Collapsing Simulation of Wooden House Retrofitted by ACM Braces During Seismic Ground Motion

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\textbf{ABSTRACT}

Major earthquakes in Japan have caused serious damage to a lot of existing wooden houses built by some old seismic design codes before 1981. One of the authors has already developed an advanced seismic retrofitting method for existing wooden house using an advanced composite material (ACM) bracing method. ACM bracing method has already applied to two existing wooden houses for seismic retrofit. On the other hand, it is also very important to accurately evaluate the seismic performance of a retrofitted wooden house under a large seismic ground motion. In this paper, the seismic performance of a wooden house retrofitted by ACM braces was numerically confirmed by a collapsing process analysis based on the Distinct Element Method.

\textbf{1. INTRODUCTION}

A great number wooden houses in Japan have suffered severe damage such as large deformation and collapsing against several earthquakes with Magnitude 7 to 9, because most of the collapsed wooden houses were built by some old earthquake design codes before 1981. Seismic retrofitting policy for a lot of old wooden houses has become an urgent and important issue to solve as quickly as possible in Japan. In general, a seismic retrofitting work for existing wooden house can be schematically and statically decided by an upper structural index and some investigation data of its house, and does not need any seismic response of wooden house in the decision process of its seismic retrofit design. This upper structural index is a ratio of the possessive resistant force to the necessary one of wooden house.

In this paper, a seismic response analysis of wooden house is carried out by using a structural analysis software “Wallstat” (Nakagawa \textit{et al.} 2010, Nakagawa 2011) based on the Distinct Element Method (Cundall \textit{et al.} 1979) in order to investigate the seismic performance.
2. ACM BRACING METHOD AND VIBRATION EXPERIMENT

In Japan, there are many seismic retrofitting countermeasures for wooden houses such as timber brace, additional wall, connecting steel plate, and so on. One of the authors has already developed an advanced seismic retrofitting method for existing reinforced concrete (RC) and steel (S) building structures using ACM bracing method which consists of Carbon Fiber Reinforced Plastic (CFRP) plate and steel plates (Takatani et al. 2011, Takatani 2012a). By an advanced improvement of RC structural ACM bracing technique, Takatani (2012b) has developed a new ACM bracing method using an e-plate for old wooden house. E-plate is a thin plate of CFRP with 1.2mm thickness and 25mm width. This seismic retrofitting method has applied to several wooden houses as shown in Photo 1. Photo 2 shows three types in ACM bracing method proposed by one of the authors, and a horizontal resistant force and displacement relationship of each ACM brace type was experimentally obtained. As seen from Photo 1, types 2 and 3 indicated in Photo2 were applied to an existing wooden house.

On the other hand, some vibration experiments using an oscillator-measurement system shown in Photo 3 were conducted in some wooden houses retrofitted by ACM bracing method using e-plate, and the effect of seismic retrofitting work was confirmed by making an accurate evaluation of some transmission functions obtained from the
vibration experiments. However, the seismic performance effect of ACM bracing method has not been confirmed against a strong earthquake ground motion caused a collapsing phenomenon of wooden house, because these vibration experiments previously mentioned were conducted to accurately evaluate the natural frequency characteristics of the retrofitted wooden house by means of a sweep vibration technique with small amplitude.

In this paper, a seismic response analysis of wooden house is carried out by using “Wallstat” in order to investigate the collapsing behavior of wooden house and the seismic performance effect of ACM bracing method. An earthquake ground motion wave record with Japan Meteorological Agency (JMA) seismic intensity of “6 upper” level is used as an input motion in the collapsing analysis. Also, some transmission functions are evaluated from seismic responses at arbitrary measuring points on the wooden house, and also transmission functions obtained in the collapsing analysis of “Wallstat” are compared with those obtained in vibration experiments using an oscillator-measurement system.

3. OUTLINE OF COLLAPSING ANALYSIS

Target of the collapsing process analysis in this paper is a two-story wooden house built in 1961. Vibration experiments using an oscillator-measurement system were conducted for this wooden house before and after seismic retrofitting work using ACM bracing method in 2011. Fig. 1 shows the wooden house floor plans before and after seismic retrofitting work, and locations of a vibration sensor and an oscillator shown in Photo 3 are indicated in Fig. 1, too. The wooden house was retrofitted by outside, inside and corner ACM bracing techniques as shown in Photo 1. Some types of ACM bracing method for wooden house as illustrated in Photo 2 have already developed by Takatani (2012b). This ACM bracing method for wooden house is characterized by short construction period, more economical cost, and more durable countermeasure compared to other traditional seismic retrofit countermeasures.

In this paper, a structural analysis software of “Wallstat” is conducted in order to investigate the seismic response behavior and the collapsing process of wooden house during a large earthquake ground motion. This software has an original analysis technique (Nakagawa et al. 2010) using the basic theory of the Distinct Element Method proposed by Cundall et al. (1979), and can be taken into consideration the extremely
Fig. 1 Floor plan of wooden house (locations of a sensor [open triangle] and an oscillator [solid triangle])

Fig. 2 Framing plan of wooden house
non-linear properties of timber members breaking or being dispersed. Fig. 2 illustrates a typical framing plan of Japanese two-story wooden house built by a traditional wooden-based building method. In the collapsing process analytical calculation, a wooden house can be modeled by a lot of timber elements such as beam and column connected with non-linear spring as shown in Fig. 2, and also can be modeled by lumped mass and the weight of each floor in wooden house model can be obtained from each structural element as illustrated in Fig. 3.

![Fig. 3 Weight of floor in the analytical model of wooden house (Nakagawa 2011)](image)

### 3.1 Modeling of Structural Element

#### Modeling of Frame

Timber frame is modeled by two elasto-plastic rotational springs (plastic hinge) and an elastic beam component as shown in the left-hand side of Fig. 4. The spring can be defined by a relationship between the bending moment $M$ and the angle of rotation $\theta$ with the skeleton curve indicated in the right-hand side of Fig. 4. The bending moment starts to fall once if it is over the maximum bending moment, and the rotating spring changes to a pinned joint state at the point if the bending moment reaches 0, and then the beam component can be judged to have been broken.

![Fig. 4 Schematic diagram and skeleton curve of frame spring (Nakagawa 2011)](image)

#### Modeling of Joint Spring

Joint spring can be modeled by both an elasto-plastic spring and a rotational spring as shown in Fig. 5(a). Timber characteristic of the compression and tensile elasto-plastic spring consist of an elastic part and slip-type part indicated in Fig. 5(b), and also timber characteristics of the rotational spring is assumed to be a slip-type relationship between ending moment $M$ and angle of rotation $\theta$ shown in Fig. 5 (c). When the elasto-plastic spring or the rotational spring of the joint exceeds the maximum structural
strength or moment and their strength values becomes 0, the joint will be adjudged to have been broken and then the spring will be annihilated.

Modeling of Shear wall and Bracing

Vertical shear wall indicated in Fig. 6 can be modeled by the replacement of truss component with a load-displacement non-linear relationship shown in Fig. 8. Also, bracing shear wall illustrated in Fig. 7 can be modeled by the replacement of compression and tensile truss components defined by a set of bi-linear and slip skeleton curve shown in Fig. 8, too.

Parameters of Structural Element

In this paper, Young's modulus and the maximum bending moment of timber com-
ponent are assumed to be 2,000MN/m² and 10kNm, respectively. External and internal walls in wooden house can be assumed to be lath mortal wall and clay wall, respectively. For seismic retrofit work, plywood is used as internal wall. Parameters of hysteretic characteristics of their walls are shown in Table 1. Parameters of stub tenon jointed at the interface between beam, column and corner bracing used for seismic retrofit work are described in Table 2. Table 3 shows the parameters of hysteretic characteristics of timber brace and ACM brace element.

### Table 1 Parameters for hysteretic characteristics of vertical shear wall (Nakagawa 2011)

<table>
<thead>
<tr>
<th></th>
<th>$P_1$</th>
<th>$P_2$</th>
<th>$P_3$</th>
<th>$P_4$</th>
<th>$D_1$</th>
<th>$D_2$</th>
<th>$D_3$</th>
<th>$D_4$</th>
<th>$h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay Wall</td>
<td>0.5</td>
<td>1.75</td>
<td>2.0</td>
<td>0.0</td>
<td>0.010</td>
<td>0.05</td>
<td>0.10</td>
<td>0.5</td>
<td>2</td>
</tr>
<tr>
<td>Lath Mortal Wall</td>
<td>1.0</td>
<td>3.50</td>
<td>4.3</td>
<td>0.0</td>
<td>0.002</td>
<td>0.01</td>
<td>0.05</td>
<td>0.2</td>
<td>2</td>
</tr>
<tr>
<td>Structural Plywood</td>
<td>3.0</td>
<td>9.50</td>
<td>10.5</td>
<td>0.0</td>
<td>0.010</td>
<td>0.06</td>
<td>0.12</td>
<td>0.3</td>
<td>2</td>
</tr>
</tbody>
</table>

$h$: viscous damping factor

### Table 2 Parameters for hysteretic characteristics of elasto-plastic spring (Tajima et al. 2000, Nakagawa 2011)

<table>
<thead>
<tr>
<th></th>
<th>$K_{s1}$</th>
<th>$K_{s2}$</th>
<th>$K_{s3}$</th>
<th>$D_1$</th>
<th>$D_2$</th>
</tr>
</thead>
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<tr>
<td>Stub Tenon</td>
<td>900</td>
<td>-18.919</td>
<td>-33.333</td>
<td>0.0015</td>
<td>0.02</td>
</tr>
<tr>
<td>Corner Bracing</td>
<td>5,128</td>
<td>651</td>
<td>-154</td>
<td>0.0027</td>
<td>0.015</td>
</tr>
</tbody>
</table>

### Table 3 Parameters for hysteretic characteristics of bracing spring (Nakagawa 2011)

<table>
<thead>
<tr>
<th></th>
<th>$P_1$</th>
<th>$P_2$</th>
<th>$P_3$</th>
<th>$P_4$</th>
<th>$D_1$</th>
<th>$D_2$</th>
<th>$D_3$</th>
<th>$D_4$</th>
<th>$h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timber Brace</td>
<td>0.500</td>
<td>2.500</td>
<td>2.800</td>
<td>0.000</td>
<td>0.001</td>
<td>0.015</td>
<td>0.050</td>
<td>0.250</td>
<td>2</td>
</tr>
<tr>
<td>ACM Brace (e-plate)</td>
<td>3.193</td>
<td>6.387</td>
<td>9.580</td>
<td>0.000</td>
<td>0.010</td>
<td>0.021</td>
<td>0.031</td>
<td>0.043</td>
<td>2</td>
</tr>
</tbody>
</table>

3.2 Transmission Function

In this paper, transmission functions evaluated from floor responses by “Wallstat” are compared with the results obtained from an oscillator-measurement system. These functions can be defined by the spectral ratio of Fourier spectra at two arbitrary points of wooden house. For the oscillator-measurement system, vibration response wave data obtained from two sensors and an oscillator located on the second floor of wooden house were used in the accurate evaluation of transmission functions. Transmission functions evaluated from both the oscillator-measurement system and the simulation by a collapsing process analysis are shown in Figs. 9 and 10.

Peak frequencies of transmission function obtained from an oscillator-measurement system are 4.2Hz in ridge direction and 5.5Hz in span direction, respectively. It can be seen from these figures that transmission function after seismic retrofit shifts to high frequency range in comparison with that before seismic retrofit and also peak frequencies after seismic retrofit in their functions in both ridge and span directions are higher than those before seismic retrofit. As can be seen from the transmission function obtained by “Wallstat” in Fig. 10, peak frequencies are in almost agreement with those obtained from an oscillator-measurement system.

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4. EVALUATION RESULTS OF COLLAPSING PROCESS OF WOODEN HOUSE

4.1 Input excitation

Collapsing process analysis of wooden house before and after seismic retrofit using ACM bracing method is carried out in this paper. An earthquake ground motion wave with JMA seismic intensity of “6 upper” level is employed as an input earthquake ground motion data for the collapsing analysis. The effect of the earthquake motion spectrum on the difference of seismic response can be investigated by using some

Table 4 Earthquake ground motion records

<table>
<thead>
<tr>
<th>Record Name</th>
<th>$I_{JMA}$</th>
<th>Peak Ground Acceleration (cm/s²)</th>
<th>Peak Ground Velocity (cm/s)</th>
<th>$f_p$ (Hz)</th>
<th>Duration (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JR Takatori</td>
<td>6.4</td>
<td>657</td>
<td>126</td>
<td>0.81</td>
<td>30</td>
</tr>
<tr>
<td>JMA Kobe</td>
<td>6.4</td>
<td>818</td>
<td>91</td>
<td>1.43</td>
<td>15</td>
</tr>
<tr>
<td>K-NET Tohkaimachi</td>
<td>6.2</td>
<td>1,716</td>
<td>59</td>
<td>4.47</td>
<td>45</td>
</tr>
<tr>
<td>KiK-net Higashi Naruse</td>
<td>6.4</td>
<td>2,449</td>
<td>76</td>
<td>3.06</td>
<td>50</td>
</tr>
<tr>
<td>K-NET Kashiwazaki</td>
<td>6.3</td>
<td>638</td>
<td>113</td>
<td>0.45</td>
<td>15</td>
</tr>
</tbody>
</table>

$f_p$: peak frequency of root mean square value of Fourier spectrum
seismic wave records with the same level intensity which has a different peak frequency in Fourier spectra. Table 4 shows some parameters of earthquake ground motion wave records used as an input excitation of the collapsing process analysis. JR Takatori wave record is employed in this collapsing analysis, and there are peak frequencies in JR Takatori wave record in the frequency range of 0.5 to 1.0 Hz, which causes severe damage on a lot of old wooden houses reported by Sakai et al. (2002).

4.2 Collapsing Process and Seismic Response

Fig. 11 shows the displacement wave data and Fourier spectra for both NS and EW components obtained from JR Takatori wave record. It can be seen from this figure that the displacement amplitude after 5 seconds becomes much larger than that before 5 seconds. These displacement wave data are used as input motions in the collapsing analysis of wooden house.

![Displacement waves and Fourier spectra of JR Takatori wave record](a) Displacement waves  
(b) Fourier spectra

Fig. 11 Displacement waves and Fourier spectra of JR Takatori wave record

Figs. 12 and 13 show collapsing process behavior of wooden house under Japan Railway (JR) Takatori wave record used as input earthquake ground motion. In this collapsing process analysis, NS and EW components in JR Takatori wave record are used as input motion to the ridge direction and the span direction of wooden house’s floor plan illustrated in Fig. 1, respectively. The wooden house in Fig. 12 has no seismic retrofit work, and the house in Fig. 13 is retrofitted by the ACM bracing method. If a wall with gray color has a damage, the wall color changes to other color. When the degree of its damage increases during seismic motion, the wall color changes from gray to yellow, orange, and red. It can be seen from Fig. 12 that some walls have severe damages after 4 seconds and also both walls and roof on the first floor begin to collapse after 6 seconds. After 8 seconds, large deformation occurs at the center of the first floor, and the wooden house leads to the collapse after 10 seconds. On the other hand, although some walls in the wooden house retrofitted by ACM bracing method illustrated in Fig. 12 starts to have some damages after 6 seconds, the wooden house does not collapse even after 30 seconds.

Absolute displacement responses on the second and third floors of wooden house are illustrated in Fig. 14. The solid line in Fig. 14 means the displacement response before seismic retrofit and the dash line does the displacement response after seismic retrofit. As can be seen from Figs. 14(a) and 14(b), the absolute displacement response on the second floor before seismic retrofit becomes much larger after 5 seconds com-
Fig. 12 Seismic response of no-retrofitted wooden house during JR Takatori wave record

Fig. 13 Seismic response of retrofitted wooden house during JR Takatori wave record
pared to that after seismic retrofit. On the other hand, it is noted from Figs. 14(c) and 14(d) that the absolute displacement response on the third floor before seismic retrofit becomes much larger after 7 seconds compared to that after seismic retrofit. This implies that the collapse of the third floor of wooden house occurs after that of the second floor which is caused by a large plastic deformation due to JR Takatori wave record.

Fig. 14 Absolute displacement responses of wooden house before and after seismic retrofit

5. CONCLUSIONS

In this paper, a structural analysis based on the Distinct Element Method was conducted in order to investigate the collapsing behavior of wooden house during a large earthquake ground motion and the seismic performance effect of ACM bracing method using e-plate. Moreover, transmission functions obtained from the collapsing process analysis were compared with those obtained in vibration experiments using an oscillator-measurement system.

In summary, the following conclusions can be made based on the results presented in this paper.

(1) Seismic performance of an old wooden house retrofitted by ACM bracing method can be numerically confirmed by a collapsing process analysis. Seismic response of the wooden house greatly depends on the spectral characteristics of input earthquake ground motion used in the collapsing analysis.

(2) Transmission function of retrofitted wooden house almost accords with vibration measurement result obtained by an oscillator-measurement system. Transmission
function after seismic retrofit shifts to high frequency range in comparison with that before seismic retrofit.

(3) The wooden house without any seismic retrofit collapses for JR Takatori wave record, whose peak frequency in Fourier spectrum is within the range from 0.5Hz to 1.0Hz. Consequently, there exists a dangerous earthquake ground motion with peak frequency of 0.5-1.0Hz in Fourier spectrum for no-retrofitted wooden house.

(4) As the wooden house retrofitted by ACM bracing method does not suffer severe damage against any earthquake ground motion waves, ACM bracing method for old wooden house may be an effective seismic retrofit.

Although the effect of earthquake ground motion spectrum on the seismic response of wooden house is not presented in detail in this paper, it is necessary for an intensive study on the effect of earthquake ground motion spectrum on the seismic response of wooden house by using some earthquake ground motion wave data, which have the same level intensity with a different peak frequency in Fourier spectra. In addition, further investigation may be needed to simulate the collapsing process phenomenon of wooden house with or without seismic retrofit and make some concrete conclusions.

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REFERENCES


