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Study on the Effectiveness of Controlled Wooden Houses Based on Energy Balance

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ABSTRACT: This study analyses a typical wooden house with added hysteretic dampers employing a lumped mass system, and discusses the effectiveness and design methods of vibration damping devices, using cumulative plastic deformation, ductility and equivalent loading coefficient. The analysis model was based on typical one- to three-story ZEH wooden houses, while the parameters included the number of floors, seismic elements, damper yield displacement and ratio for the structure, as well as the input seismic motions and number of repeating quakes. The input waves used were those of six earthquakes. The n-value significantly decreased when the number of repeating quakes was from one to two, however no significant decrease was observed from two to three. The n-value of the epicentral earthquake Kobe NS, showed a tendency to be small.

KEYWORDS: Wooden house, Vibration damping structure, Energy method

1 – INTRODUCTION

In the 2016 Kumamoto Prefecture Earthquake and the 2024 Noto Peninsula Earthquake, many of the affected wooden houses experienced not only the main shocks, which registered a seismic intensity of 7, but also aftershocks exceeding a seismic intensity of 5-lower. To reduce damage caused by repeating large earthquake motions, it is also effective to add vibration damping devices to wooden houses. Although such devices also have the advantage of being able to cope with repeating quake motions, a seismic design method for wooden houses that takes multiple earthquakes into consideration, has not yet been established in Japan. This study analyses a lumped mass system model, which simulates a typical wooden house with added hysteretic dampers and thereby discusses the effectiveness and design methods of vibration control devices, using cumulative plastic deformation, ductility and equivalent loading coefficient.

2 – PROJECT DESCRIPTION

A structural characteristic of wooden structures is that the restoring force is known to be the slip type. Therefore, it is necessary to make an analysis model in which the rigidity of the frame decreases significantly when a deformation exceeding the yield displacement occurs in the building. In this paper, the seismic energy of a wooden structure is expressed by Eq. (1), which adds the slip, bilinear and damper elements, as shown in Fig. 1.

$$E_s = E_{ws} + E_{wd} + E_d \tag{1}$$

E_s : Energy of wooden damping structure

E_{ws} : Slip element energy

E_{wd} : Bilinear element energy

E_d : Damping element energy

Here, a_{ws}, a_{wd} and a_d are coefficients representing the energy distribution to each element, and in this analysis, they are determined from the response from yield to 1/30 rad. The damper strength $\mathrm{Q_d}$ that is less than or equal to the target deformation angle for n-time(s) repeating quakes is given by Eq. (5) based on Eqs. (1) to (4). The energy of each element is obtained by Eqs. (2) to 4).

$$\mathrm{E_{ws} = a_{ws} \cdot b_{ws} \cdot Q_w(\delta_m - \delta_{ws})} \tag{2}$$

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$$E_{wd} = a_{wd}\{b_{wd} \cdot Q_w(\delta_m - \delta_{wd})\} \quad (3)$$

$$E_d = a_d\{Q_d(\delta_m - \delta_d)\} \quad (4)$$

$$Q_d = \frac{(a_{ws}b_{ws}\delta_{ws} + a_{wd}b_{wd}\delta_{wd})Q_w - (a_{ws}b_{ws} + a_{wd}b_{wd})Q_w\delta_m + E_s}{(\delta_m - \delta_d)a_d} \quad (5)$$

Finally, the effectiveness of the simple calculation method was confirmed by the calculation of response values by time history response analysis using Q_d, and confirmation of the consistency with the results of time history response analysis. This study aimed to obtain the target value of a maximum deformation angle of 1/75 rad or less with three-time repeating quakes. Furthermore, when calculating the response using the energy method, the load-deformation relationship during n-time repeating earthquakes can be obtained from Eq. (6) using cumulative plastic deformation $\bar{\eta}$ and ductility μ^*.

$$n = \frac{\bar{\eta}}{\mu^*} = \frac{\frac{E_a}{2F_y \cdot \delta_y}}{\frac{|\delta_{max}|}{\delta_y} - 1} \quad (6)$$

3 – ANALYSIS MODEL

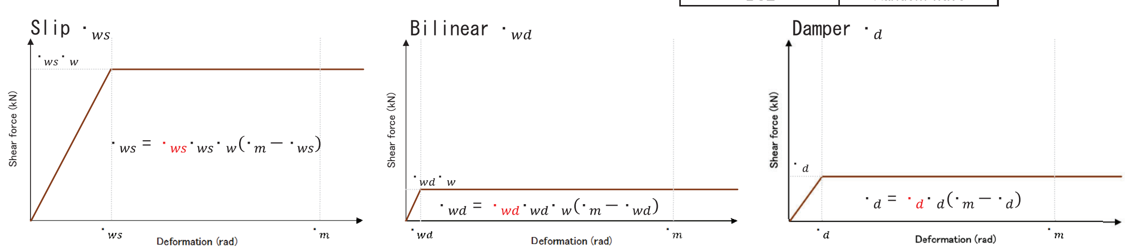
A lumped mass system model, simulating damping of a wooden house is analysed to determine the coefficients a_{ws}, a_{wd} and a_d, which represent the energy distribution to each element and the n-value. The analysis model is outlined in Fig. 2. The model applies one- to three-mass systems to represent typical one- to three-story wooden houses, and masses are calculated based on the wall volume suggested for ZEH standard structures, and standardized at the mass of the ground floor. The restoring force is based on the three elements shown in Fig. 1 to formulate Eq. (1), and the load-deformation relationship is evaluated based on the responses from the yield to 1/120-1/30 rad arising from n-times repeating quakes. The parameters shown in Table 1 include the number of floors, earthquake-resistant elements, and damper yield displacement and ratio concerning the structure, as well as the input seismic motions and number of repeating quakes concerning the external forces. The input seismic motions

Table 1: *Analysis parameters*

Mass point	Calculated from wall volume calculation and standardized by first floor mass (mortar wall)
Proof strength	Slip + Bilinear + Damper Slip bilinear elements (bracing, structural plywood, etc.) Damper element (vibration damping device)
Displacement	Ry−1/30rad
Analysis parameters	Floor number (1−3 mass point system) Earthquake−resistant elements (7 types) Input seismic motion (6 types) Number of repetitions (1−3 times) Yield displacement of damper (5−20mm @5mm) Damper percentage (0−50% @10%)

Table 2: *Type of input seismic motions*

Input seismic motion	Remarks
El Centro NS	50 kine
Taft EW	
Hachinohe NS	
Kobe NS	Original wave
Kobe NS−L2	Kobe NS phase
BSL	Random wave



a) Slip element b) Bilinear element c) Damping element

Fig. 1: *Load deformation relationship of each element*

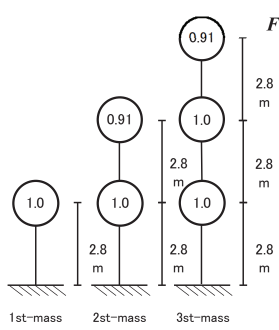


Fig. 2: *Analysis model*

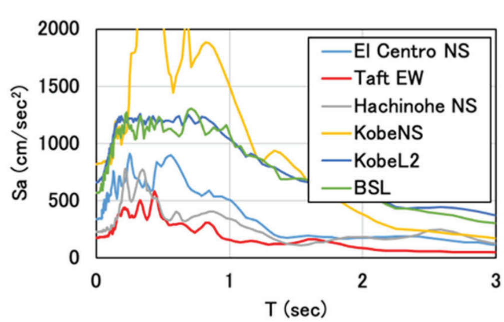


Fig. 3: *Acceleration response spectrum*

are those of the six earthquakes (Table 2). The target deformation angle is set at 1/75 rad or less after three-time repeating quakes. Fig. 3 shows the acceleration response spectrum.

4 – ANALYSIS RESULT

4.1 EACH ENERGY COEFFICIENTS

As an example, Fig. 4 shows the relationship between $\bar{\eta}$ and μ^* when the damper ratio is 20% for a single-mass system. In addition, the results for each element, a_{ws}, a_{wd} and a_d are shown in Figs 5, 6 and 7 respectively. $\bar{\eta}$ is averaged by dividing the number of repeating quakes. The results of n-values for each number of repeating quakes for each mass system are shown in Table 3. The n-value significantly decreased when the number of repeating quakes was from one to two, however no significant decrease was observed from two to three. In Reference 1, a wooden structure (damper ratio 0%) had an n-value of 1.6, which is similar to the n-value obtained in this paper. The

Table 3: *Summary of n-values*

	1–mass system	2–mass system	3–mass system
1–time	3.3	2.0	2.3
2–time	2.5	1.6	1.6
3–time	1.8	1.5	1.3

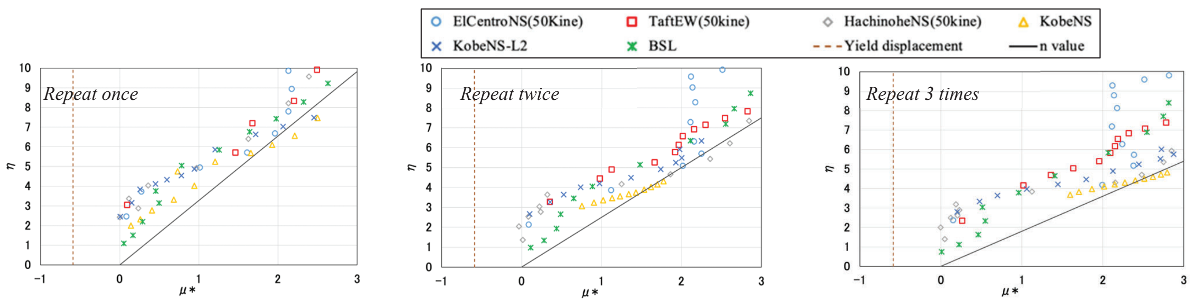


Figure 4 : *Cumulative plastic deformation magnification and plasticity rate (1 mass point system damper ratio 20%)*

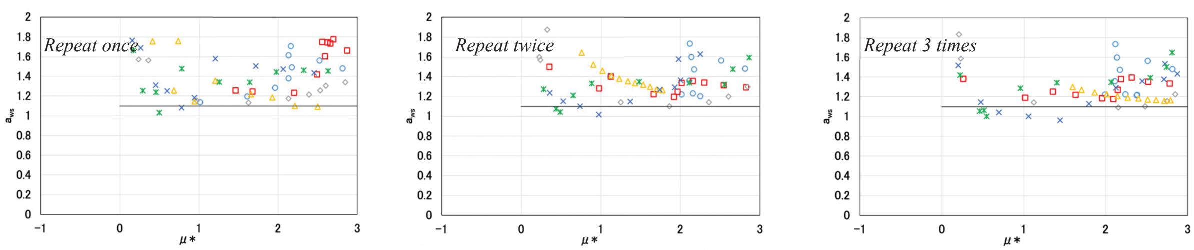


Figure 5 : *Slip element (1 mass point damper ratio 20%)*

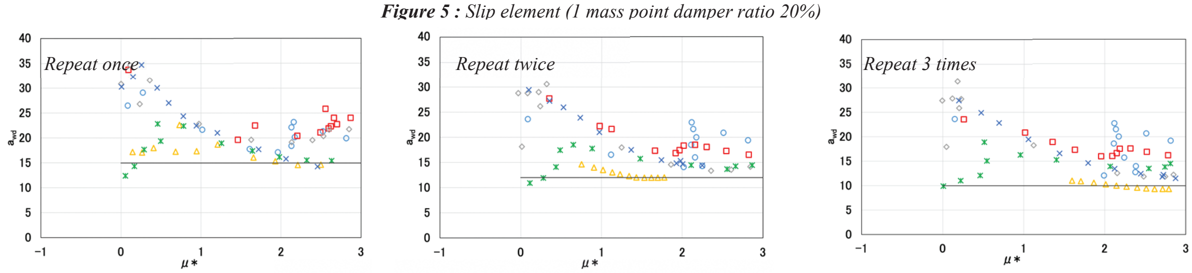


Figure 6 : *Bilinear element (1 mass point damper ratio 20%)*

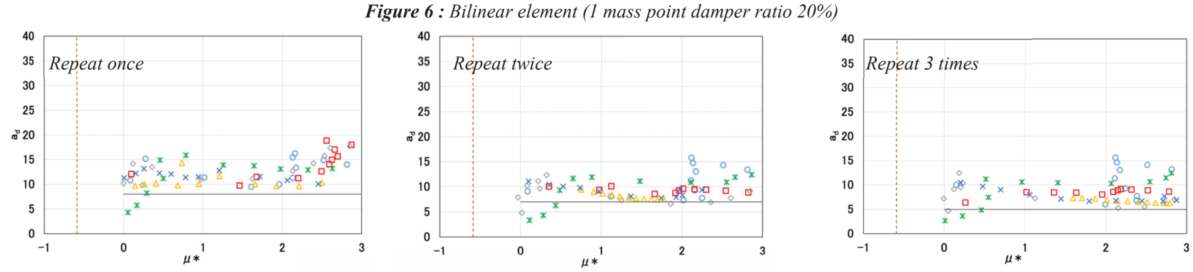


Figure 7 : *Damper element (1 mass point damper ratio 20%)*

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n-value of epicentral earthquake Kobe NS had a tendency to be small.

The slip element was stable at 1.1, as shown in Fig. 5, while the damper and bilinear elements tended to have less energy absorption as the deformation increased. Table 3 summarizes the n values for Result 1.

4.2 PARAMETRIC STUDY

In the second result, the authors changed the damper ratio parameter. The relationship between the coefficients a_{wd} and a_d representing energy distribution to each element, and the damper ratio in the proof stress are shown in Figs. 8 and 9. The slip element was stable at 1.1, and no change was observed depending on the damper ratio. From these figures, it can be seen that both coefficients tend to decrease as the damper ratio increases. This is considered to indicate that the higher the damper ratio (the larger the number of dampers), the smaller the deformation of each damper.

In order to confirm the consistency of the simple design method, the authors used a two-mass system BSL wave input (one repetition) with a damper ratio of 20% and a yield displacement of 10 mm as an example, and thereby compared the simple calculation method and time history

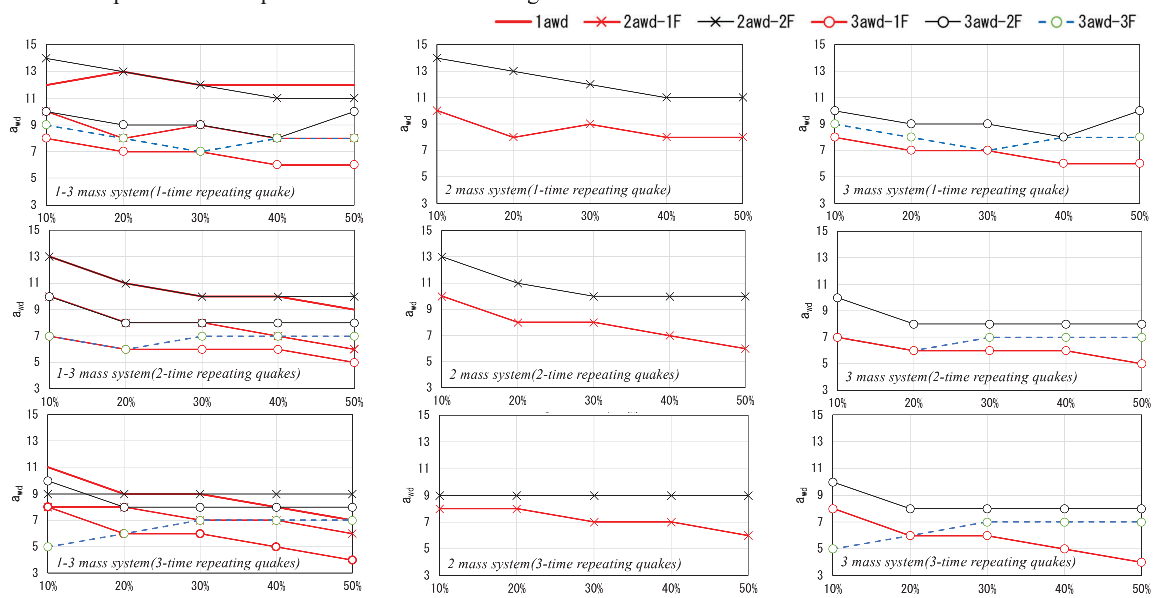

Fig. 8: *Relationship between a_{wd} and damper ratio*

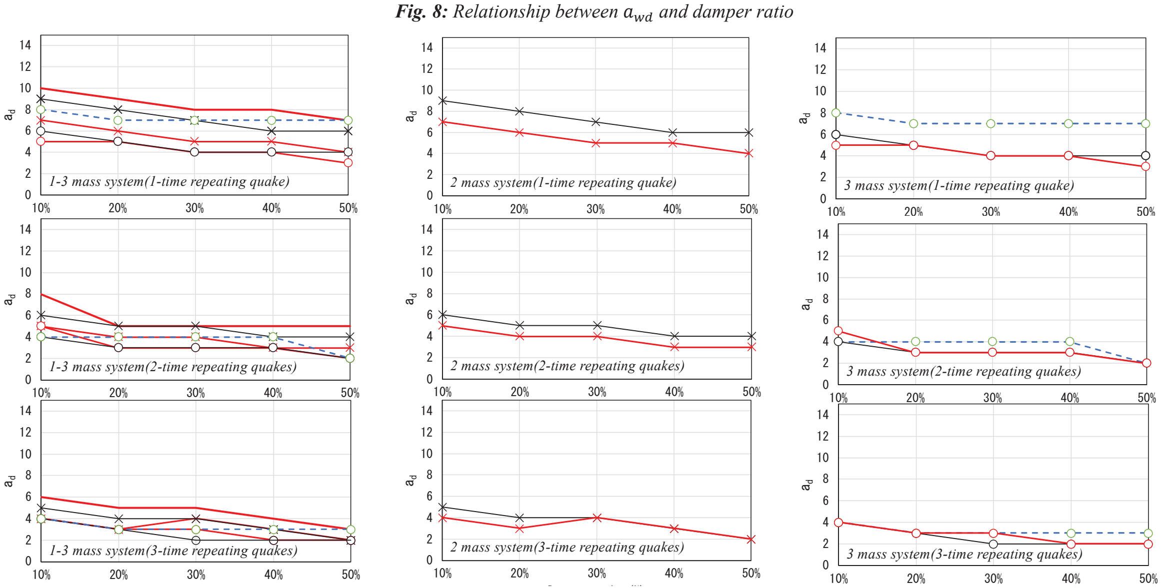

Fig. 9: *Relationship between a_d and damper ratio*

response analysis (maximum deformation of 3.73 cm). The results by the simple calculation were $\delta_1 = 2.67$cm for the first layer and $\delta_2 = 3.81$cm for the second layer, confirming that they are close to the values found in the time history response analysis. Each coefficient shown in the figures calculated using a large number of response analysis results was a lower limit value. Therefore, the authors believe that a safer design is possible by a calculation using each of these coefficients.

5 – SUMMARY

In order to apply the energy method to the seismic design of wooden houses, an analysis was carried out on a lumped mass system simulating a typical house. The n-value, for a single-mass point system, was 3.3 when the number of repeating quakes was one, 2.5 when two, and 1.8 when three, showing that the n-value varied greatly from one to two-time repeating quakes. The n-value for a wooden building without any damper is known to be about 1.6, which is greater by 0.2 than the n-value of three-time repeating quake for a single-mass point system. As a result, the n-values of two-time repeating quakes for both two- and three-mass point systems were found to be the same level. In this paper, the analysis results on the model with a damper ratio of 20% (one layer) for a single-mass point system, were selectively introduced. However, when observing all single- to three-mass point systems, it was found that the damper element absorbed energy after the building reached its yielding point, and the bilinear element tended to absorb less energy as deformation became greater. Therefore, Result 1 confirmed the effectiveness of the damper.

Furthermore, in order to propose a simple calculation for wooden seismic damping buildings using the energy method, coefficients representing the energy distribution of each seismic element used in the calculation were determined by analysis of a mass point model. The authors compared the simple calculation results using the coefficients with time history response analysis, thereby confirming that similar response values were obtained. It also showed that the coefficients representing the energy distribution became smaller as the damping ratio became larger.

6 – REFERENCES

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