ABSTRACT: The objective of this study is to propose the maximum response deformation evaluation method of traditional wooden houses based on microtremor measurements and the amplitude dependency of natural frequency of the houses. The equation of the amplitude dependency of natural frequency is based on the results of seismic observation of traditional wooden houses, shaking table tests and static lateral loading tests of wooden frame specimens. To confirm the accuracy of the proposed evaluation method, the maximum response deformation angle of the first story of full scale specimens of shaking table tests is evaluated. It is found from the maximum response deformation angle evaluation that increasing natural frequency is effective to reduce the maximum response deformation angle against random waves but it is not effective against particular pulse-like ground motions.

KEYWORDS: Traditional wooden houses, Microtremor measurements, Amplitude dependency of natural frequency, Maximum response deformation angle

1 INTRODUCTION

There are many traditional wooden houses forming historical townscapes in Japan. Microtremor measurements can be useful to evaluate seismic performance of these houses easily because the microtremor measurements are conducted without destruction and in a short time. Although several researches estimate the seismic capacity grade or the yield base shear coefficient of the houses based on natural frequency which is obtained from the microtremor measurements, these researches do not evaluate the maximum response deformation angle of the houses against earthquake ground motions.

In our previous study [1], we have proposed the amplitude dependency of vibration characteristics such as natural frequency and damping ratio on the basis of shaking table tests of wooden frame specimens. Applying this amplitude dependency of vibration characteristics into the response spectrum method [2, 3], the maximum response deformation angle of the wooden frame specimens against an input wave has been estimated approximately.

In this paper, we develop the amplitude dependency of natural frequency to be applicable for existing traditional wooden houses and establish the maximum response deformation angle evaluation method using the microtremor measurements and the amplitude dependency of natural frequency.

2 MAXIMUM RESPONSE EVALUATION METHOD

In this chapter, we establish the maximum response deformation angle evaluation method using the microtremor measurements and the amplitude dependency of natural frequency.

2.1 CONVERSION INTO EQUIVALENT SDOF MODEL

First, traditional wooden houses are regarded as the two degree of freedom models. The two degree of freedom models are converted into the equivalent single degree of freedom (SDOF) model. In this method, natural frequency of the houses evaluated from the microtremor measurements $f_0$, the height of the first story and the second story $H_1$ and $H_2$, the mass ratio $m_2 / m_1$ and the amplitude ratio of the first mode $u_2 / u_1$ are needed. Note that $m_1$ and $m_2$ are the mass of the first story and the second story. $u_1$ and $u_2$ are the amplitude of the eigenvector of the first mode at the first story and the second story.

The equivalent height of the equivalent SDOF model $H_e$ is given by Equation (1).

\[ H_e = \frac{H_1 + (m_2 / m_1) \cdot (u_2 / u_1) \cdot (H_1 + H_2)}{1 + (m_2 / m_1) \cdot (u_2 / u_1)} \]
2.2 EVALUATION OF MAXIMUM RESPONSE OF EQUIVALENT SDOF MODEL

The maximum response deformation of the equivalent SDOF model \( D_{\text{max}} \) is evaluated from the response spectrum method \([2, 3]\) which uses the equivalent performance response spectrum \( S_{w} \). \( S_{w} \) is calculated by Equation (2).

\[
S_{w}[f(R), R] = 
\frac{(2\pi f_{s})^{2} RH_{s}}{f_{s}}
\]  

(2)

where the variables in the square bracket \([ \] \) in the equations means that they are used to calculate the variables of the left side of the square bracket. \( R \) is the deformation angle of the equivalent SDOF model. \( H_{s} \) is defined by Equation (1) above regardless of \( R \). \( f_{s} \) is the equivalent natural frequency. \( f_{s} \) is expressed by the amplitude dependency of natural frequency which is shown in Equation (3) below.

\[
f_{s}[h(R)] = \frac{b \alpha \log_{10}(R \cdot 10^{1}) + 1}{1 + \frac{h[R]}{\alpha}}
\]  

(3)

where \( a \) and \( b \) are the parameters of the amplitude dependency of natural frequency and they are discussed in the chapter three in detail. \( F_{b} \) is the reduction factor expressed by Equation (4) on the basis of the previous method \([4]\).

\[
F_{b}[h(R)] = \frac{(1 + 0.05\alpha a)}{(1 + h[R] \cdot \alpha)}
\]  

(4)

where \( \alpha \) is the coefficient of input waves; \( \alpha = 10 \) \([4]\) when input waves are random waves, \( \alpha = \pi \) \([5]\) when input waves are pulse like ground motions. \( h_{e} \) is the equivalent damping ratio expressed by Equation (5) on the basis of the previous method \([4]\).

\[
h_{e}[R] = 0.05 + 0.2 \cdot \left[ 1 - \frac{1}{(\max(R/R_{y}) + 1)} \right]
\]  

(5)

where \( R_{y} \) is the yield deformation angle and \( R_{y} = 1/100 \text{rad} \) in this study on the basis of the previous study \([6]\). In the previous study \([6]\), \( R_{y} \) was determined on the basis of the earthquake observations of the traditional wooden houses in Japan.

Acceleration response spectrum (damping ratio \( h=0.05 \)) \( S_{h} \) is calculated from input waves.

The equivalent natural frequency \( f_{e} \) is calculated by Equation (6) when \( f_{e} \) satisfies \( S_{h} = S_{w} \).

\[
S_{w}[f_{\text{max}}(R_{\text{max}}), R_{\text{max}}] = S_{h}[f, R_{\text{max}}]
\]  

(6)

The maximum deformation angle of the equivalent SDOF model \( D_{\text{max}} \) is calculated from substitution \( f_{e} \) into Equation (3). The maximum response deformation of the equivalent SDOF model \( D_{\text{max}} \) is calculated from multiplication \( R_{\text{max}} \) and \( H_{s} \) shown in Equation (7).

\[
D_{\text{max}} = R_{\text{max}} \cdot H_{s}
\]  

(7)

2.3 EVALUATION OF MAXIMUM RESPONSE OF EACH STORY

The maximum response deformation of the first story and the second story \( D_{1}\text{max} \) and \( D_{2}\text{max} \) are expressed by Equation (8).

\[
D_{\text{max}} = \beta_{u} H_{s} D_{\text{max}}, D_{2\text{max}} = \beta_{u} H_{s} D_{\text{max}}
\]  

(8)

where \( \beta_{u} \) is the participation vector of the first story, \( \beta_{u} \) is the participation vector of the second story. \( \beta_{u} \) and \( \beta_{u} \) are given by Equation (9), (10).

\[
\beta_{u} = \frac{1 + (m_{1}/m_{2}) \cdot (u_{1} / u_{2})}{1 + (m_{1}/m_{2}) \cdot (u_{1} / u_{2})^{2}}
\]  

(9)

\[
\beta_{u} = \frac{(u_{1} / u_{2}) + (m_{1}/m_{2}) \cdot (u_{1} / u_{2})^{2}}{1 + (m_{1}/m_{2}) \cdot (u_{1} / u_{2})^{2}}
\]  

(10)

The maximum deformation angle of the first story and the second story \( R_{1}\text{max} \) and \( R_{2}\text{max} \) are expressed by Equation (11).

\[
R_{\text{max}} = D_{\text{max}} / H_{s}, R_{2\text{max}} = D_{2\text{max}} / H_{s}
\]  

(11)

3 EVALUATION OF THE AMPLITUDE DEPENDENCY OF NATURAL FREQUENCY

3.1 AMPLITUDE DEPENDENCY OF NATURAL FREQUENCY OF WOODEN FRAME STRUCTURE

In this section, we calculate the amplitude dependency of natural frequency from the result of the static loading tests of wooden frames with full walls (full wall specimens). Three full wall specimens are used in this study \([7, 8]\). The full wall specimens consist of columns, cross beam, ground sills and walls. The elevations of the specimens are shown in Figure 1 and the details of the specimens are shown in Table 1.

The specimens are named in the following rules. The initial character "F" means the full wall. The number "12" means the section size of the columns (12cm). As the type of walls, "#" means the mud plaster wall and "-" means the wall of the dry mud panels. The last character "N" means the specimen with the mud plaster wall whose thickness is 60mm and the last character "T" means the specimen with the mud plaster wall whose

| Table 1: Details of full wall specimens |
|-------------------|-----------|----------|----------|
| Wall | Thickness (mm) | Weight (kN) | Stiffness \( k_{1/100} \) (kN/mm) |
| F12#12N | Mud plaster | 60 | 5.0 | 25.7 | 1.37 |
| F12#12T | Mud plaster | 200 | 14.2 | 25.7 | 1.39 |
| F12-12 | Dry mud panels | 26 | 1.6 | 25.7 | 1.18 |

Figure 1: Elevations of full wall specimens (Unit : mm)
thickness is 200mm. Note that the dry mud panels are precast panels made of clay, waste paper and wood [9]. The thickness of the dry mud panels are 26mm and the dry mud panels are fixed to the crosspiece by screws. The reversed cyclic loading in the horizontal direction is conducted by increasing the amplitude of the deformation angle. To prevent pullout of the columns, the capital and base of each column are fixed with joint metals and hold down hardware, and 25.7kN vertical load is weighted on each specimen. The ground sills are bound to a steel foundation with anchor bolts. The thickness of the dry mud panel s are approximately the same although the maximum load is weighted on each specimen. The ground sills are made of clay, waste paper and wood [9].

Deformation angle $R$ of the full wall specimens is calculated dividing the horizontal top displacement by the height of the specimens (2.7m). In this study, $R$ of the positive direction is used. Restoring force $P$ is measured with load cells attached to the cross beam. The amplitude dependency of natural frequency of the static loading tests $f_R / f_{1/1000}$ is calculated using the skeleton curve of the restoring force characteristics as shown in Figure 2 (a). The amplitude dependency of natural frequency of the static loading tests $f_R / f_{1/1000}$ is calculated using $k_R$ and $k_{1/1000}$ by Equation (12).

$$f_R / f_{1/1000} = \sqrt{k_R / k_{1/1000}} \quad (12)$$

The amplitude dependency of natural frequency of the static loading tests $f_R / f_{1/1000}$ is shown in Figure 2 (b). $k_{1/1000}$ is shown in Table 1. $k_{1/1000}$ of the three specimens are approximately the same although the maximum restoring force and the shape of the restoring force characteristics are different as Figure 2 (a). Figure 2 (b) indicates that $f_R / f_{1/1000}$ do not differ so much around $R=1/100$ although $f_R / f_{1/1000}$ differs from $R=1/1000$rad to $R=1/100$rad.

Next, we establish the evaluation formula of $f_R / f_{1/1000}$ shown in Equation (13) on the basis of Figure 2 (b).

$$f_R / f_{1/1000} = (b/0.6) \cdot [a \log_{10}(R \cdot 10^3) + 1] \quad (13)$$

Figure 3 shows the comparison between the evaluation formula of $f_R / f_{1/1000}$ in Equation (13) and the experimental results of Figure 2 (b).

We determine the parameter $a$ as $a=-0.4$ in Equation (13) because the formula fits well to the experimental result when $a=-0.4$. The parameter $b$ is chosen as $b=0.6$. The parameter $b=0.5, 0.7$ are used to express the dispersion of the amplitude dependency of natural frequency of the static loading tests $f_R / f_{1/1000}$. The application range of the evaluation formula in this study is $R=1/1000$–$1/10$rad because some of the specimens did not conduct the experiment more than $R=1/10$rad.

3.2 EVALUATION FORMULA OF AMPLITUDE DEPENDENCY OF NATURAL FREQUENCY

In this section, the amplitude dependency of natural frequency of traditional wooden houses is evaluated from the result of seismic observation, shaking table tests and the result of section 3.1. Figure 4 shows the amplitude dependency of natural frequency $f_R / f_0$ which is calculated from seismic observations of the three wooden houses located in Kyoto [10, 11] and the shaking table tests results of the two-storied traditional wooden frame structures [12].

$$f_R / f_0 = (b/0.6) \cdot [a \log_{10}(R \cdot 10^3) + 1]$$

Figure 3: Comparison between the evaluation formula and the experimental results of the amplitude dependency of natural frequency of the full wall specimens

Figure 4: Comparison between the evaluation formula, the observed and the experimental results of the amplitude dependency of natural frequency
The outline of the traditional wooden houses in Kyoto is as follows [10, 11]. Two of the traditional wooden houses have typical slender plans and their natural frequency is \( f_0 = 2.2, 2.7 \)Hz in the ridge direction and \( f_0 = 5.3, 4.6 \)Hz in the span direction. The other one traditional wooden house is suburban style and natural frequency is \( f_0 = 6.4 \)Hz at the weak axis and \( f_0 = 2.2, 2.7 \)Hz in the ridge direction and \( f_0 = 3.7 \)Hz in the span direction. The deformation angle \( R \) of the traditional wooden houses calculated dividing the maximum relative displacement by the height of the houses. The maximum relative displacement is calculated from the integration of acceleration waveforms at the ground and at the roof frame. The result of the both axes are used in Figure 4.

The outline of the two-storied traditional wooden frame structures is as follows [12]. There are four types of two-storied traditional wooden frame structures and two types are shown in Figure 5. Bn and Bw have the columns which are separated from the first and second storied traditional wooden frame structures and two Bn and Bw are made of the same wooden frame. Cn and Cw have the wall only at the second story. Cn and Cw are also the same wooden frame. All the columns stand on the stones and are not fixed at all. The specimens are composed of the two parallel two-storied wooden frames combined by the binding beams, structural plywood and stainless steel braces. There are weights on the first and second floor and ceiling; 3.7kN, 19.6kN and 19.6kN. \( f_0 \) of Bn, Bw, Cn, Cw are 1.3Hz, 2.3Hz, 1.3Hz, 2.5Hz, respectively.

In Equation (14), \( f_{1,1000} / f_0 \) is equivalent to \( b \) and \( f_{1,1000} / f_0 \) means the degradation of natural frequency from \( f_0 \) at \( R = 1/1000 \)rad. Figure 4 indicates that \( f_{1,1000} \) of traditional wooden houses is about 0.6 times compared to \( f_0 \). Therefore the parameter \( b \) is determined \( b = 0.6 \) in this study and the parameter \( a \) is determined \( a = 0.4 \) from section 3.1. The parameter \( b = 0.5, 0.7 \) can be used to express the dispersion of the amplitude dependency of natural frequency.

### 4 ACCURACY VERIFICATION AND APPLICATION EXAMPLES

#### 4.1 BASE SHEAR COEFFICIENT

In this section, we evaluate the base shear coefficient \( C_b \) of the equivalent SDOF model from \( f_c / f_0 \) in Equation (14). Note that we regard the deformation angle of the equivalent SDOF model as \( R \) in Equation (14). In Equation (15), \( C_b \) is calculated from the base shear divided by the total weight.

\[
C_b = \mu (2 \pi f_c)^2 H / g \tag{15}
\]

where \( g \) is the gravitational acceleration, \( H \) is the equivalent height in Equation (1) and \( \mu \) is the equivalent mass ratio in Equation (16) below.

\[
\mu = \frac{m_e}{m_c + m_e} = \frac{1 + (m_c / m_e) \cdot (u_c / u_c)^2}{1 + (m_c / m_e) \cdot (u_c / u_c)^2} \cdot (1 + m_c / m_e) \tag{16}
\]

where \( m_e \) is the equivalent mass. Figure 6 shows \( C_b \) of the equivalent SDOF model which is \( f_0 = 3Hz, \mu = 0.9, H = 4.5m \). \( C_b \) is calculated by substituting \( f_c \) of Equation (14) into Equation (15). \( R_{\text{Chmax}} \) is the deformation angle when \( C_b \) is the maximum shown in Equation (17). Equation (17) is calculated from Equation (14), (15).

\[
R_{\text{Chmax}} = 10^{-((a+1)/e)} / e^2 \tag{17}
\]

where \( e = \text{base of natural logarithm} \). As Equation (17) indicates, \( R_{\text{Chmax}} \) is determined only by the parameter \( a \). \( C_{\text{Chmax}} \) is the base shear coefficient when \( C_b \) is the maximum shown in Equation (18). Equation (18) is calculated from Equation (14), (15), (17).

\[
C_{\text{Chmax}} = f_0^2 \cdot (\mu H / g) \cdot 4 \pi a b (\log_{10} e / e)^2 \cdot 10^{-((a+1)/e)} \tag{18}
\]

![Figure 5: Elevations of two-storied traditional wooden frame structures (Unit:mm)](Image1)

![Figure 6: Base shear coefficient \( C_b \) versus deformation angle \( R \) \( f_0 = 3Hz, \mu = 0.9, H = 4.5m, a = 0.4 \)](Image2)
In the previous study [11], Equation (19) below is proposed from the regression of $f_0$ and the yield base shear coefficient $C_y$ of six traditional wooden houses in Kyoto.

$$C_y = f_0^2 / 60$$  \hspace{1cm} (19)

where $C_y$ is calculated dividing the base shear at 1/30rad by the total weight $W$. Note that base shear is calculated from the summation of each load bearing element and the total weight $W$ is the weight higher from the half of the first story. The comparison between $C_y$ versus $f_0$ (Equation (19)) and $C_{bmax}$ versus $f_0$ (Equation (18)) is shown in Figure 7. The investigation results of the 16 traditional wooden houses in Kyoto [13] are also shown in Figure 7. The result are both the ridge and span directions. $C_{bmax}$ is 1.3~2.5 times larger than $C_y$ according to $b$ at the same $f_0$. One of the reason $C_{bmax}$ is larger than $C_y$ is that $C_y$ in Equation (19) is the value for design although $C_{bmax}$ in Equation (18) is the value calculated from the experiments.

Figure 8 shows the relation between $L_1/W$ and $f_0$ of the 16 traditional wooden houses in Kyoto [13]. $L_1$ is the total length of the full walls of each direction of the first story, $W$ is the total weight. Figure 8 indicates that there is a correlation between $L_1/W$ and $f_0$, and $f_0$ will be higher if we increase the amount of the walls.

**Figure 7:** Yield base shear coefficient $C_y$ and maximum base shear coefficient $C_{bmax}$ versus natural frequency $f_0$ [$f_0=3$Hz, $\mu$=0.9, $H_c$=4.5m, $a$=-0.4]

**Figure 8:** Total length of full walls of the first story divided by total weight $L_1/W$ versus natural frequency $f_0$ [$f_0=3$Hz, $\mu$=0.9, $H_c$=4.5m, $a$=-0.4]

4.2 ACCURACY VERIFICATION USING FULL SCALE SHAKING TABLE TESTS

To confirm the accuracy of the proposed maximum response deformation angle evaluation method, we evaluate the maximum response deformation angle of the first story $R_{1max}$ of traditional wooden houses of full scale shaking table tests [14-17].

4.2.1 Overview of full scale shaking table tests

In this section, we describe the outlines of the full scale shaking table tests of the traditional wooden houses [14-17]; feature of the specimen, input waves and damage. There are three specimens and they are named "Suburb typical house", "Suburban typical house" and "Kyo-machiya", respectively.

(A) Suburb typical house [14]

a) Feature of the specimen

The dimension of the plan is 10.91x5.45m. The cross section of the columns and the beams are smaller than Suburban typical house. The long side is the span direction and the narrow side is the ridge direction. The mud plaster is used as the walls, whose thickness is 80mm or 65mm.

b) Input wave

In this study, we use BCJ-L2 and JMA Kobe among the input waves in the experiment. BCJ-L2 is provided by the building center of Japan [18]. BCJ-L2 is a random wave which is likely (not the same) to Design spectra in Japan. The shaking table was excited one direction at each horizontal direction separately. We use the result of 100% amplitude of the displacement in the experiment.

JMA Kobe which is observed in 1995 Hyogoken-Nambu earthquake was input at triaxial in the experiment. NS direction wave is input in the long side and EW direction wave is input in the narrow side. In this study, we evaluate the result of each direction independently.

Ground acceleration of BCJ-L2 and JMA Kobe NS are shown in Figure 9. Figure 10 shows the acceleration response spectrum (damping ratio $\alpha$=0.05) $S_a$ versus displacement response spectrum (damping ratio $\alpha$=0.05) $S_d$ of two inputs. The equivalent performance response spectrum $S_{eq}$ versus deformation $R*H_c/F_b$ are also shown in Figure 10. Note that the parameters of the amplitude dependency of natural frequency are $a$=-0.4, $b$=-0.6. The parameter of $F_b$ is $\alpha=10$ when BCJ-L2 is input, $\alpha=\pi$ when JMA Kobe is input. Three $f_0$ ($f_0=2$, 3, 4Hz) are used to calculate $S_{eq}$. Representative $R$ ($R=1/60$, 1/30, 1/20, 1/15, 1/10rad) is shown on $S_{eq}$ versus $R*H_c/F_b$

Input waves in this evaluation are not the record on the shaking table but from the original data [18] when BCJ-L2 is input, and the observed seismic ground motion when JMA Kobe is input.

c) Damage

When BCJ-L2 100% was input, there were cracks on the walls of the first story though there was no failure at the wooden frame. The column base was also uplifted. When JMA Kobe was input, many walls and columns were damaged and the column base was also uplifted.
(B) Suburban typical house [15]

a) Feature of the specimen
The dimension of the plan is 11.82x5.91m. The cross section of the columns and the beams are larger than Suburb typical house. The long side is the span direction and the narrow side is the ridge direction. The mud plaster is used as the walls, whose thickness is 80mm or 65mm.

b) Input wave
The same as (A) Suburb typical house.

c) Damage
When BCJ-L2 100% was input, there were cracks and damages on the walls and the columns. The column base was also uplifted. In JMA Kobe, many walls columns were damaged and the column base was also uplifted.

(C) Kyo-machiya [16, 17]

a) Feature of the specimen
The dimension of the plan is 12.87x6.14m. The long side is the span direction and the narrow side is the ridge direction. The mud plaster is used as the walls at the first story, whose thickness is 65mm. The dry mud panels with mud coating is used as the walls at the second story.

b) Input wave
BCJ-L2 whose maximum ground acceleration is adjusted 4.0 m/s² is used in this experiment. JMA Kobe is the same as (A).

c) Damage
Before JMA Kobe excitation, there were slight damages as cracks of the coating of the walls. When JMA Kobe was input, many walls and columns were damaged and the column base also moved.

4.2.2 Evaluation method
To evaluate the maximum deformation angle of the first story \( R_{1\text{max}} \), the specimens are modelled as Table 2. \( f_0 \) is natural frequency which was obtained from the mirotremor measurements before the shaking table tests. \( H_1 \) and \( H_2 \) are the height of the first and second story, \( m_1 \) and \( m_2 \) are the mass of two degree of freedom models which are converted from the weight of the specimens for evaluating seismic force [14-17]. The amplitude ratio of the first mode \( u_2 / u_1 \) is calculated as eigenvalue from the mass ratio \( m_2 / m_1 \) and the stiffness ratio \( k_2 / k_1 \). \( k_2 / k_1 \) is regarded the same as the ratio of the length of the walls of the first story and second story \( L_2 / L_1 \). The equivalent height of the equivalent SDOF model \( H_e \) is calculated by Equation (1). The equivalent mass ratio \( \mu \) is calculated in Equation (16). The parameters of the amplitude dependency of natural frequency are \( a = -0.4 \) and \( b = 0.5 \), 0.6, 0.7. The coefficient of input waves is \( \alpha = 10 \) when BCJ-L2 is input, \( \alpha = \pi \) when JMA Kobe is input.

| Table 2: Details and modelling of full scale specimens |
|---------------------------------|----------|----------|---------|---------|-------|------------|-----------------|
| Side                           | \( f_0 \) (Hz) | \( H_1 \) (m) | \( H_2 \) (m) | \( m_1 \) (ton) | \( m_2 \) (ton) | \( L_2/L_1 \) | \( u_2/u_1 \) | \( H_e \) (m) | \( \mu \) | JMA Kobe | BCJ-L2 | PGA (m/s²) |
| Suburban typical house         | Long     | 3.3      | 2.76     | 2.60     | 18.6    | 14.6 | 0.82 | 1.69 | 4.25 | 0.93 | NS | 3.56 |
|                                | Narrow   | 3.0      |          |          |         |      |      |      |      |      |     |      |
| Suburban typical house         | Long     | 2.8      | 2.85     | 2.75     | 21.2    | 17.7 | 0.76 | 1.78 | 4.50 | 0.92 | NS | 3.56 |
|                                | Narrow   | 2.6      |          |          |         |      |      |      |      |      |     |      |
| Kyo-machiya                    | Long     | 4.7      | 2.75     | 2.80     | 14.8    | 14.7 | 0.94 | 1.66 | 4.49 | 0.94 | NS | 4.00 |
|                                | Narrow   | 2.5      |          |          |         |      |      |      |      |      |     |      |
4.2.3 Evaluation result

In this section, the evaluation result is compared from the experimental result. There are three plane of structures at long side and four plane of structures at narrow side. All of plane of structures of all the specimens have the maximum response deformation angle of the first story $R_{1\text{max}}$ in the experiment. Figure 11 shows the experimental and evaluation $R_{1\text{max}}$ of each plane of structure on both long and narrow side. We use $b=0.5, 0.7$ as the parameter $b$ in Figure 11. Figure 12 shows the $R_{1\text{max}}$ of simplified two degree of freedom model of $m_2/m_1=1, u_2/u_1=2, H_1=H_2=2.7m$. We change $f_0$ from 2Hz to 5Hz. In Figure 12, the mean $R_{1\text{max}}$ of each plane of structure is also described. We use $b=0.5, 0.6, 0.7$ as the parameter $b$ in Figure 12.

(A) BCJ-L2

As Figure 11 (a) indicates, we can evaluate $R_{1\text{max}}$ nearly the same or larger than the mean of the experimental $R_{1\text{max}}$ using $b=0.7$. Using $b=0.5$, the evaluated $R_{1\text{max}}$ is larger than the experimental $R_{1\text{max}}$. Note that the previous study [15] reported that experimental $R_{1\text{max}}$ of narrow side of Suburban typical house varies at each plane of structures because the torsion occurred. Figure 12 (a) indicates the evaluated $R_{1\text{max}}$ decreases as $b$ increases. It is also founded that the evaluated $R_{1\text{max}}$ decreases as $f_0$ increases.

(B) JMA Kobe

As Figure 11 (b) indicates, we evaluate $R_{1\text{max}}$ approximately except for the long side of Kyo-machiya. The reason the experimental $R_{1\text{max}}$ is much smaller than the evaluated $R_{1\text{max}}$ is that the column base moved and the specimen did not deform so much. Note that the previous study [14] reports the experimental $R_{1\text{max}}$ of the narrow side of Suburb typical house varies at each plane of structures because the torsion occurred. Figure 12 (b), (c) indicates the evaluated $R_{1\text{max}}$ does not differ so much according to $b$ and $f_0$.

Figure 11: The maximum deformation angle of the first story $R_{1\text{max}}$ of full scale specimens [$m_2/m_1, H_1, H_2$: Experimental value, $u_2/u_1$: Evaluated value]

Figure 12: The maximum deformation angle of the first story $R_{1\text{max}}$ versus natural frequency $f_0$ of full scale specimens and simplified two degree of freedom model [$m_2/m_1=1, u_2/u_1=2, H_1=H_2=2.7m$]
4.3 APPLICATION EXAMPLES

4.3.1 Evaluation method and result

As an application example, simulation analyses using this proposed evaluation method is conducted against two types of acceleration response spectra shown in Figure 13 changing natural frequency $f_0$.

One of the response spectrum is Design spectra in Japan (soil type 2, adjustment factor according to number of stories $p=0.85$) [4]. The other is the spectrum of Ricker wavelet which characterizes pulse-like ground motions (predominant period $T_p=1s$, maximum ground velocity $V_p=0.75cm/s$). Figure 14 shows the ground acceleration and velocity of Ricker wavelet.

Figure 15 shows the $R_{1max}$ of the simplified two degree of freedom model of $m_2/m_1=1$, $u_2/u_1=2$, $H_1=H_2=2.7m$. We change $f_0$ from 2Hz to 5Hz and use $a=-0.4$, $b=0.6$ in Figure 15. The coefficient of input waves is $\alpha = 10$ when Design spectra in Japan is input, $\alpha = \pi$ when Ricker wavelet is input. Figure 15 indicates that the maximum response deformation angle of the first story $R_{1max}$ decreases as natural frequency of the houses $f_0$ increases in case of Design spectra in Japan. In case of Ricker wavelet, $R_{1max}$ do not change so much by $f_0$.

4.3.2 Discussion

On the basis of the maximum response evaluation result, important points of earthquake-resistant measures of the traditional wooden houses are described as follows.

$R_{1max}$ decreases as $f_0$ increases against Design spectra in Japan and random waves such as BCJ-L2. Therefore, increasing strength by installing walls is effective to reduce $R_{1max}$ against such waves. This is because there is a correlation between the total length of the full walls $L_1$ and $f_0$ as Figure 8 indicates. On the other hand, $R_{1max}$ does not decrease as $f_0$ increases against particular pulse-like ground motions such as JMA Kobe and Ricker wavelet. Therefore, improving deformation capacity of houses is effective because increasing strength by installing walls is not necessarily effective.

5 CONCLUSIONS

In this study, following conclusions have been drawn.

1) The maximum response deformation angle evaluation method of traditional wooden houses based on natural frequency which is obtained from microtremor measurements and the amplitude dependency of natural frequency has been established.

2) The amplitude dependency of natural frequency which can be applicable for existing traditional wooden houses has been developed from the results of seismic observation of existing traditional wooden houses, shaking table tests and static lateral loading tests of wooden frame specimens.

3) It is found from the maximum response deformation angle evaluation that increasing natural frequency is effective to reduce the maximum response deformation angle against random waves but it is not effective against particular pulse-like ground motions.

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