Preventing Collapse of Vulnerable R/C Buildings Using Wood Interlocking Blocks

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Abstract

This paper proposes a wood interlocking block infill to prevent vulnerable R/C buildings from collapsing, and discusses its viability through experimental and analytical investigations. A series of structural tests were performed using one-story, one-bay R/C frame specimens with/without installing the proposed infill to verify its contributions. As a result, the infill significantly improved the seismic performance, particularly axial resistance and ductility, of the overall frame. Moreover, an analytical study was also conducted to clarify the distinctive characteristics of the proposed infill. Probabilistic analyses were carried out focusing on a vulnerable R/C building damaged during the 2007 Sumatra, Indonesia earthquakes, which was investigated after the earthquakes by the authors. Comparing the probabilities of collapse for three cases—without infills, with typical brick infills, and with the proposed infills—an alternative concept to prevent building collapses and to save human lives was introduced.

1. Introduction

Masonry elements are widely used as infill, spandrel, and wing walls throughout the world. The contributions of these masonry walls are generally ignored in the seismic design of buildings due to a lack of knowledge of their performance under seismic excitations. However, several past studies point out that masonry walls effectively contribute to the seismic performance of R/C buildings (e.g. Hashemi and Mosalam 2007; Maidiawati and Sanada 2008). On the other hand, 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. Therefore, one of the authors of this paper proposed an interlocking block infill system, and investigated its performance as a device for retrofitting existing vulnerable buildings (Sanada et al. 2008). As a result, it was experimentally verified that the proposed block infill, made of a fiber-reinforced cement composite, significantly improved the seismic performance of an existing R/C frame. For this study, the material of the blocks is replaced by another material to expand the potential applications of the system, as described below.

Wood is a major natural material and is widely used for building construction around the world. Focusing on its unique advantages: light weight, ease of processing, and relatively high strength, it is adopted as an alternative material for interlocking blocks. In this study, a new wood interlocking block infill is proposed and discussed on the basis of experimental and analytical investigations.

2. Wood interlocking block system

Figure 1 shows an interlocking block made of a fiber-reinforced cement composite developed in a previous study (Sanada et al. 2008). Although an infill consisting of the 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 forms in the panel when the infill is subjected to shear deformation by the surrounding frame, as illustrated in Fig. 2. This interaction generally contributes to increasing the strength of the overall frame. When the surrounding frame consists of vulnerable R/C members (in existing buildings), however, the resultant punching shear causes more severe damage to the ends of members, as shown in the figure. 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, the current study focused on wood as a substitute material for interlocking blocks because of its lower stiffness. Moreover, it has distinguishing advantages: one of the major materials for building construction around the world, light weight, ease of processing, and relatively high strength. Figure 3a illustrates three...
types of wood interlocking block developed in this study. These blocks were designed based on the cement blocks previously developed as shown in Fig. 1 (Sanada et al. 2008), however, which were originally referred to typical concrete blocks used in Japan. Figure 3b shows one of the blocks made of Japanese cedar. The top, middle, and bottom blocks in Fig. 3a are for the top, middle, and bottom layers when assembled, respectively. The assembly procedure is described in detail later. Wood properties differ on each mutual perpendicular axis. The property values are generally the highest along the longitudinal axis, which is the direction of wood fibers. Therefore, the vertical axes of blocks correspond to the longitudinal axis to support high axial loads, as shown in Fig. 3b. The wood properties of interlocking blocks are summarized in Table 1.

### 3. Experimental program

#### 3.1 Specimens

Two 3/10-scale R/C one-bay frame specimens were prepared, and one of them was strengthened by installing the infill system developed in this study. The bare frame specimen (BF) represents the first story of a typical low-rise R/C building constructed before the 1970s in Japan. The cross-sectional dimensions of the columns were 180 x 180 mm, with 8-D10 longitudinal rebars and 2-D4@120 transverse hoops, considering the scale reduction. The clear height of columns was 900 mm. The configuration and bar arrangements of the BF specimen are shown in Fig. 4a. Figure 4b shows the other specimen (WB) infilled with wood interlocking blocks produced as presented in Fig. 3. The details of the main frame were the same as those of BF. As mentioned above, the blocks were originally designed based on typical concrete blocks used in Japan. In this feasibility study, although the width/height of 390/190 mm of blocks was not reduced to the applied scale, only the thickness of 60 mm was designed considering the scale reduction because the axial stress level should be equivalent to that of the real scale. A wood interlocking block infill was constructed as illustrated in Fig. 5. For the top layer, however, blocks were produced as two pieces divided in half as shown in Fig. 3a, placed from both sides, and fixed with steel bolts, because other types of block, used for lower layers, could not be physically inserted due to the existence of interlocking shear keys. After assembling the blocks, L-shaped aluminum angles were provided at every corner to prevent the wood infill from overturning in the out-of-plane direction. The mechanical properties of concrete and reinforcements used for the specimens are shown in Tables 2 and 3.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Mechanical properties of wood.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_w ) (GPa)</td>
<td>( f_w ) (MPa)</td>
</tr>
<tr>
<td>2.9</td>
<td>0.13</td>
</tr>
</tbody>
</table>

\( E_w \), \( f_w \): Young’s modulus of wood (maximum instantaneous stiffness) along the longitudinal, and radial (refer to Fig. 3b) axes, respectively. \( f_w \): peak compressive strength of wood along the longitudinal, and radial (refer to Fig. 3b) axes, respectively.
3.2 Loading system and program

The specimens were tested at a testing facility, Toyohashi University of Technology, as shown in Fig. 6. Reversed cyclic lateral loads were applied to the specimens under a constant axial load of 200 kN (≈ 0.15 to 0.20 x (2 x Ac fc)), where Ac: cross-sectional area of each column). Incidentally, although initial conditions of axial stress might be a little different between the infilled specimen and actual structures considering construction procedures, the stress level of wood infill theoretically calculated (= 0.4 N/mm²) was relatively low compared to the strength shown in Table 1 (= 10.9 N/mm²), and the resultant major findings seemed not to be affected by the initial condition. Figure 7 shows the transducers set-up. Drift angle R (rad.), ratio of lateral displacement, which was measured by the transducer A in Fig. 7, to the column height, was used for controlling incremental loading. The lateral loading program had an initial cycle to R = 1/800 followed by two cycles to R = 1/400, 1/200, 1/100, 1/50, and 1/25 for each specimen. However, 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. Figure 8 gives the lateral loading history.

### Table 2 Mechanical properties of concrete.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Ec (GPa)</th>
<th>fc (MPa)</th>
<th>fcr (MPa)</th>
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<tbody>
<tr>
<td>BF</td>
<td>19.3</td>
<td>17.6</td>
<td>1.5</td>
</tr>
<tr>
<td>WB</td>
<td>17.6</td>
<td>16.4</td>
<td>1.7</td>
</tr>
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</table>


### Table 3 Mechanical properties of reinforcements.

<table>
<thead>
<tr>
<th>Bar no.</th>
<th>Type</th>
<th>Es (GPa)</th>
<th>fy (MPa)</th>
<th>ft (MPa)</th>
</tr>
</thead>
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<tr>
<td>D10</td>
<td>Deformed</td>
<td>184</td>
<td>352</td>
<td>492</td>
</tr>
<tr>
<td>D4</td>
<td>Deformed</td>
<td>164</td>
<td>383</td>
<td>537</td>
</tr>
</tbody>
</table>

Es: Young’s modulus of reinforcement (secant stiffness at a strain of 0.001), fy: yield stress of reinforcement, ft: peak strength of reinforcement.
4. Experimental results

The responses under reversed loading, in particular deformation behavior, of BF were significantly improved by installing the proposed block infill. Figure 9 compares lateral force-top drift ratio (R) relationships. Their failure processes, also indicated in this figure, are described in the following.

**BF specimen**

An initial flexural crack occurred during the first cycle when the specimen was subjected to a lateral load of 38.5 kN. A shear crack appeared at the compressive column (east column in Fig. 6) during the cycle to R = 1/200. Longitudinal reinforcements started to yield during the cycle to R = 1/200, but a transverse reinforcement initially yielded during the cycle to R = 1/50. A maximum strength of 93.5 kN was recorded at a 1.35% drift ratio under the cycle to 1/50. Then, the east column failed in shear at a 1.56% drift ratio in this cycle. After the shear failure of the column, the strength of the overall frame began to deteriorate and it could not resist the axial load in the subsequent cycle. The final damage to BF is shown in Fig. 10a.

**WB specimen**

Flexural cracks were observed at the top/bottom of compressive/tensile column during the first cycle when the specimen was subjected to lateral loads of 13.0 kN/23.0 kN, respectively. Separations between the wood infill and both columns began to appear during the cycle to R = 1/400. Shear cracks occurred at the bottom/top of the compressive/tensile column under the cycle to R = 1/200. Initial yielding of longitudinal and transverse reinforcements was detected during the cycles to R = 1/100 and 1/50, respectively. Lateral strength began to degrade after shear failing of the compressive column at a 2.03% drift ratio during the cycle to 1/25. Soon after strength degradation, however, noticeable changes appeared in the behavior of the specimen, which were a recovery of strength, as shown in Fig. 9, and an increase of compressive deformation in the compressive (east) column, as shown in Fig. 11. These results indicate that the column rapidly lost its axial resistance at the same time as the shear failure in Fig. 9, and that the axial load, which had been supported by the collapsed column,
shifted on the infill. As a result, the lateral strength of the specimen recovered due to horizontal friction between infill blocks under the high axial load, as also discussed in our previous tests (Sanada et al. 2008). Therefore, although the wood infill began to be damaged during this cycle, it could substantially support the axial load instead of the collapsed columns, as shown in Fig. 10b. As a result, the WB specimen maintained its lateral resistance up to a 1/10 drift ratio, as shown in Fig. 9. At the ultimate deformation of R = 1/10, although an out-of-plane deformation of 40 mm was observed at the middle layers of the infill, as shown in Fig. 10c, the specimen did not lose its axial resistance.

As mentioned above, it was experimentally verified that the proposed wood infill contributed to improving the ductility of the overall frame without aggravating damage to R/C columns. The lower stiffness of the wood seemed to reduce the negative effects of installing block infills on surrounding frames as shown in Fig. 2, considering our previous test results that the cement block infill aggravated damage to the columns (Sanada et al. 2008).

5. Analytical discussions

Based on the test results, the availability of the proposed infill system is discussed through brief analyses of an Indonesian R/C building damaged during the 2007 Sumatra earthquakes, which was investigated in detail by the authors after the earthquakes (Maidiawati and Sanada 2008).

5.1 Analyzed building

Figure 12 summarizes the analyzed structure, which is a three-story R/C frame building with brick walls. According to our calculations based on two references (JBDPA 2005; AIJ 2000), seismic performance seemed to be significantly affected by brick infills. The computed performance is compared in Fig. 13, where strength is
evaluated to be higher but ductility is evaluated to be lower in the case of considering brick infills.

5.2 Modeling
The building was substituted by a three degree-of-freedom system assuming that it would form a story collapse mechanism in the first story and behave elastically in the upper stories. The weight per unit floor area was assumed to be 12.0 kN/m² according to our previous calculations. The performance of the first story was analyzed with three simplified models based on Figs. 9, 10 and 13. Two models with peak strength and secant stiffness to the peak, as shown in Fig. 13, were used for cases without/with brick infills (Case 1/Case 2, respectively), which were assumed to fail in a brittle manner after attaining their peak strength. In these models, however, initial and secondary stiffness conformed so that the initial stiffness degraded at 1/3 of peak strength and secondary stiffness was equal to 1/3 of initial stiffness. Takeda model was applied for hysteresis rules. Case 3, with the proposed wood infills installed instead of brick infills, was also considered using the same
analytical model as Case 1 combined with a post-yield model to simulate the behavior after shear failure of column in Fig. 9. Post-yield behavior was represented by a bilinear model with a post-yield stiffness 1/100 times the initial stiffness, unloading stiffness equal to secant stiffness to the yield strength, and ultimate drift angle of 1/25. Figure 14 compares three cases of seismic performance assumed for the first story. In particular, Case 3 represents lateral and axial resistances of the wood infill followed by collapse of the main frame, which is verified from Fig. 15 that compares between the test result and the assumed model. Incidentally, focusing on axial stress levels of brick infills in the analyzed building, shown in Fig. 12b, and the wood block infill tested in this study, the former level of 3.1 N/mm² (= total weight of building/gross cross-sectional area of infills) agrees well with the latter of 2.8 N/mm² (= applied axial load/cross-sectional area of wood infill). The resultant fundamental periods of the systems were 0.46, 0.26, and 0.46 sec. for Cases 1, 2, and 3, respectively. Viscous damping was assumed to be proportional to instantaneous stiffness with a damping constant of 5%.

5.3 Input earthquake motions
Eight artificial earthquake ground motions were generated assuming a bilinear function for the Fourier amplitude spectrum, as shown in Fig. 16, and Gaussian envelopes with different standard deviations (σ = 0.01, 0.02, 0.04, 0.06, 0.10, 0.14, 0.20, 0.26 (× 2π rad.)) for the phase difference spectra (Kuwamura et al. 1997). Table 4 summarizes the input motions, and Fig. 17 shows the acceleration response spectra at 5% damping. The Sₐ index in Table 4 means averaged spectral acceleration for the range from 0.26 to 0.46 sec., which covers the fundamental periods of analytical models. Ground motions were scaled to the specified levels of Sₐ up to 15.0 m/sec² every 0.5 m/sec². (Talaat and Mosalam 2009). As reference, according to seismic hazard analyses by Petersen et al. (2004), the peak ground acceleration at 10% probability of exceedance in 50 years for rock site conditions ranges 0.3 to 0.4 g at the location of the building.

5.4 Analytical results
Examples of the analytical results are shown in Fig. 18, which gives the time history of the first story drift in each case under the Art 4 motion, scaled to Sₐ of 3.0 m/sec², in Table 4. The figure means that Cases 2 and 3 did not exceed the deformation capacity, defined for each model in Fig. 14, because of brick and wood infills, while Case 1 collapsed around 16 sec. Moreover, the probability of exceeding the deformation capacity for each model at
each spectral acceleration level was computed and is plotted in Fig. 19, to introduce the development concept of the wood infill proposed in this study. Although only brief analyses were conducted, significant differences among the seismic performance of all analytical cases clarify the viability of both types of infill. Comparing Cases 1 and 2, although brick infills contributed to reducing damage to buildings under more severe ground motions, the improvement was relatively slight due to brittle failure posterior to the peak strength assumed in the analyses. On the other hand, a much greater improvement was observed in Case 3. In this case, however, although the limit state with regard to life safety is shown by the circle in Fig. 19, failure of the main frame is represented by the square. Namely, the proposed wood infill aims to prevent/mitigate total collapse of vulnerable buildings, while allowing damage to main structures. This figure analytically verifies its realistic potential to satisfy such a development concept.

Moreover, in this study, the analyses were neglecting the out-of-plane performance of masonry infills. More significant differences are possibly obtained between Cases 2 and 3, considering vulnerable out-of-plane performance of brick infills. Figure 20 summarizes push-over loading tests of the proposed wood infills in the out-of-plane direction. Figure 21 gives the relationship between vertical load and deflection at the mid-span, which is shown as the averaged value of three specimens. It was found that the proposed wood infill exhibited high ductility in the out-of-plane direction, as also shown in Fig. 22. Therefore, further study is needed to quantify out-of-plane performance, and/or evaluate its contributions to preventing the collapse of vulnerable buildings through more precise numerical modeling.

6. Conclusions

A wood interlocking block infill system was proposed, and its beneficial performance was verified through structural tests and numerical analyses. The new infill was developed to reduce negative effects on surrounding structural elements due to the application of wood with a lower stiffness. Structural tests on 3/10-scale R/C one-bay frame specimens were performed with/without installing the proposed wood infill. Installing the infill significantly improved the seismic performance of the overall frame, particularly axial resistance and ductility. The infill exhibited lateral resistance as well as axial support up to a 1/10 drift ratio, nevertheless, the main frame collapsed much earlier. Compared to the performance of a bare frame, however, the ductility of the infilled frame did not decrease in accordance with the design concept of the proposed infill. Numerical analyses
of the Indonesian building damaged by the 2007 earthquakes were also conducted using simplified modeling. The contributions of the proposed infill were mainly discussed through the probabilities of collapse computed under several artificial earthquake ground motions. An alternative retrofit strategy focusing on preventing collapse was introduced from the analytical results showing that the limit state with regard to life safety could be significantly improved.

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References


