Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 622

EXPERIMENTAL COMPARISONS OF THE SEISMIC PERFORMANCE OF R/C FRAMES INFILLED WITH DIFFERENT KINDS OF MASONRY BLOCKS

Maidiawati[1] and Yasushi Sanada[2]

ABSTRACT

An experimental investigation compares the seismic behavior of R/C frames infilled with different kinds of block wall. In this study, three 3/10-scale R/C one-bay frame specimens (one of them: BF specimen) were prepared, and two of them were infilled with typical concrete blocks (CB specimen) and new wood interlocking blocks (WB specimen). Quasi-static cyclic loading tests on the specimens were carried out in the in-plane direction. As a result, significant differences of performance were observed among three specimens. The lateral strength of CB specimen was much higher than that of BF specimen. However, the ductility performance of CB specimen was decreased. Moreover, after shear failure of the columns of BF and CB specimens, their lateral strengths were degraded and axial resistances were finally lost. In the case of WB specimen infilled with wood blocks, the lateral strength did not increase significantly, but ductility performance was much higher than those of BF and CB specimens. The wood infill not only supported the axial load in place of the collapsed columns, but also seemed to maintain the lateral resistance caused by friction between blocks. These results indicate that the proposed wood interlocking block infill can enhance the axial performance of existing RC structures, and that roles of infills can be controlled by their materials.

Introduction

Masonry elements are widely used as infill, spandrel, and wing walls around the world, particularly in developing countries. The contributions of these masonry walls have been ignored in the seismic design of buildings due to a lack of knowledge of their performance under seismic loads. However, several studies point out that masonry infills strongly affect the seismic performance of R/C buildings (e.g., Maidiawati and Sanada 2008, Pujol et al. 2008).

Focusing on the actual performance of masonry infills, the second author of this paper proposed an interlocking block infill system, and verified its availability as a device for retrofitting existing vulnerable buildings (Sanada et al. 2008). This experimental study demonstrated that the interlocking infills contributed to improving the strength of R/C frames,

[1]Graduate Student, Graduate School of Engineering, Toyohashi University of Technology
[2]Associate Professor, Faculty of Engineering, Toyohashi University of Technology

but decreased their ductility. Although an infill consisting of interlocking blocks resists out-of-plane loads due to the interlocking action between blocks, it also resists in-plane loads when it is surrounded by boundary elements. This is because an inclined compression strut is formed in the panel when the infill is subjected to shear deformation by the surrounding frame. This interaction generally contributes to an increase in the strength of the overall frame. When the surrounding frame consists of vulnerable RC members (in existing buildings), however, the resultant punching shear causes more severe damage to the member ends. This is possibly caused by the relatively high stiffness of the cement composite used for blocks, which means that an alternative material with lower stiffness may reduce such negative effects on surrounding elements.

Therefore, in this study, an alternative retrofit method focusing on wood as a substitute for interlocking blocks was proposed. Compared to typical concrete blocks, the wood block has higher tensile strength and deformability. Moreover, a panel consisting of wood interlocking blocks can prevent overturning in the out-of-plane direction and loss of structural integrity with interlocking actions between blocks; therefore, construction works can be greatly simplified. For practical uses, however, although fire protections should be applied to the wood panel, it was not considered focusing only on the structural performance in this feasibility study.

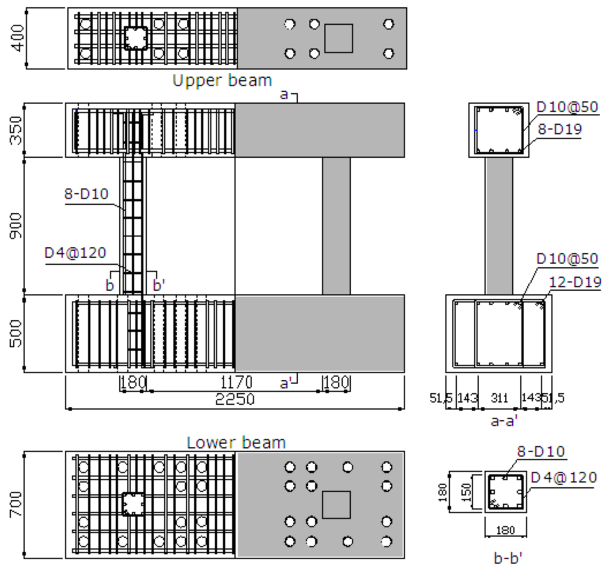
In the following, the seismic behavior and performance of R/C frames with a typical concrete block infill were compared with those with the developed wood infill, and the availability of this new device was investigated experimentally.

Experimental Programs

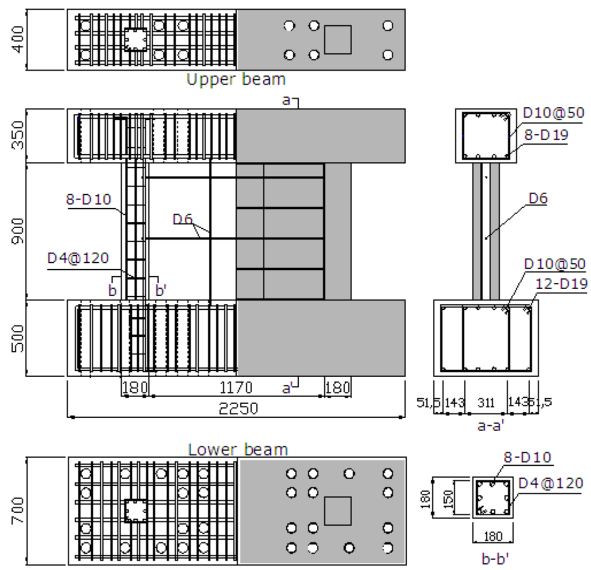
Description of Specimens

Three 3/10-scale R/C one-bay frame specimens were prepared, and two of them were strengthened by installing different kinds of block wall. The bare frame (BF) specimen represents the first story of typical low-rise R/C buildings constructed before the 1970s in Japan. The cross-sectional dimensions of the columns were 180 x 180 mm, with 8-D10 longitudinal rebars and D4@120 (mm) transverse hoops, considering the scale reduction. The clear height of columns was 900 mm. The configuration and rebar arrangements of BF specimen are shown in Fig. 1a).

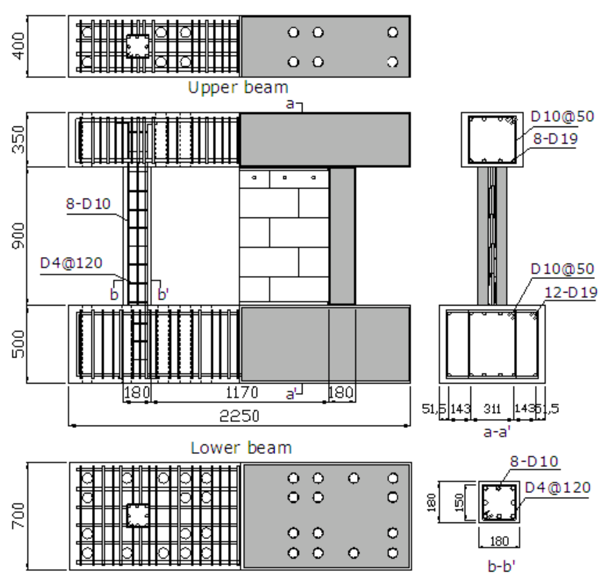
The other specimens were infilled with typical concrete blocks (CB) and new wood interlocking blocks (WB) developed in this study. The details of main frames were the same as those of BF. The concrete blocks, 70 mm in width, 390 mm in length and 190 mm in height, were laid up to the interior clear height of the main frame with mortar joint and reinforcements of D6@400 (mm) in both horizontal and vertical directions, as shown in Fig. 1b). Although the width/height of blocks was not reduced to the applied scale, the thickness was designed considering the scale reduction because the axial stress level should be equivalent to that of the real scale. On the other hand, wood interlocking blocks were designed based on the past study (Sanada et al. 2008) and assembled as follows. 1) Three types of block, prepared as illustrated in Fig. 2, 2) were laid up to the interior clear height of the main frame, as shown in Fig. 3. The first and the third types of wood blocks were placed at the bottom and top layers, respectively, and the second type was placed at middle layers. For the top layer, however, blocks were produced as two pieces divided in half, placed from both sides, and fixed with steel bolts that penetrated the block, because other types of block, used for lower layers, could not be physically inserted due to the existence of interlocking shear keys. 3) Finally, L-shape steel angles were provided at every corner of the lower and upper beams as shown in Fig. 3 to prevent the wood wall from overturning in the out-of-plane direction. Figure 1c) illustrates the details of WB specimen.



a) BF specimen



b) CB specimen



c) WB specimen

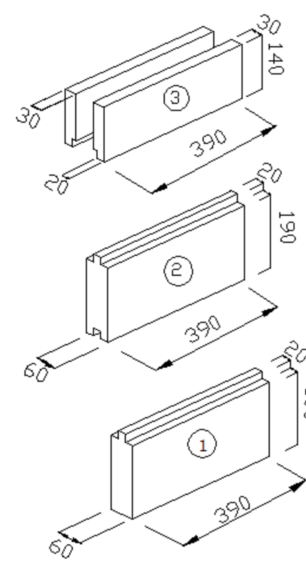


Figure 1 Detailed drawings of specimens

Figure 2 Types of wood block

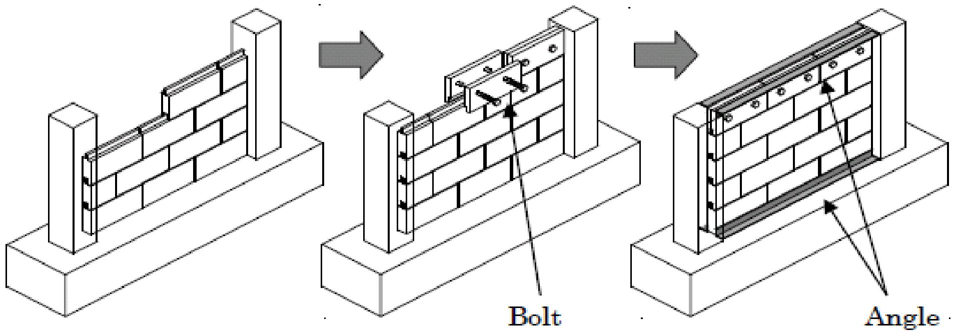


Figure 3 Installation procedure of wood block wall

Material Properties and Structural Performance of R/C frames

The mechanical properties of concrete and reinforcements used for the specimens are shown in Tables 1 and 2. Wood properties differ on each mutual perpendicular axis. The property values are generally the highest along the longitudinal axis (Winandy 1994). The wood properties of interlocking blocks are summarized in Table 3.

Table 1 Concrete properties

Parameters / Specimen	Young's modulus (GPa)	Compressive strength (MPa)	Tensile strength (MPa)
BF	19.3	17.6	1.5
CB	21.2	24.2	2.0
WB	17.6	16.4	1.7

Table 2 Steel properties

Parameters / Bar No.	Young's modulus (GPa)	Yield stress (MPa)	Yield strain (μ)	Tensile strength (MPa)
D4	164	383	2332	537
D10	184	352	1913	492

Table 3 Wood properties

Parameters / Axes	Young's modulus (GPa)	Compressive strength (MPa)
Longitudinal direction	2.9	10.9
Radial direction	0.13	2.8

R/C columns of all specimens were designed to fail in shear prior to flexural yielding based on the Japanese standard (Japan Building Disaster Prevention Association 2005). Flexural and shear strengths were calculated using Eqs. (1) and (2), respectively. The performance of columns is summarized in Table 4.

$$Q_{mu} = \frac{2M_u}{h_0} \quad (1)$$

$$M_u = 0.8.a_t.\sigma_y.D + 0.5N.D\left(1 - \frac{N}{b.D.F_c}\right)$$

$$Q_{su} = \left[\frac{0.053\,.\,p_t^{0.23}\cdot(18+F_c)}{M/(Q\cdot d)+0.12} + 0.85\sqrt{p_w\cdot\sigma_{wy}} + 0.1.\sigma_o\right]\cdot b\cdot j \quad (2)$$

$$p_t = \frac{a_t}{b\,.\,D}, \quad p_w = \frac{a_w}{b\,.\,s}, \quad \sigma_o = \frac{N}{b\,.\,D}$$

where, Q_{mu}: shear force at flexural strength, Q_{su}: shear strength of column, M_u: flexural strength of column, h_o: clear height of column, a_t: total cross-sectional area of tensile longitudinal rebars, σ_y: yield stress of longitudinal rebars, D: column depth, N: axial force, b: column width, F_c: compressive strength of concrete, p_t: tensile longitudinal rebar ratio, M/Q: shear span length: default value is $h_o/2$, d: effective depth of column, p_w: shear reinforcement ratio, σ_{wy}: yield stress of shear reinforcement, σ_o: axial stress in column, j: distance between tension and compression forces: default value is $0.8D$, a_w: total cross-sectional area of shear reinforcements, s: spacing of hoops.

Table 4 Column performance

Parameters / Specimen	Flexural strength, (kN.m)	Shear force at flexural strength, (kN)	Shear strength, (kN)
BF	19.4	43.0	37.3
CB	19.8	44.0	40.0
WB	19.2	42.7	36.8

Loading and Measurement Methods

All of the specimens were tested at the testing facility, Toyohashi University of Technology. Reversed cyclic lateral loads were applied to the specimens with a constant axial load of 200 *kN*, which was determined based on axial stress levels of structural components in an Indonesian earthquake-damaged building (Maidiawati and Sanada 2008). A schematic representation of test set-up and loading system is shown in Fig. 4.

Drift angle *R* (rad.), ratio of lateral displacement to column height, was used for controlling incremental loading. Lateral loading program was initial cycle to R=1/800 followed by two cycles to R=1/400, 1/200, 1/100, 1/50, and 1/25. Although loading stopped when the specimens failed and could not support axial loads, a following pushover load to R=1/10 was applied when they maintained lateral and axial resistances. The lateral loading history is shown in Fig. 5.

The horizontal, vertical, and diagonal relative displacements of the specimens were measured with transducers. The applied loads and displacements were monitored throughout the tests. At the peak and residual drifts in each loading cycle, initiated cracks and crack propagation were marked on the specimens to identify the failure mechanisms of specimens.

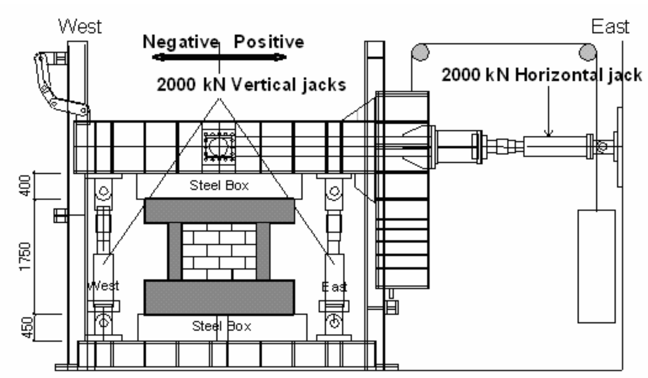


Figure 4 Schematic view of test set-up

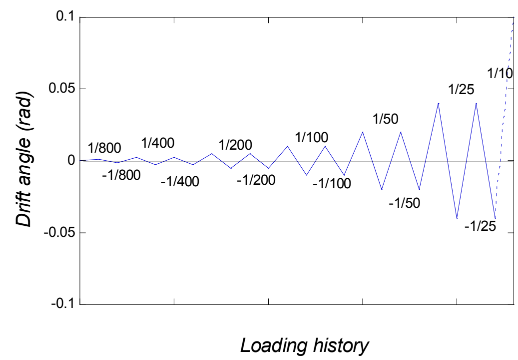


Figure 5 Loading history

Experiment Results and Discussion

Failure Process

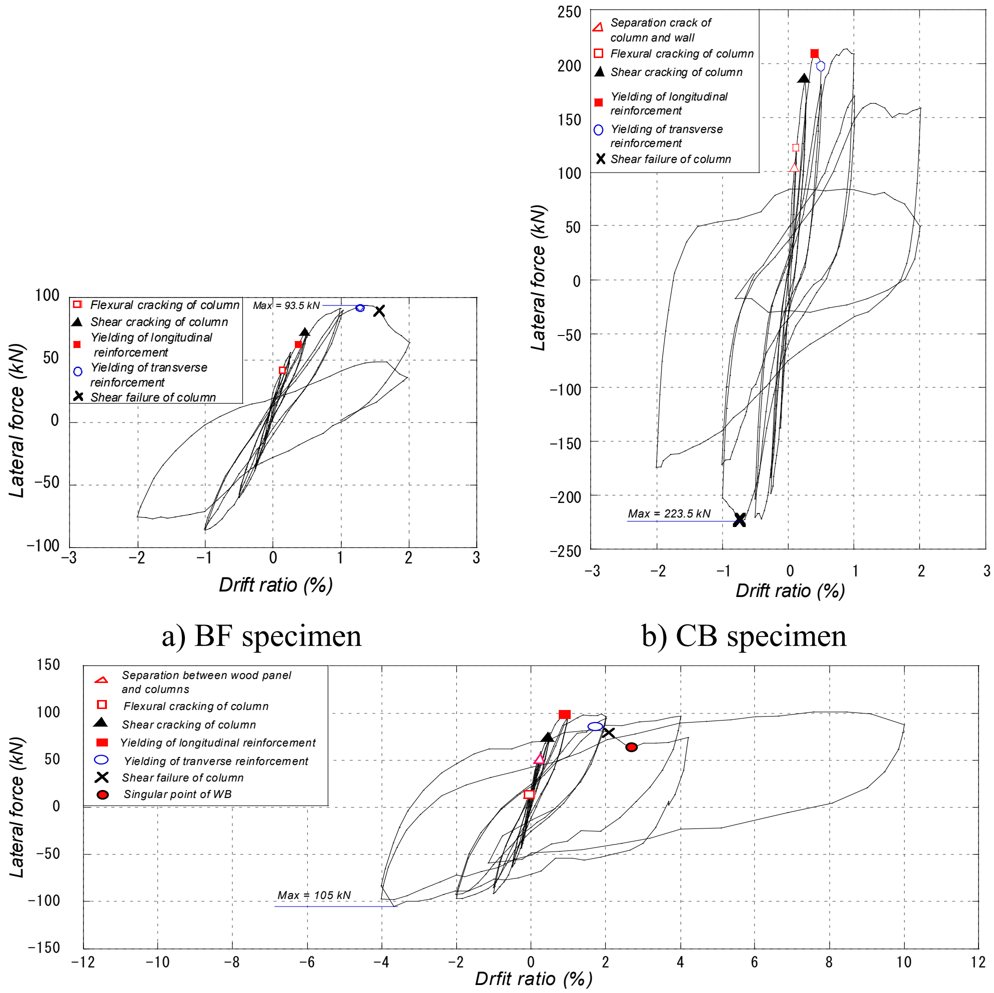
Significant differences of performance were observed among three specimens as shown in Fig. 6, the relationships between lateral force and top drift ratio, which were observed up to the cycles to R=-1/50 for the BF and CB specimens, and R=+1/10 for the WB specimen.

BF specimen

An initial flexural crack occurred during the first cycle when the structure was subjected to a lateral load of 38.5 kN. A shear crack appeared at the compressive column (west column) during the cycle to R=+1/200. The longitudinal reinforcements started to yield during the cycle to R=+1/200, but the transverse reinforcement initially yielded during the cycle to R=+1/50. The maximum strength of 93.5 kN was recorded at a 1.35% drift ratio under the cycle to R=+1/50. Then, the east column failed in shear at a 1.56% drift ratio in this cycle. After the shear failure of column, the strength of the frame began to deteriorate and it could not resist the axial load in the subsequent cycle. The final damage to the BF specimen is shown in Fig. 7a).

CB specimen

Separations between the infill wall and both columns were observed during the first cycle. Flexural cracks were also observed on the compressive and tensile columns in this cycle. Under the cycles to R=+1/400, shear cracks appeared in the compressive column and concrete block wall. Yielding of longitudinal and transverse reinforcements was observed at drift ratios of 0.42% and 0.51%, respectively. Soon after the maximum strength of -223.5 kN was recorded at a -0.7% drift ratio during the cycle to R=-1/100, the columns failed in shear and lateral strength started to decline. After shear failing of the columns, although they could not support the axial load, the block wall seemed to support it in place of the collapsed columns up to the first cycle to R=-1/50. However, the overall frame finally lost lateral and axial resistances due to shear failure of the wall, as shown in Fig. 7b).



a) BF specimen

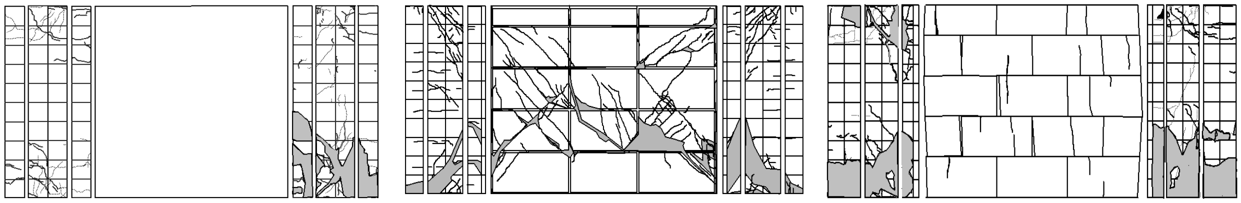
b) CB specimen

c) WB specimen

Figure 6 Lateral force-top drift ratio relationships

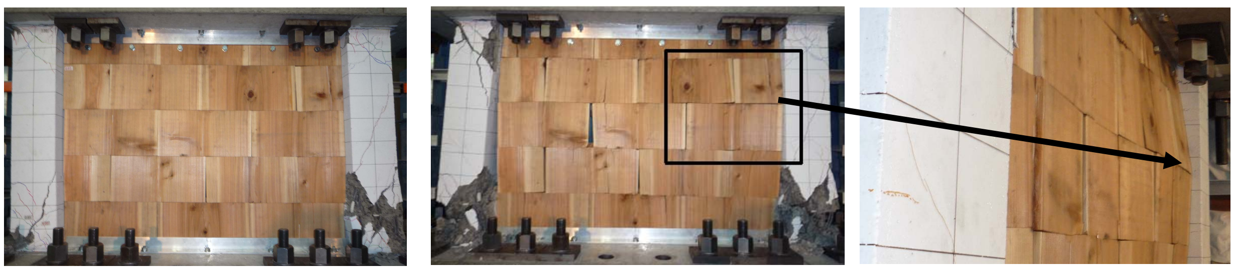
WB specimen

Flexural cracks were observed at the top of the compressive column and the bottom of the tensile column during the first cycle when the specimen was subjected to lateral loads of 13 kN and 23 kN, respectively. Separations between the wood infill and both columns began to appear during the cycle to R=+1/400. Shear cracks appeared at the bottom of the compressive column and at the top of the tensile column during the cycle to R=+1/200. Initial yielding of longitudinal and transverse reinforcements was detected during the cycles to R=+1/100 and R=+1/50, respectively. Lateral strength began to degrade after shear failure of the columns at a 2.03% drift ratio during the cycle to R=1/25. Soon after the strength degradation, however, significant changes appeared in the behavior of the specimen, which were a recovery of strength, as shown in Fig. 6c), and an increase of compressive deformation in the east column, as shown in Fig. 8. Although the wood wall began to sustain damage during the cycles to R=1/25, it could substantially support the axial load in place of the collapsed columns, as shown in Photo 1a). Moreover, the WB specimen maintained the lateral resistance up to a 1/10 drift level, as shown in Fig. 6c), which seemed to be caused by friction between blocks. At the ultimate deformation of R=+1/10, although a deformation of 40 mm in the out-of-plane direction was observed at the middle layers of the wood panel, as shown in photo 1b), the specimen did not lose its axial resistance.



a) BF b) CB c) WB

Figure 7 Final crack patterns of specimens



a) Slight damage to wood wall under the cycle to R=1/25

b) Final damage to wood wall under the cycle to R=1/10

Photo 1 Damage to WB specimen

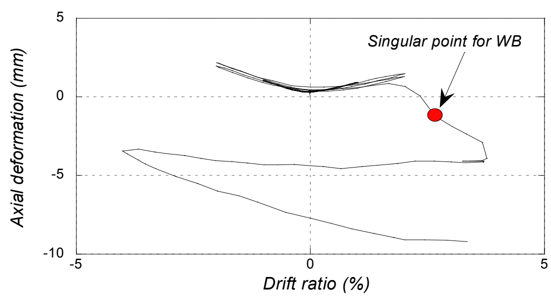


Figure 8 Axial deformation of east column vs. drift ratio relationship

Comparisons of Seismic Performance

Figure 9 compares the seismic performances of all specimens in the envelop curves. It shows that the lateral strength of CB specimen was much higher than that of BF specimen. However, the ductility performance of CB specimen was decreased by installing the concrete block wall. This seemed to be caused by a compression strut forming in the infill when it was subjected to shear deformation by the surrounding frame. Therefore, the resultant high punching shear acted on the bottom/top of compressive/tensile column. In the case of WB specimen infilled with wood blocks, the lateral strength did not increase significantly, but ductility performance was much higher than those of BF and CB specimens.

On the other hand, Figure 10 compares the energy dissipations of all specimens. From the first cycle of loading, the CB specimen performed with a much higher energy dissipation compared to the WB and BF specimens, which was caused by its higher strength. However, the energy dissipation of WB specimen increased rapidly after shear failure of the columns, as the strength of main frame degraded.

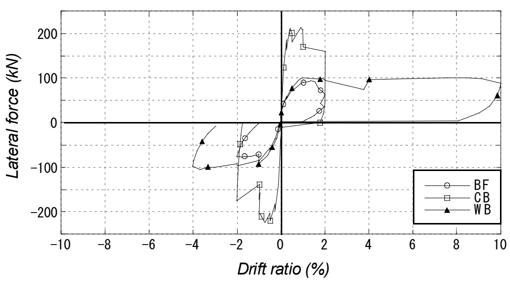


Figure 9 Comparison of envelop curves

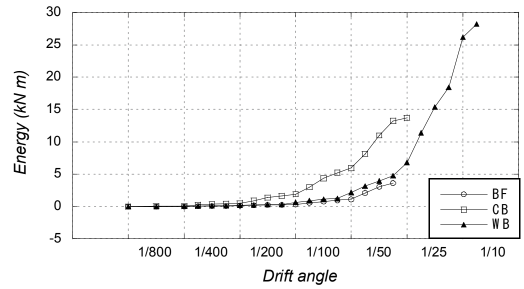


Figure 10 Comparison of dissipated energy

The proposed wood infill did not accelerate damage to the columns, because its lower stiffness (refer to Table 3) reduced the negative effects on the RC columns. These results indicate that the proposed wood infill can enhance the axial performance of existing R/C structures, and that the roles of infills can be controlled by the materials of infill blocks.

Out-of-Plane Performance of Wood Interlocking Wall

The wood wall consisting of interlocking blocks presented in this study is expected to support axial loads, even if it is subjected to large lateral deformations in the out-of-plane direction. Therefore, an additional element test was conducted to investigate the out-of-plane performance. Three specimens were manufactured using three types of block, as shown in Fig. 11.

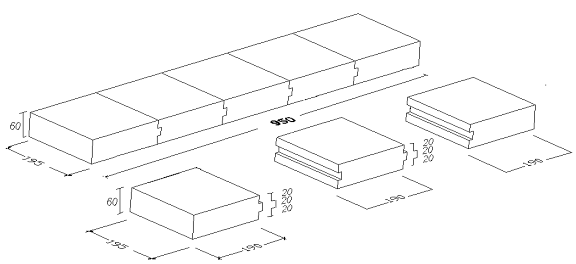


Figure 11 Detailed drawing of specimens for out-out-plane loading tests

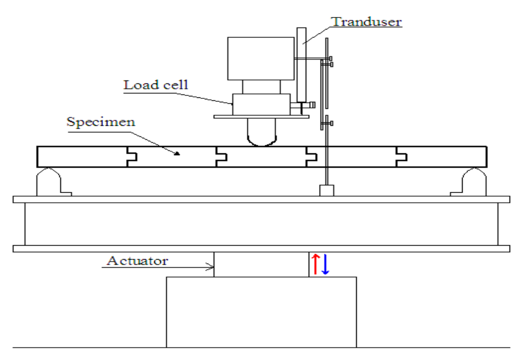


Figure 12 Set-up for out-of-plane loading tests

The set-up and loading system of fracture tests are shown in Fig 12. Fracture tests were performed in which each specimen was loaded in the out-of-plane direction at the center of the span. A transducer was placed to measure the vertical displacement at the loading point. The applied load and vertical displacement were monitored throughout the tests.

Figure 13 shows the relationship between applied load and drift ratio (= vertical displacement/

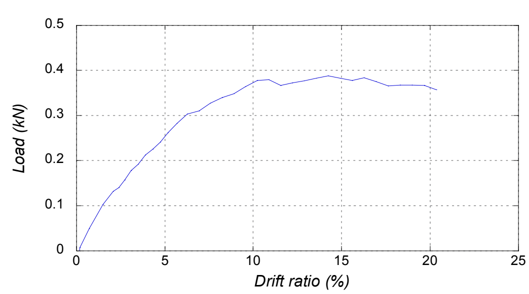


Figure 13 Vertical load-displacement relationship from out-of-plane loading

half of the span length) in the out-of-plane direction that is the averaged performance of three specimens. It indicates that the wood walls can maintain structural integrity under large out-of-plane deformations.

Conclusions

A retrofit method was proposed to improve the seismic performance of existing R/C buildings using a new wall system consisting of wood interlock blocks. Comparing the seismic performance of one R/C bare frame and two more frames infilled with typical concrete blocks and the developed wood blocks, the effects of installing the proposed wall system were investigated experimentally. Major findings are summarized as follows.

1. The typical concrete block infill contributed to enhancing the strength of overall frame, but induced earlier collapses of R/C columns. On the other hand, although the wood infill did not increase the overall strength, it significantly contributed to improving the ductility performance. The wood panel also maintained its lateral resistance due to friction between blocks.
2. The bare frame and the concrete block infilled frame finally lost the lateral and axial resistances due to shear failure. On the other hand, the wood block infilled frame maintained the axial resistance under extremely large deformations.
3. These results indicate that the roles of infills can be controlled by their materials.
4. The proposed wood panel also exhibited the sufficient ductility performance to resist large deformations in the out-of-plane direction.

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Acknowledgments

This study was financially supported by Grant-in-Aid for Young Scientists (A) (No. 19686033), Japan Ministry of Education, Culture, Sports, Science and Technology (MEXT).