Maximum response evaluation of two-storied traditional wooden buildings for pulse-like ground motions

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ABSTRACT: The objective of this study is to evaluate the maximum response of two-storied traditional wooden buildings against pulse-like ground motions. It was found from the shaking table test of four kinds of two-storied wooden frame structure that structural properties cause response coupling between the first and second story, asymmetric restoring force characteristics, and uplift of column base against pulse-like ground motions. Based on the experiment, we suggest two of maximum response evaluation method; simplified and rigorous method. In simplified method, the maximum deformation of entire building \( D_{(1+2)}^{\text{max}} \) is evaluated from the equivalent frequency of building \( T_e \), pulse period \( T_p \) and maximum displacement \( D_p \). In rigorous method, the maximum response is evaluated in detail using the frame analysis model which can consider the structural properties of traditional wooden buildings such as uplift of column base and pull out of column.

1 INTRODUCTION

Many old wooden buildings collapsed in the Hyogo-ken Nambu earthquake in 1995 or recent inland shallow earthquakes. In these earthquakes, pulse-like ground motions have been observed which caused severe damage to buildings. Incidentally, there are many traditional wooden buildings forming the historical townscape in Japan. However, little is known about structural properties of traditional wooden buildings affect the response of the buildings against pulse-like ground motion. The objective of this study is to evaluate the maximum response of two-storied traditional wooden buildings against pulse-like ground motions. To confirm the behavior of traditional wooden buildings, the shaking table test of four kinds of two-storied wooden frame structure are conducted. Based on the experiment, we suggest two of maximum response evaluation method; simplified and rigorous method.

2 SHAKING TABLE TEST

2.1 Specimens

Four types of two-storied traditional wooden frame structures shown in Figure 1 are used in this experiment. Bn and Bw have ‘jointed columns’ which are separated from first and second story by large cross section beams. Cn and Cw have ‘through columns’ which pass straight through stories both ends of columns. Bw and Cw have walls which are made of dry mud panel both first and second stories, although Bn and Cn have the wall only the second story. Note that Bn and Bw is made of the same wooden frame. Cn and Cw is also the same wooden frame. All columns of specimens stand on the stones and are not fixed at all. Walls are installed asymmetrically.

Specimens are composed of two parallel two-storied wooden frames combined by binding beams, structural plywood and stainless steel brace. There are weights on the first and second floor and ceiling. The mass \( m_0 \), \( m_1 \) and \( m_2 \) and natural frequency of first mode \( f_0 \) are listed in Table 1 and the properties of woods in this experiment are listed in Table 2. Thickness of dry mud panel is 26 mm and dry mud panel is fixed to the crosspiece by screws. Figure 2 shows the details of mortise and tenon joint in the specimens.
Table 1. Mass and natural frequency of specimens.

<table>
<thead>
<tr>
<th></th>
<th>$m_0$ (kg)</th>
<th>$m_1$ (kg)</th>
<th>$m_0$ (kg)</th>
<th>$f_0$ (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bn</td>
<td>2416</td>
<td>2477</td>
<td>653</td>
<td>1.25</td>
</tr>
<tr>
<td>Bw</td>
<td>2410</td>
<td>2513</td>
<td>689</td>
<td>2.27</td>
</tr>
<tr>
<td>Cn</td>
<td>2473</td>
<td>2473</td>
<td>649</td>
<td>1.25</td>
</tr>
<tr>
<td>Cw</td>
<td>2473</td>
<td>2509</td>
<td>685</td>
<td>2.52</td>
</tr>
</tbody>
</table>

Table 2. Properties of woods.

<table>
<thead>
<tr>
<th>Wood species</th>
<th>Dimension (mm)</th>
<th>Young’s modulus (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column</td>
<td>120 × 120</td>
<td>7770</td>
</tr>
<tr>
<td>Beam</td>
<td>270 × 120</td>
<td>10000</td>
</tr>
<tr>
<td>Joist</td>
<td>120 × 120</td>
<td>10000</td>
</tr>
<tr>
<td>Pin</td>
<td>15 × 15</td>
<td>10000</td>
</tr>
</tbody>
</table>

Figure 2. Joints in the specimens.

2.2 Input waves and measuring method

Shaking table is excited by one direction and controlled by displacement. Sinusoidal pulse, Ricker wavelet and the random wave are used in this experiment. The acceleration of the sinusoidal pulse is made by one cycle of sine wave and pulse period $T_p$ is the period of one cycle. $T_p$ of ricker wavelet is the peak of fourier spectra. $D_p$ is the maximum displacement of input wave. In contrast, random wave which continues long time compared to sinusoidal pulse and ricker wavelet is also used in this experiment. Random wave is simulated ground motion which continues in 165 seconds and made by using the random phase to be suitable for the standard acceleration response spectra (damping ratio 5%) on free engineering bedrock at the safety limit (level 2) in building standard law of Japan.

The displacement wave form is shown in Figure 3. Table 3 shows input waves in this experiment. $T_p$ and $D_p$ are determined considering the performance limit of shaking table.

To confirm their dynamic response characteristics, two accelerometers and displacement sensors are set up on each floor and each joint of specimens. Measurement data is filtered by cosine tapered high cut filter decreasing from 9 Hz to 10 Hz. Each analysis data is calculated from two measurement data. It is also executed microtremor measurements putting micrometer machine before and after each excitation. Deformation angle is calculated from relative displacement divided by height of each story.

3 EXPERIMENTAL RESULTS

3.1 Deformation and damage

Figure 4 shows maximum deformation of specimens calculated from deformation of each story and rotation of each joint excited by Ricker wavelet $T_p = 0.7s$,
$D_p = -250 \text{ mm}$. Note that only more than 5 mm of uplift and pull out of column is shown in Figure 4 and $R_{1\text{max}}$ and $R_{2\text{max}}$ are the maximum deformation angle on the first and second stories. Bn deforms mostly on the first story although Cn deforms equally between on the first and second story. Rotation of the wall on the first story of Bw without shear failure causes the uplift of column base more than 70 mm at the right column, pull out of the column more than 50 mm and break the pin at the center column. The pin of left end of the joist is broken and the wall on the first story cracks at the upper part. Nearly the same damage is happened at Cw, but uplift and pull out of column of Bw are larger than those of Cw because deformation angle of Bw is larger than Cw.

3.2 Restoring force characteristics

Figure 5 shows the relation between inertial force $Q_1$ and deformation angle $R_1$ of Cw on the first story. Note that inertial force is calculated as one structural plane. In Figure 5, Ricker wavelet $T_p = 0.7 \text{ s}$, $D_p = -250 \text{ mm}$ excitation is shown in solid line. Skelton curve of Cw is shown in Figure 6. As Figure 6 indicates, restoring force characteristics are asymmetrically. In negative, inertial force does not increase until in positive and only deformation angle increases because of uplift of column.

3.3 Movement of column base

Figure 7 shows the relationship between movement of left column base after each excitation and the maximum deformation angle on the first story $R_{1\text{max}}$ of Bn and Bw. Column base of Bn almost never moves although column base of Bw moves according to $R_{1\text{max}}$ increasing. This is because the movement of column base is occurred by uplift of column base. When Bw is excited by random wave, movement is the largest although $R_{1\text{max}}$ is not so large. As the Figure 8 indicates, column base moves gradually against the ground motion which lasts long time. In this study, we take no account of the influence of movement of column base further analysis because the maximum movement is so small such as less than 5 mm.
3.4 Uplift of column base and pull out of column

Figure 9 shows the relationship between uplift of right column base during each excitation and the maximum deformation angle on the first story $R_{1 \text{max}}$ of Bn and Bw in negative. Bn almost never uplifts although Bw uplifts according to $R_{1 \text{max}}$ increasing.

Figure 10 shows the relationship between pull out of the top of center column on the first story during each excitation and the maximum deformation angle on the first story $R_{1 \text{max}}$ of Bn and Bw in negative. Bn almost never pulls out although Bw pulls out according to $R_{1 \text{max}}$ increasing. To pull out of column, pins and tenons of column are broken. Thus, uplift of column base causes breaking of joints around walls although uplift of column base prevents walls from shear failure.

3.5 Maximum deformation of entire building

The deformation of entire building $D_{(1+2)}$ of Bn excited by sinusoidal pulse $T_p = 0.5, 1.0, 2.0 \text{s}, D_p = -100 \text{mm}$ is shown in Figure 11. Despite of the same $D_p$, as $T_p$ becomes shorter, $D_{(1+2)}$ becomes larger and the period of Bn becomes longer. Figure 12 shows maximum deformation of entire building $D_{(1+2)\text{max}}$ of four specimens according to the change of $T_p$ excited by sinusoidal pulse $D_p = -100 \text{mm}$. $D_{(1+2)\text{max}}$ of all specimens increase according to $T_p$ decreasing. Though column less affects to $D_{(1+2)\text{max}}$ such as Bn and Cn or Bw and Cw. The wall on the first story greatly affects $D_{(1+2)\text{max}}$ especially in $T_p = 1.0 \text{s}$ although $D_{(1+2)\text{max}}$ of all specimens is approximately the same in $T_p = 0.5 \text{s}$. Maximum deformation of each story is analyzed in the next section.

3.6 Maximum deformation of each story

Figure 13 shows the deformation on the each story $D_i$ of Bn and Cn excited by sinusoidal pulse $T_p = 0.5 \text{s}, D_p = -100 \text{mm}$. Deformation concentrates on the first story in Bn. In Cn, $D_2$ is larger than $D_2$ of Bn although $D_1$ is smaller than $D_1$ of Bn.

Figure 14 shows the bar graph of $D_{1\text{max}}$ and $D_{2\text{max}}$ normalized by the sum of $D_{1\text{max}}$ and $D_{2\text{max}}$ excited by sinusoidal pulse $T_p = 0.5 \text{s}, D_p = -100 \text{mm}$. Deformation ratio between $D_{1\text{max}}$ and $D_{2\text{max}}$ of Cn differs from Bn because the deformation of the first and second story is coupled by through columns. If there are walls both first and second story, deformation ratio does not differ so much regardless of through columns.
4 SIMPLIFIED METHOD OF MAXIMUM RESPONSE EVALUATION

4.1 Natural frequency

Natural frequency is used for simplified method to evaluate the maximum response. Natural frequency of during excitation $f_e$, during free vibration $f_f$ and after excitation $f_m$ of Cn are evaluated in this section. First, natural frequency during excitation $f_e$ is evaluated from fourier spectrum ratio on the ceiling divided by on the shaking table measured by accelerometer. Second, natural frequency during free vibration $f_f$ is evaluated from time interval of each peak of deformation on the first story during free vibration. Lastly, natural frequency after excitation $f_m$ is evaluated from the peak of a fourier spectrum ratio on the ceiling divided by on the shaking table measured by microtremor measurements.

The relation between natural frequency $f$ and deformation angle on the first story $R_1$ is showed in Figure 15. As Figure 15 indicates, $f_e$ is lower than $f_m$ and transition of natural frequency from $f_e$ to $f_m$ can evaluate using free vibration after excitation $f_f$. The smaller $R_1$ becomes, the larger $f_f$ becomes and $f_f$ goes from $f_e$ to $f_m$.

4.2 Maximum response evaluation

Regardless of specimens, the maximum deformation of entire building $D_{(1+2)\text{max}}$ can be evaluated from the displacement response spectrum normalized by $D_p$ and $T_p$ approximately using equivalent natural period of specimens $T_e$ shown in Figure 16. Note that $T_e$ is the reciprocal of $f_e$ and $h$ is the damping ratio. Figure 16 indicates that $D_{(1+2)\text{max}}$ changes greatly depends on the relation between equivalent natural period of specimens $T_e$ and the pulse period $T_p$ especially around $T_e/T_p = 1$. In Figure 16(b), $D_{(1+2)\text{max}}$ of Bw and Cw are very large from displacement response spectrum because of uplift of column base.

5 RIGOROUS METHOD OF MAXIMUM RESPONSE EVALUATION

5.1 Simulation model

To evaluate maximum response in detail, the frame analysis model which can consider the structural properties of traditional wooden houses such as uplift of column base and pull out of column is needed. The frame analysis model of Cw is shown in Figure 17. Beams and columns are simulated by elastic line element. Stiffness is determined by the cross section and Young’s modulus of woods.
Figure 17. The frame analysis model of Cw.

Figure 18. Comparison of Uplift of column base Cw between experiment and simulation.

Column base has axial spring which is elastic in compression side and free in tension side on the pin joint to express uplift. Stiffness in compression side is determined to be the same Young’s modulus with columns.

Elasto-plastic axial and rotational springs are placed at each joint. Moment resistance of each joint consists of embedding force, compression frictional force and resistance force of pin. Restoring force characteristics of rotation is tri-linear slip type which is the superposition of moment resistance calculated from embedding force, compression frictional force and resistance force of pin. Restoring force characteristics of axial force is bi-linear slip type which is embedding force in compression side and resistance force of pin in tension side.

Walls are expressed by the braced model which has the same lateral strength as the past experimental data of dry mud panel. Restoring force characteristics of brace model is tri-linear slip type.

5.2 Maximum response evaluation

Figure 18 shows the relation between $R_{1\text{max}}$ and uplift of column base of Cw excited by sinusoidal pulse. In this frame analysis model, uplift of column base is well simulated because of the axial spring placed at each joint. If there is no axial spring, simulation overestimates inertial force $Q_1$ and hysteresis loop area because of shear deformation of the wall on the first story as Figure 19 indicates.

Figure 19. Comparison of hysteretic characteristics on the first story of Cw between experiment and simulation excited by sinusoidal pulse $T_p = 0.5 \text{ s}, D_p = -100 \text{ mm}$.

Figure 20. Comparison of $R_{1\text{max}}$ of Cw between experiment and simulation excited by sinusoidal pulse $T_p = 0.5 \sim 3.0 \text{ s}, D_p = -100 \text{ mm}$.
transition of $R_{1\text{max}}$ according to the change of $T_p$. However, $R_{1\text{max}}$ of simulation especially overestimates $R_{1\text{max}}$ of experiment in $T_p = 1.0$ s. This is because the frame analysis model underestimates its stiffness less than 0.01 rad and $R_{1\text{max}}$ changes drastically around $T_e / T_p = 1$.

Figure 21 shows the sum of the maximum deformation at the first story $D_{1\text{max}}$ and second story $D_{2\text{max}}$ of Bn and Cn normalized by $D_p$. The response coupling of the through column which decreases $D_{1\text{max}}$ and increases $D_{2\text{max}}$ is well simulated in the frame analysis model of Cn.

6 CONCLUSIONS

The objective of this study is to evaluate the maximum response of two-storied traditional wooden buildings against pulse-like ground motions. To confirm the behavior of traditional wooden buildings, the shaking table test of four kinds of two-storied wooden frame structure are conducted. Based on the experiment, we suggest two of maximum response evaluation method; simplified and rigorous method. As results, following conclusions have been drawn.

1) The structural properties of two storied traditional wooden buildings cause specific response such as response coupling between the first and second story, asymmetric restoring force characteristics, and uplift of column base against pulse-like ground motions.

2) It is important to estimate pulse period $T_p$ of estimated ground motion because the maximum response changes drastically especially around $T_e / T_p = 1$.

3) The equivalent natural frequency of building $T_e$, pulse period $T_p$ and maximum displacement $D_p$ are needed for simplified method to evaluate the maximum response approximately.

4) The frame analysis model which can consider the structural properties of traditional wooden houses such as uplift of column base, pull out of column and through column is needed for rigorous method to evaluate the maximum response in detail.

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REFERENCES


