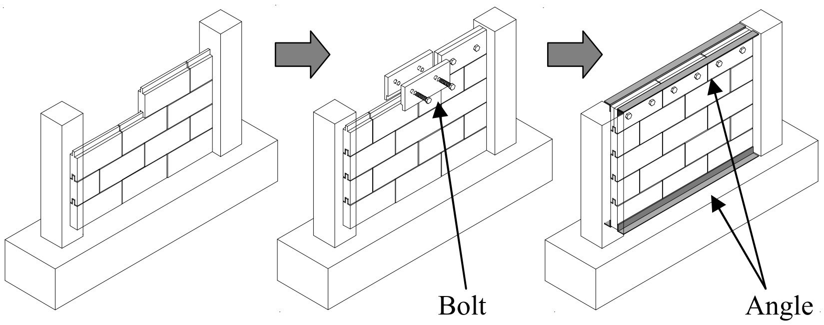


Figure 4 Process of installing an infill

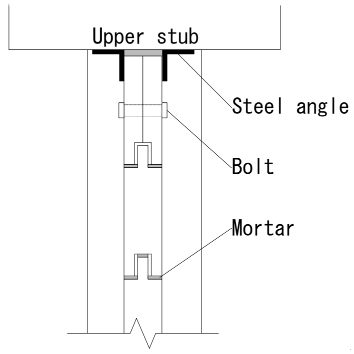


Figure 5 Vertical cross-section of the retrofitted specimens

3.3. Test System and Loading Program

Quasi-static cyclic loading tests were carried out at the testing laboratory of Earthquake Research Institute, University of Tokyo. The loading system consisted of one horizontal hydraulic jack and two vertical ones, as shown in Figure 6. Every specimen was subjected to cyclic lateral loading in the in-plane direction under a constant axial load of 200 kN (≈ 0.15 A_c f_c, where A_c: cross-sectional area of the column). For the I-Frame (R), then, out-of-plane loading was also applied under the same level of axial load after the specimen was rotated 90 degrees on the base of loading system. During the tests, however, the shear span to depth ratio (= h / l in Figure 6) of 0.8 was maintained by controlling both vertical jacks. The applied loading histories in both directions are illustrated in Figure 7. Figure 8 shows the set-up of transducers to measure horizontal, vertical, and diagonal relative displacements of the specimens. Vertical strains on the front and back surfaces of the bottom center block, shown in Figure 8, were also measured for the retrofitted specimens.

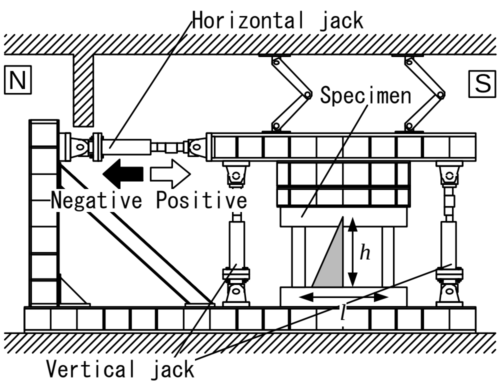


Figure 6 Loading system

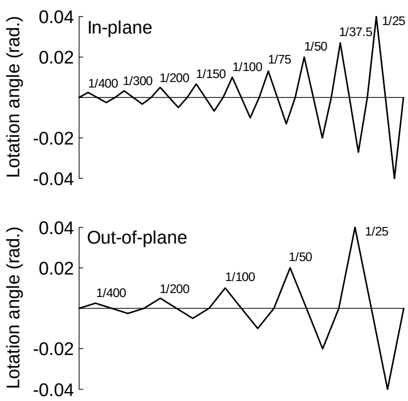


Figure 7 Loading histories

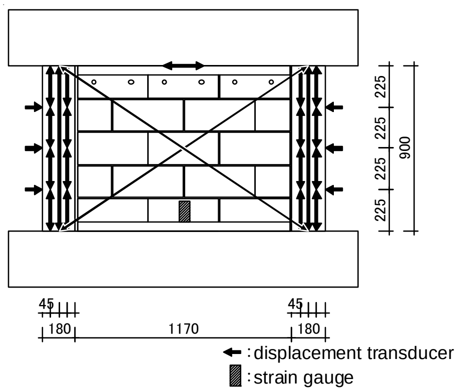
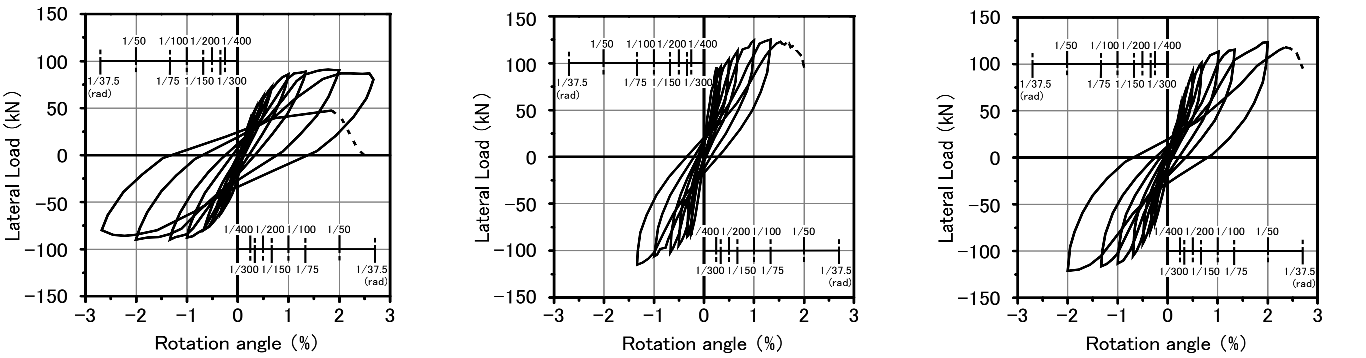


Figure 8 Transducers set-up

4. EXPERIMENTAL RESULTS AND DISCUSSION

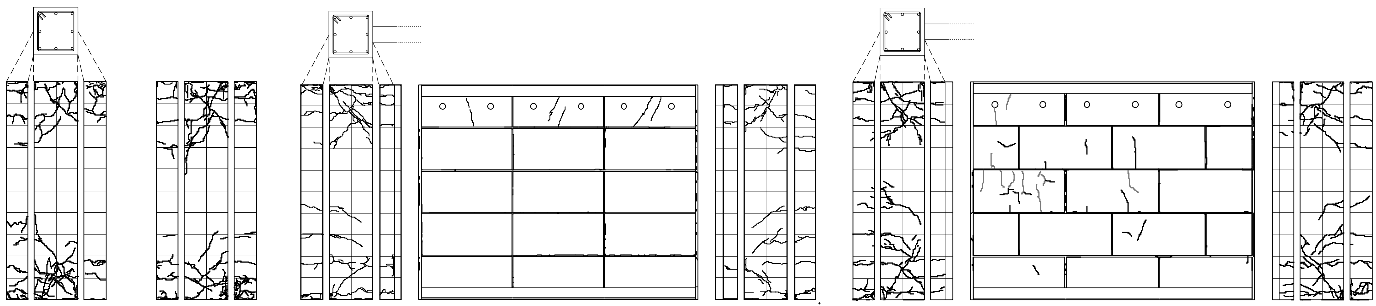
4.1. Behavior up to Shear Failures of Columns

Although both columns in each specimen finally failed in shear, significant differences were observed among the performance of three specimens. Figure 9 shows the relationships between lateral force and top drift ratio for all specimens until the columns failed in shear, which was observed up to the cycles to +1/25 rad., +1/50 rad. and +1/37.5 rad. in B-Frame, I-Frame (S) and I-Frame (R), respectively. Figure 10 compares the crack patterns of the specimens just before the shear failure of the columns



(a) B-Frame (b) I-Frame (S) (c) I-Frame (R)

Figure 9 Lateral force-top drift ratio relationships up to shear failure of the columns



(a) B-Frame (b) I-Frame (S) (c) I-Frame (R)

Figure 10 Crack patterns just before shear failure of the columns

<u>B-Frame</u>

Plastic hinges were formed at the tops and bottoms of both columns around a 1% drift ratio according to Figures 9 (a) and 10 (a). The maximum strength of 90.6 kN was recorded at a 1.78% drift ratio during the cycle to +1/50 rad. A shear crack at the bottom of the tensile column began to open around the peak drift of the cycle to +1/37.5 rad. due to tensile yielding of lateral reinforcements. Strength as well as stiffness had significantly decreased in the following cycle to +1/25 rad. Consequently, both columns failed in shear at a 1.93% drift ratio in this cycle. Spindle-shaped hysteresis loops were observed until brittle failure of the specimen. Although the columns were designed to fail in shear at a relatively small drift level, they exhibited much higher ductility because of an accidental error between the specified and actual properties of concrete as mentioned above.

<u>I-Frame (S)</u>

Installing the masonry infill, the strength of I-Frame (S) was much higher than that of B-Frame. The maximum strength, before shear failure of the columns, was 126.1 kN, which was 1.39 times higher. The columns failed in shear, and began to degrade at a 1.53% drift ratio during the cycle to +1/50. Then, however, no crack was observed on the infill blocks except for the top layer where slight cracks had occurred during the installation work, as shown in Figure 10 (b). As a result, it was verified that the strength of the specimen increased but ductility decreased by installing the masonry infill.

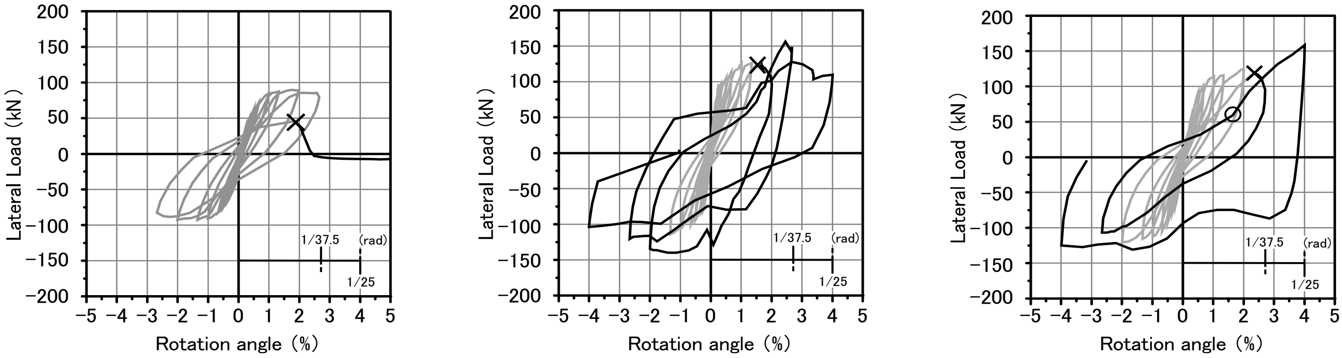
These results can be explained by the same mechanism observed in our past study shown in Figure 2: strength was increased by a compression strut in the panel and ductility was decreased due to a resultant punching shear acting on the bottom/top of the compressive/tensile column.

I-Frame (R)

The failure process of I-Frame (R) was quite similar to that of I-Frame (S). In this specimen, however, the columns failed in shear during the cycle to +1/37.5, and the ductility performance was higher compared to that of I-Frame (S), which was caused by the difference between compressive strength of concrete as shown in Table 1. Moreover, slight cracks were also observed on the blocks in this case.

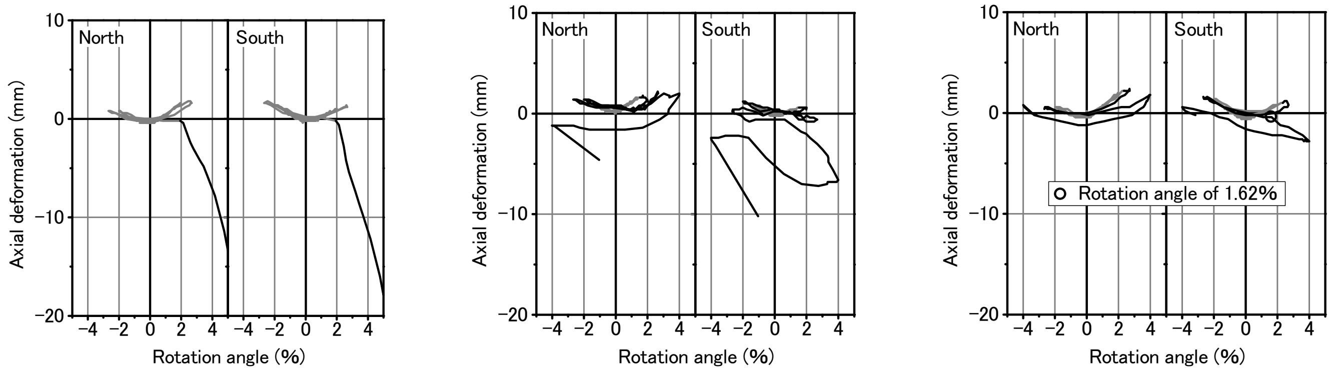
4.2. Behavior after Shear Failures of Columns

Figures 11 and 12 show the lateral force-top drift relationships after the columns failed in shear, and the relationships between axial deformation of each column and top drift, respectively.



(a) B-Frame (b) I-Frame (S) (c) I-Frame (R)

Figure 11 Lateral force-top drift ratio relationships after shear failure of the columns



(a) B-Frame (b) I-Frame (S) (c) I-Frame (R)

Figure 12 Axial deformation of each column vs. top drift ratio

B-Frame

The axial load could not be supported after shear failure of the columns and lateral strength was rapidly degraded. Although an attempt was made to apply an axial load after failure, only lateral drift and compressive deformation of the columns increased as shown in Figures 11 (a) and 12 (a). The loading was stopped when the lateral drift ratio and the averaged compressive deformation were about 7% and 4%, respectively.

I-Frame (S)

On the other hand, the I-Frame (S) did not lose its lateral and axial resistances soon after the columns failed in shear during the cycle to +1/50. After the following cycle to -1/50, however, rocking behavior of the infill blocks at the middle layers began to be observed, as shown in Photo 1. As a result, the horizontal joints between the lowest and second layers were severely damaged. This seemed to be caused by local stress concentration on the blocks, which occurred because rocking of the middle layers was confined by the top and bottom layers. It is important to prevent such stress concentration, because damage to the concave sections, as shown in Photo 1, causes a loss of interlocking action between the blocks, and induces a total collapse of the infill. As mentioned below, however, rocking of the blocks can be prevented by the running bond pattern adopted for I-Frame (R). From Figure 11 (b), although this specimen exhibited a higher lateral strength than the maximum observed before shear failure of the columns due to frictional resistances between the blocks, irregular hysteresis loops were observed because of repeated stress releases with failure of the blocks. Moreover, the specimen supported the axial load during the in-plane loading, but could not support during the following out-of-plane loading.

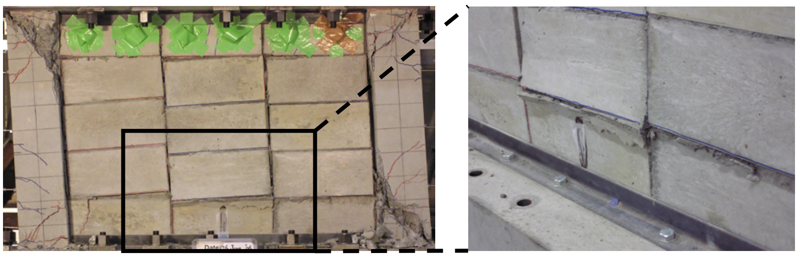


Photo 1 Damage to I-Frame (S) at the peak drift during the cycle to -1/25

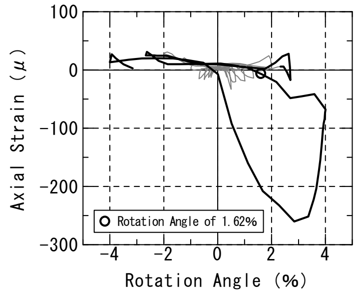


Figure 13 Strain of the bottom center block vs. top drift ratio

<u>I-Frame (R)</u>

The I-Frame (R) could stably support the axial load in spite of the shear failure of the columns. As damage to the columns progressed due to shear during the following cycle to +1/25, significant changes appeared in the behavior of the specimen. Figures 11 (c) and 12 (c) exhibit the beginnings for a recovery of strength and an increase of compressive deformation at a 1.62% drift ratio, respectively. From Figure 13, which gives the relationship between strain on the bottom center block and top drift of the specimen, strain measured on the surface of block also began to increase at the same time. These results indicate that the columns rapidly lost axial resistance from the singular points in these figures, and that axial load, which had been supported by the columns, shifted on the infill. Therefore, the lateral strength of the specimen also recovered due to horizontal friction between infill blocks. Accordingly, as deformation of the specimen and strain of the block progressed, the lateral strength increased to 158.2 kN, which was much higher than that recorded before shear failure of the columns. A typical hysteresis loop for frictional resistance was observed in Figure 11 (c) after unloading in the cycle to +1/25. The lateral drift did not recover in the unloading pass from the peak of +1/25, and it seemed to decrease after the following negative loading attained the static frictional strength in the negative direction.

4.3. Out-of-Plane Behavior of the I-Frame (R)

The infill presented in this study is not expected to exhibit lateral strength in the out-of-plane direction. But it is expected to support axial loads, even if it was subjected to a large lateral deformation in the out-of-plane direction. Therefore, the out-of-plane performance should also be verified through the test. In this study, out-of-plane loading was also applied to

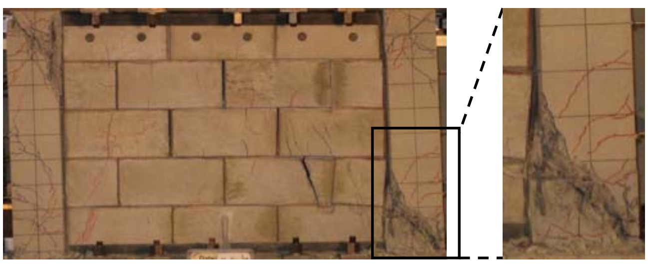


Photo 2 Damage to I-Frame (R) after in-plane loading

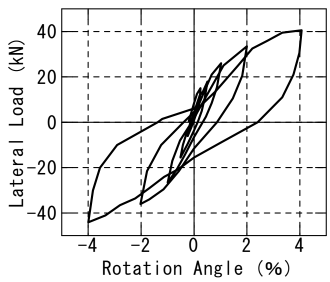


Figure 14 Lateral force vs. top drift during out-of-plane loading

the I-Frame (R) followed by in-plane loading. Photo 2 shows the I-Frame (R) after in-plane loading, which indicates that the columns seemed to have been lost their axial resistance. Figure 14 shows the relationship between lateral force and top drift in the out-of-plane direction. The specimen could exhibit stable hysteresis loops as well as sufficient axial support throughout out-of-plane loading.

5. CONCLUSIONS

A new retrofit method using interlocking masonry infills capable of resisting out-of-plane loads was proposed and applied to a reinforced concrete frame. The effects of installed infills on the seismic behavior and performance of the frame were investigated through quasi-static cyclic loading tests. Major findings are summarized below.

1. The installed infills contributed to enhance the in-plane strength of the frame, although the infills were designed so that their interlocking mechanism was effective only for out-of-plane loads. This was caused by forming an inclined compression strut in the panel when the infills were subjected to shear deformation by the surrounding frame. As a result, the strength of retrofitted specimens (I-Frame (S) and (R)) was about 1.4 times that of the un-retrofitted one (B-Frame).

2. On the other hand, the ductility of the columns decreased. This was caused by higher shear forces acting on the bottom/top of the compressive/tensile column, which were generated as reactions to compression in the strut.

3. The un-retrofitted specimen axially collapsed as soon as both columns failed in shear. In the case of the retrofitted ones, however, the block infills supported axial loads instead of the collapsed columns throughout lateral loading up to a 1/25 drift level in the in-plane direction. When the axial loads were transferred and acted on the block infills, the infills exhibited high frictional resistances. As a result, the maximum strength of the retrofitted frames corresponded to about 1.3 times each maximum recorded before shear failure of the columns.

4. Compared between the retrofitted specimens, damage to infill blocks under the large deformation was more severe in the case of I-Frame (S), which was caused by rocking of the blocks and resultant stress concentration. As a result, this specimen could not finally support axial loads due to failure of the blocks. Such brittle failure can be prevented by the running bond pattern adopted for the I-Frame (R).

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