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DEVELOPMENT OF PASSIVELY CONTROLLED SMALL WOODEN STRUCTURES AND THE DESIGN METHOD

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Abstract

In this paper, application of passive control devices to small wooden structures is introduced. Chapter 2 discusses the seismic behavior and the performance of structural components of conventional post and beam wooden structures especially focusing on behavior of connections. They are modeled by combination of inelastic axial, shear and rotational spring based on results of fundamental material and fasteners tests. Chapter 3 introduces the experiments and analyses for the structural behavior of the energy dissipation walls which involve unique mechanics to dissipate most energy in the dampers. In Chapter 4, the seismic behavior of passively controlled wooden structures is investigated through both experimental test and numerical analysis. Detailed framing analysis models for energy dissipation wall and plywood sheathing wall are also introduced. Furthermore, a design methodology for passively controlled wooden houses is proposed in Chapter 5. The accuracy of the results by the proposed method is confirmed through time history analyses.

Keywords: wooden frame, passively controlled structure, earthquake response, deformation control design

1. Introduction

The current seismic design methodology in Japan has been developed to ensure that buildings are capable of withstanding rare and moderate earthquakes without being damaged, and protecting the occupants' life safety under very rare and major earthquakes even if they were damaged to some extents. In recent years, however, energy shortage and environmental issues have placed a demand for buildings to have longer life cycles, which makes the functional continuity and quick recovery after earthquakes a major problem.

The 27.5 million detached houses form the foundation of most Japanese citizens' life, among which about 25.4 million (about 93%) are wooden houses. Therefore, the seismic performance and property-retention capability of such houses are of essential importance. This study focuses on post and beam wooden structure which is the structural system in more than 90% of the detached wooden houses in Japan.

In the 2011 Tohoku Earthquake, a lot of wooden houses were severely damaged by the strong ground motion even though damage from tsunami was focused on. In addition, a series of large aftershocks triggered collapses of wooden houses. This reveals that more resiliency is required for wooden houses, and the enhancement solutions should be established.

Passive control techniques, which have been well developed for tall buildings, are re-explored for a low-cost solution to the enhancement of the seismic performance and property-retention capability of detached wooden houses. For such small houses, the current study proposes a passive-controlled wooden structure consisting of a low-rise wooden frame structure and energy dissipation walls, which are a combination of wooden components and passive dampers.

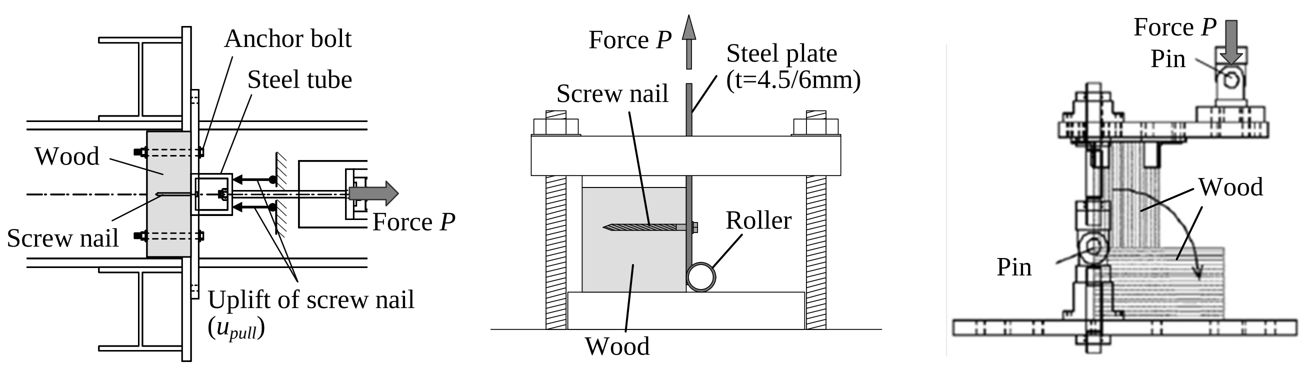
There are various relevant works on application of passive control devices for wooden structures. Filiatrault(1990) proposed application of friction dampers to light framed wooden shear wall, and investigated the efficiency of seismic response reduction by time history analysis [1]. Symans(2002) introduced various examples of wooden structures with supplemental damping systems by literature review [2]. Although various dampers such as viscoelastic damper, hysteretic damper and viscous damper have been applied so far, comprehensive study including developing simple design method is being required to spread the technology.

In this paper, development of high performance energy dissipation walls and the application to wooden frame focusing on Japanese post and beam structures are introduced. The efficiency is confirmed through a lot of experiments and analyses. Simple design method to presume the maximum deformation of wooden houses is also proposed because the reduction in deformation is important for controlling the damages.

2. Mechanical behavior of wooden frame

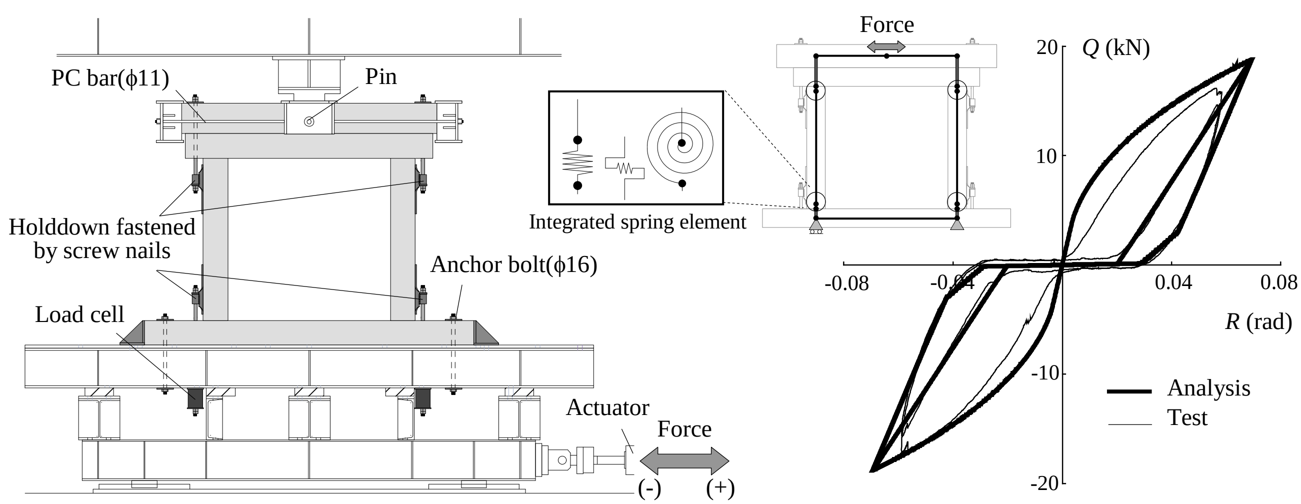
Conventional wooden frame shows slip and pinching behavior which is derived from local embedment of timber, yielding of fasteners and so on, which results in residual deformation of buildings after sever earthquake. It is not suitable behavior from a point of view of earthquake resistant because of the less energy dissipation.

In order to simulate behaviors of wooden frame, evaluation of connections is the most important because most of deformation and the non-linearity of wooden frame is derived from the one of the connections. Japanese conventional wooden connection consists of mortise-tenon joint, bolts, screw nails and other metal parts. The connection can be modeled by combination of axial, shear and rotational spring. Fig. 1 shows fundamental tests of material and fasteners constituting wooden connections [3, 4]. Their behaviors are modeled by inelastic springs, and they are integrated into three inelastic springs representing the axial, shear and rotational deformations of the connection. Fig. 2 shows an example of wooden unit frame and the experiment [3]. Result of framing analysis shows close agreement with test result.



(a) Pullout test of screw nail (b) Shear test of screw nail (c) Local embedment test

Fig. 1 –Examples of fundamental test of wooden material and fasteners



(a) Test setup (b) Shear force-story drift angle relation

Fig. 2 –Test on wooden unit frame and the framing analysis

3. Mechanical behavior of energy dissipation walls

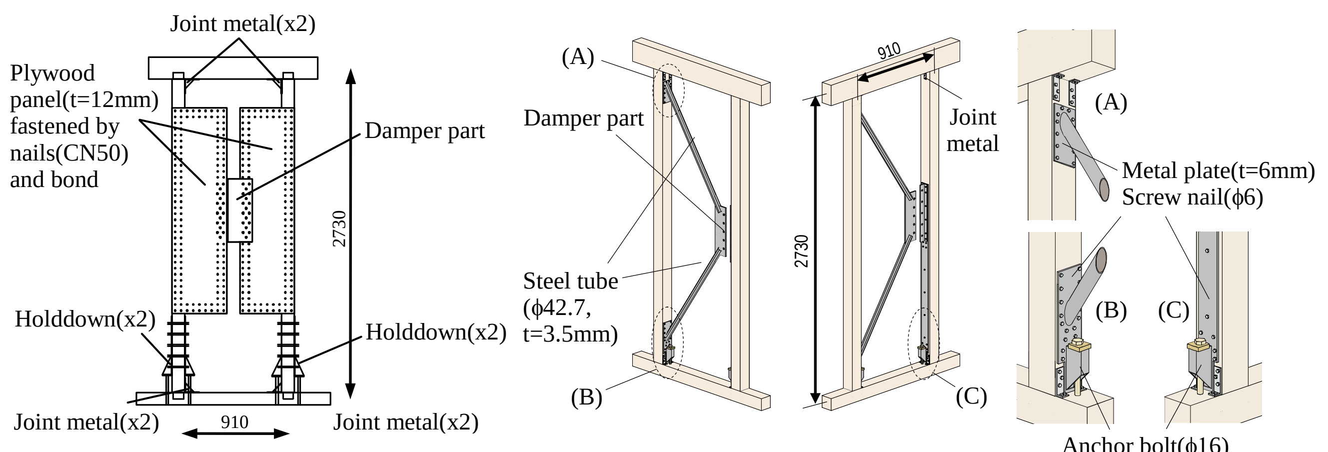
3.1 Design of energy dissipation wall

In order to improve the seismic performance of wooden frame, special mechanics are developed as shown in Fig. 3 [5, 6]. They use shear-link mechanics and involve passive dampers. They are able to be installed in wooden frame whose connections are specially reinforced. As for K-brace type, damper force is directly transmitted to anchor bolts through steel members which are fastened to wooden members by screw nails(ϕ=6mm). In damper part, various type of dampers can be installed. Fig. 4 shows examples of dampers for K-brace type. Acrylic type viscoelastic material is used for viscoelastic damper. H-shaped steel element is used for steel damper. The web is subjected to out-of-plane bending and dissipates energy by yielding. The shape in top view is determined to enhance the fatigue performance. Friction pad which is originally products of autotrack's brake pad is used for friction pad.

Fig. 5 shows schematic design model of energy dissipation wall to determine stiffness and strength of the damper. The target strength is 9.8kN at 1/120rad which is commonly-used limitation of story drift angle in moderate earthquake, and the necessary amount of damper is calculated by assuming the contribution of each component. Contribution of damper to shear force and story drift angle is determined by geometric relation. Contribution of others can be predicted based on the fundamental tests shown in the last chapter. Since their balance determines the performance, the amount of damper should be carefully designed to satisfy the target.

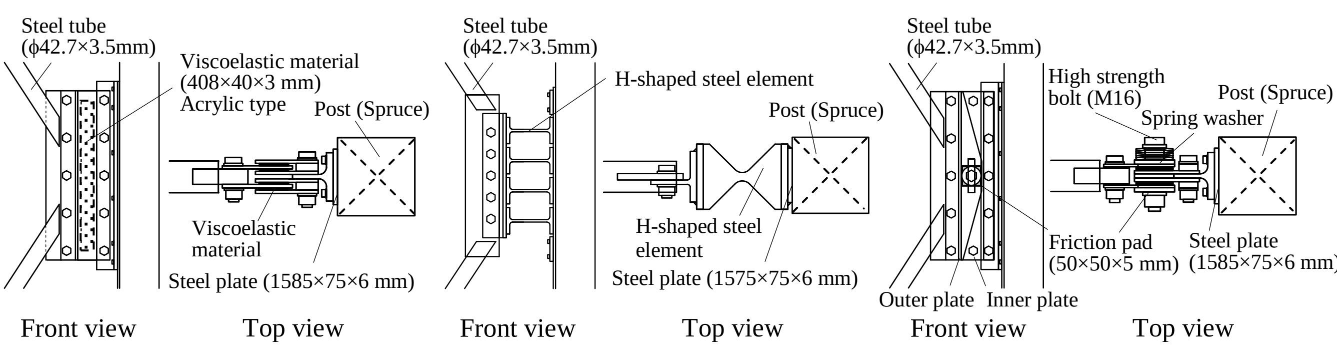
3.2 Dynamic loading test on energy dissipation wall

Fig. 6 shows results of dynamic loading test on the energy dissipation walls having viscoelastic damper(VE) and steel damper(ST). The hysteresis loops look ellipse and parallelogram, respectively. Typical slip and pinching



(a) Plywood panel type (b) K-brace type

Fig. 3 – Specimens of energy dissipation wall



(a) Viscoelastic damper (b) Steel damper (c) Friction damper

Fig. 4 – Detail of dampers for K-brace type

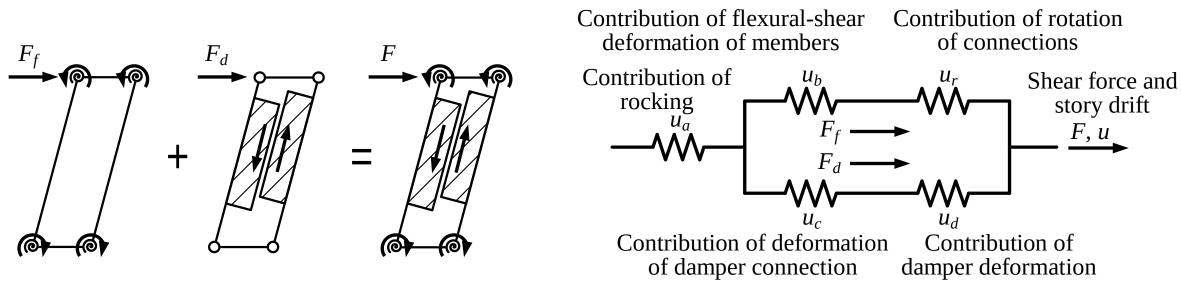
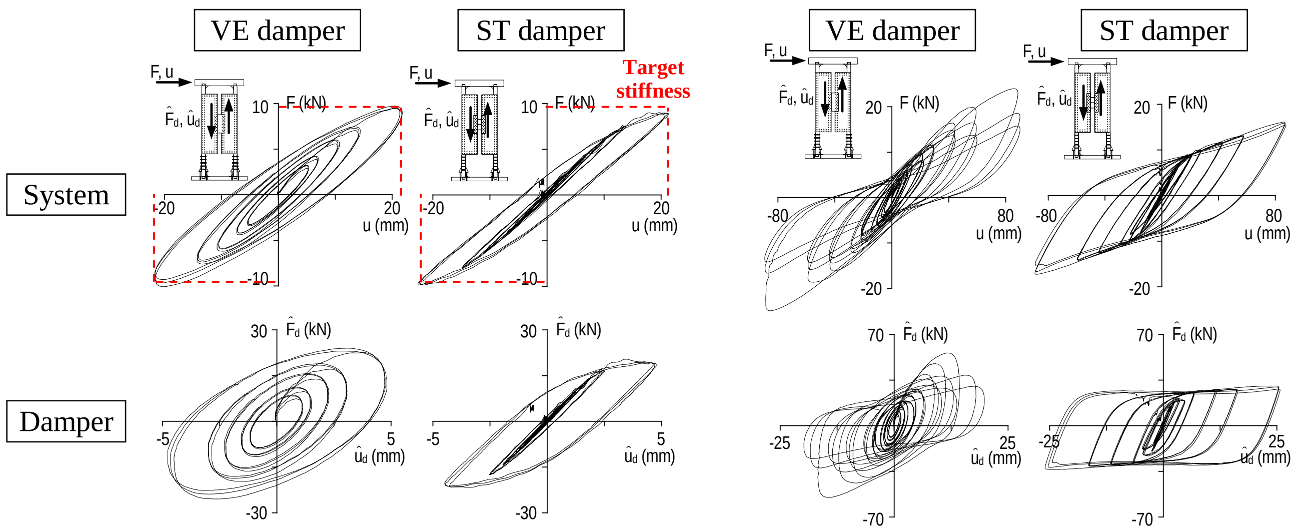


Fig. 5 – Schematic design model of energy dissipation wall



(a) Up to 1/120rad (b) Up to 1/30rad

Fig. 6 – Hysteresis loop of the energy dissipation wall and the damper

behavior in wooden frame structure is not observed, and the dampers work well from small to large deformation amplitude. In addition, design method of energy dissipation wall proposed in the last section is able to control the stiffness and strength of the energy dissipation wall by tuning the stiffness balance of damper and frame. In the case of VE damper, stiffness degradation observed in 1/60rad or larger amplitude is caused by temperature increase of viscoelastic material.

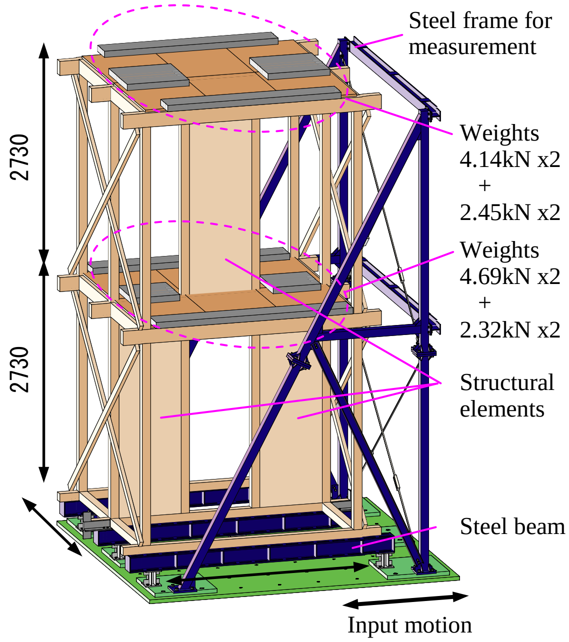
4. Mechanical behavior of passively controlled wooden frame

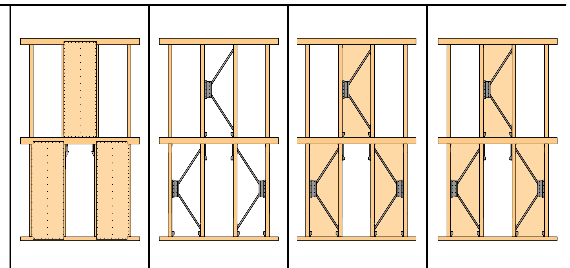
4.1 Shaking table test on two-story wooden frame

In order to discuss the dynamic behavior of wooden frame with energy dissipation walls, shaking table test was carried out [7, 8]. Fig. 7 shows the setup of shaking table test on two-story wooden frame. The parameters are wall type (plywood sheathing panel wall/K-brace energy dissipation wall) and damper type (viscous-elastic damper/friction damper).

Uni-directional input motion was applied. JMA Kobe earthquake and Taft earthquake were used and the intensity was normalized by the peak ground acceleration like "0.2g Kobe" or "0.2g Taft".

Fig. 8 shows relationship between shear force and story drift of each story. The application of energy dissipation wall to wooden frame is effective in terms of improvement of the energy dissipation and reduction of the maximum story drift.





Name		-1.6W-/W-W	-V-/V-V	-VW-/VW-VW	-FW-/FW-FW
Element	2nd story	Plywood (both side)	VE damper	Plywood + VE damper	Plywood + FR damper
	1st story	Plywood	VE damper	Plywood + VE damper	Plywood + FR damper
Wall amount	2nd story	4.8 x 1P	5.0 x 1P	8.6 x 1P	9.6 x 1P
	1st story	3.0 x 2P	5.0 x 2P	8.0 x 2P	9.0 x 2P

(*) 1P = 0.91m,

(**) Wall amount is "wall index" representing the strength multiplied by the length.

Fig. 7 – Setup of shaking table test on two-story wooden structure with energy dissipation walls and list of the specimens

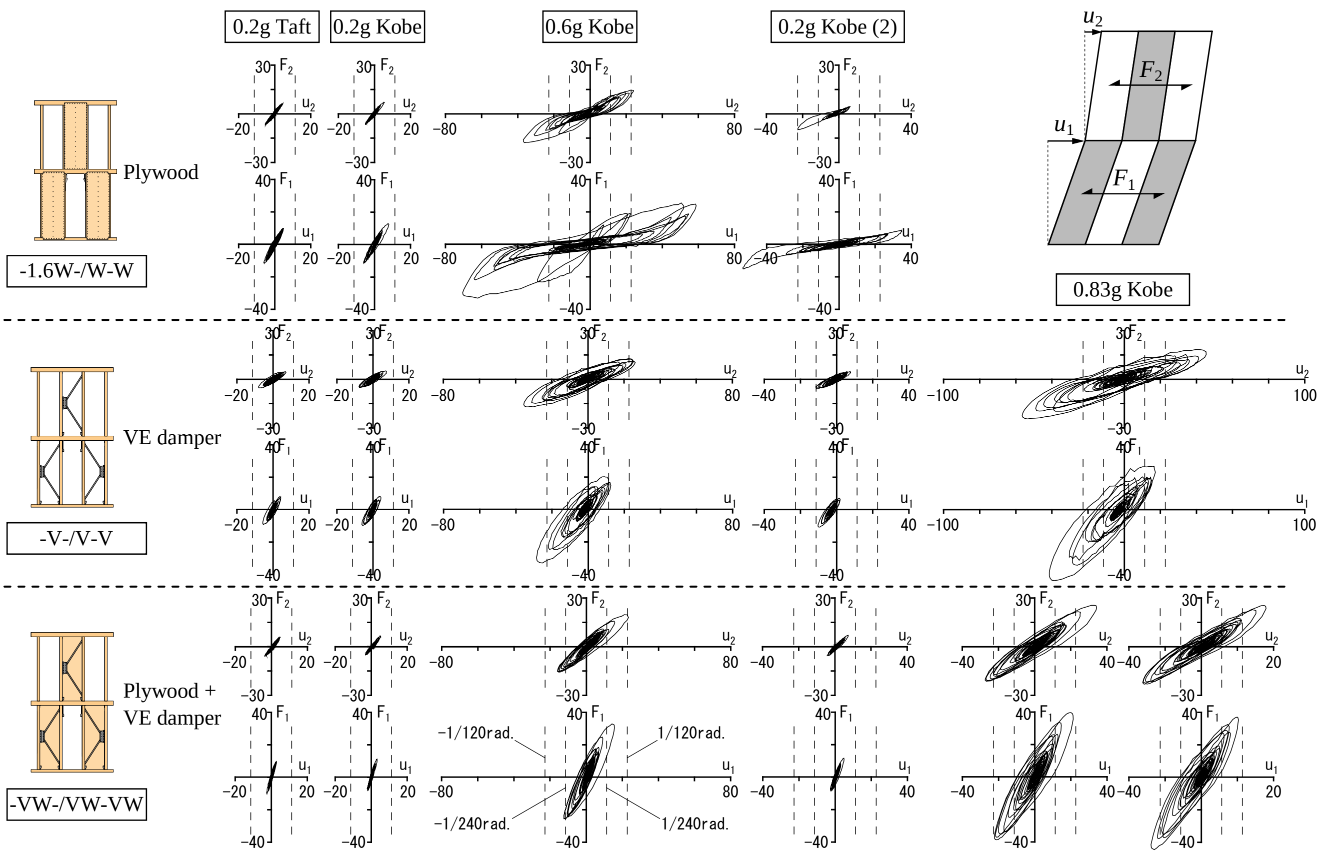
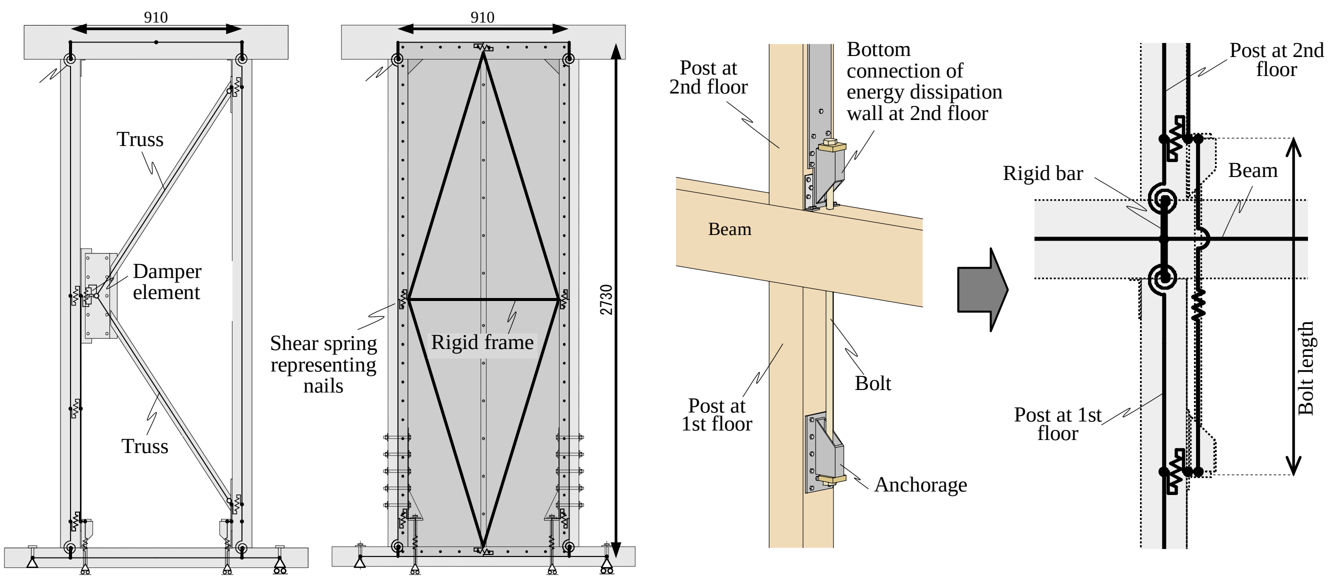


Fig. 8– Relationship between shear force and story drift of each story (Units: kN and mm)

In the case of the specimen without dampers "-1.6W-/W-W" subjected to "0.2g Kobe(2)", the maximum deformation becomes quite larger compared to that subjected to "0.2g Kobe". It is obvious that the conventional structural system cannot maintain the original performance after severe earthquake while specimens with dampers show linear behavior in all the excitations. The passively controlled systems are expected to protect the safety not only in main shock but in aftershocks.

4.2 Framing analysis

Framing analysis model is introduced to simulate not only global behavior but local behavior like connections' deformation and tensile force of anchor bolts [9, 10]. Fig. 9(a) and Fig. 9(b) are two-dimensional framing model of energy dissipation wall and plywood sheathing wall, respectively. Generally, posts and beams are modeled by elastic beam elements, and connections are modeled by inelastic spring elements whose properties are determined by results of element tests as shown in chapter 2. Fig. 9(c) shows an example of the detail around connection. The behavior of viscoelastic damper is simulated by numerical algorithm proposed by Kasai et. al [10]. Friction damper is modeled by normal bi-liner element.



(a) Energy dissipation wall (b) Plywood sheathing wall (c) Detail around connection

Fig. 9 – Framing model of energy dissipation wall and plywood sheathing wall

The framing model is applied to the specimens of shaking table test in the last section. Fig. 10 shows the comparison between analysis results and test results. Fig. 10(a) shows global behaviors like story shear force and story drift, and Fig. 10(b) focuses on local behaviors like axial deformation of connection(left side) and axial force of bolt(right side). Solid line shows test results and dash line shows analysis results. They show close agreement each other. Therefore, the framing analysis model is useful to investigate behavior in individual situation. The influence of arrangement of energy dissipation walls in two-story wooden frame has been discussed in reference [9].

5. Seismic design method of passively controlled wooden house

5.1 Philosophy

Allowable strength design method is generally used for conventional earthquake resistant structures. However, the effectiveness of energy dissipation derived from supplemental damping devices is not taken into account. In this chapter, simple design method for passively controlled wooden house is proposed. It is likely to be categorized as deformation control design method.

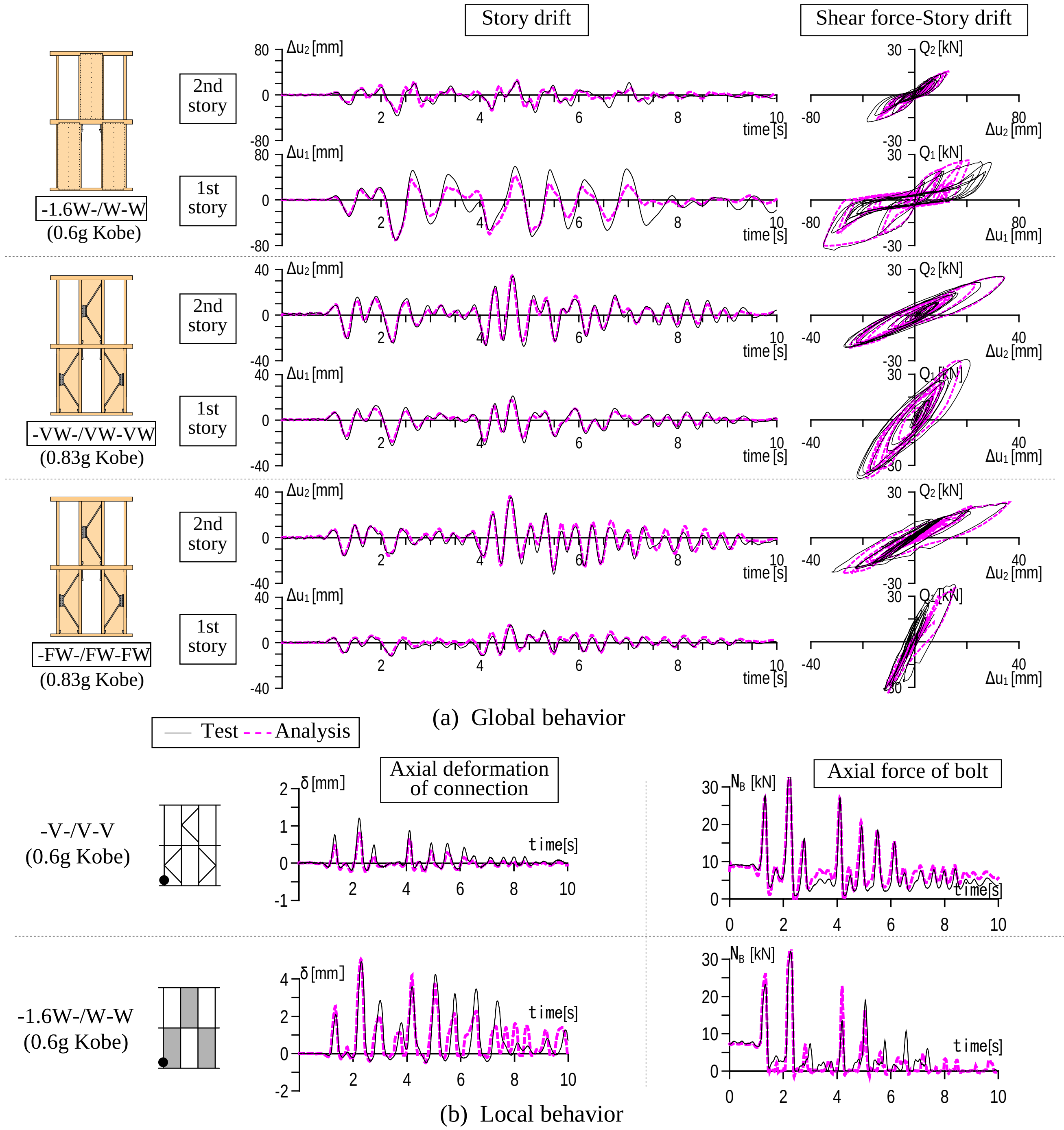


Fig. 10 – Comparison between framing analysis results and shaking table test results

The target story drift angle subjected to "level 2 earthquake" is set 1/75rad. "Level 2 earthquake" is characterized by the acceleration response (= 1G) of elastic system having 5% damping.

5.2 Evaluation method for wooden shear walls and energy dissipation walls with displacement-dependent damper

Performance of wooden shear walls is evaluated using skeleton curve up to 1/75rad. Wooden shear walls have yield point at around 1/120rad even though it is not clearly observed. Therefore, skeleton curve up to 1/75rad is approximated by elastic-perfectly plastic model (EPP) using well-known method provided by HOWTEC in Japan [12]. Allowable strength P'_a is calculated as follows.

$$P'_a = \min\left(\frac{0.2P'_u}{D'_s}, P'_y\right) \ , \quad D'_s = \sqrt{\frac{1}{2\mu' - 1}} \tag{1a,b}$$

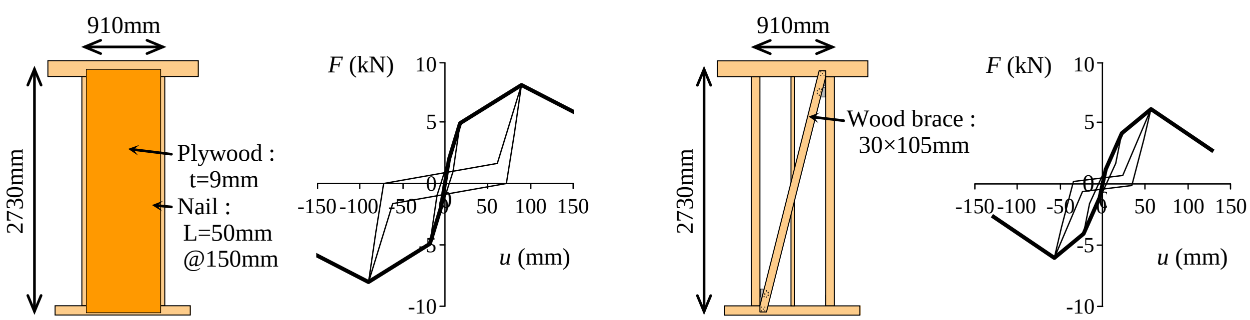
Where,

P'_u : Ultimate strength of EPP model , D'_s : Structural characteristics factor of EPP model

μ' : Ductility ratio of EPP model , P'_y : Yield strength of EPP model

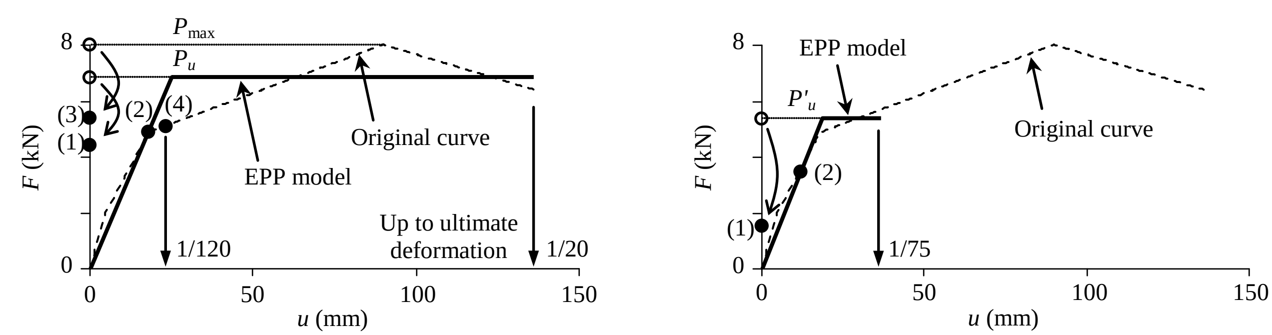
" ′ " means that the value is evaluated by new method. P'_u/D'_s is based on Energy conservation rule proposed by Newmark&Hall [13]. The larger μ' is, the smaller D'_s is and then the larger P'_a is. Although the conventional design method expects large μ (around three to six), new method uses smaller μ' than conventional μ because it does not expect ductility. By considering P'_y, minor damage against level 1 (moderate) earthquake is also prevented. Coefficient 0.2 means the ratio of seismic force between level 1 and level 2. However, P'_a is likely to be determined by $0.2P'_u/D'_s$ in many cases. As for energy dissipation walls with displacement-dependent damper, the same formula is applied because the behavior is likely to follow Energy conservation rule.

Fig. 11 shows an example of hysteresis loop of plywood sheathing wall(WP) and wooden brace wall(WB). In this paper, hysteresis loop of wooden shear walls is represented by bi-linear+slip model [14]. Fig. 12 shows the envelope curve of WP, and the EPP model is also superposed. In the conventional method[10], four indexes corresponding (1) to (4) are evaluated using the envelope curve up to the ultimate deformation. In the new method, two indexes corresponding (1) to (2) (see Eq. (1a)) are evaluated using the envelope curve up to 1/75 rad of story drift angle.



(a) Wooden panel wall(WP) (b) Wooden brace wall(WB)

Fig. 11 – Hysteresis loop of wooden shear walls



(a) Conventional method (b) New method

Fig. 12 – Evaluation of allowable strength of shear walls(WP)

5.3 Evaluation method for energy dissipation walls with velocity-dependent damper

Behavior of energy dissipation walls up to 1/75rad is likely to be almost linear having high viscous damping. Therefore, allowable strength of energy dissipation walls P_d is evaluated assuming steady state response at 1/75rad as follows.

$$P_d = \frac{0.2P_{1/75}}{D_h}\ ,\ \ D_h = \sqrt{\frac{1+\alpha h_0}{1+\alpha h_{eq}}} \tag{2a,b}$$

Where,

$P_{1/75}$: Strength of energy dissipation wall under steady state condition at 1/75rad

h_{eq} : Equivalent damping ratio , D_h : Damping effect factor (h_0 = 0.05, α = 25)

$P_{1/75}$ is divided by D_h to increase strength instead of multiplying seismic force by D_h. Therefore, reduction in seismic force by high damping is replaced by increase of strength.

Some of velocity-dependent dampers have dependency on frequency and temperature. We assume that equivalent frequency of wooden house at 1/75rad is 1.4Hz considering typical skeleton curve, and standard temperature is set at 20 degrees.

5.4 Design procedure

1) Required strength

Required strength of each story Q is calculated by weight, required base shear coefficient and distribution of seismic force similar to general structural design. Although base shear coefficient C_0 = 1.0 is actually assumed, C_0 = 0.2 is used for the purpose of calculation.

2) Building strength

Building strength before adding energy dissipation walls P is calculated as follows.

$$P = \sum P'_f + \sum P'_N \tag{3}$$

Where,

P'_f : Allowable strength of wooden shear wall , P'_N : Allowable strength of non-structural wall

3) Necessary amount of energy dissipation walls

Energy dissipation walls are added so that building strength P exceeds required strength Q. Therefore, necessary strength of energy dissipation walls ΣP_d is calculated as follows.

$$\sum P_d \geq Q - \left(\sum P'_f + \sum P'_N\right) \tag{4}$$

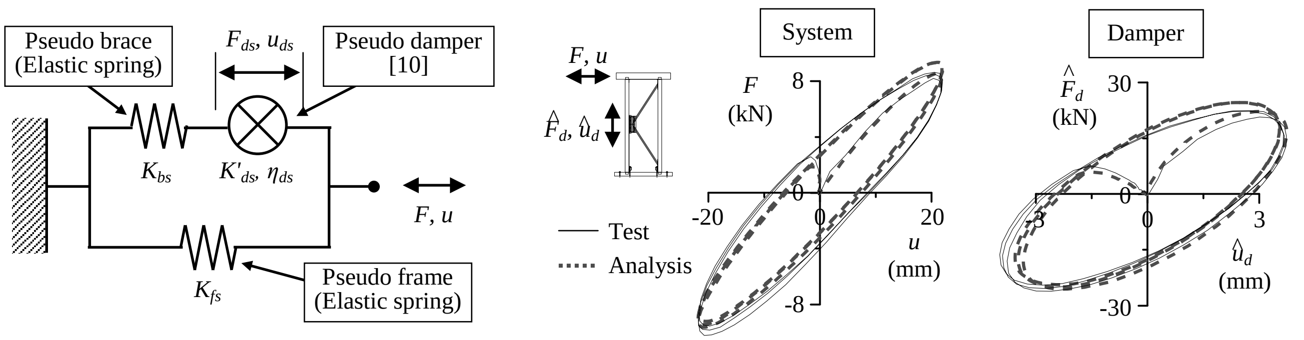
5.4 Analysis model and input motions

As stated before, bi-linear+slip model is used for WP, WB. While energy dissipation wall with displacement-dependent damper is model by normal bi-linear, analysis model shown in Fig. 13(a) is applied to energy dissipation wall with velocity-dependent damper to simulate the minor non-linearity in various situation of frequency, displacement amplitude and temperature [10, 15]. Fig. 13(b) shows comparison with result of dynamic loading test. They show close agreement.

Lumped mass-shear spring model is used to represent two-story wooden detached house. m_1 = 11.5ton and m_2 = 10.1ton are considered. Relationship between base shear coefficient and story drift angle of first story is shown in Fig. 14(a) with respect to each wall type and wall amount. The contribution of gypsum board walls as non-structural components is also taken into account. 2% of viscous damping proportional to initial stiffness is added.

Model parameters are type of wooden shear walls (WP, WB), type of energy dissipation walls (VE, ST) and wall amount. Wall amount is defined as P_f/Q which means the ratio between allowable strength of wooden shear walls calculated by conventional method and required strength. Therefore, P_f/Q = 1 represents a standard model based on conventional seismic design method.

Four artificial waves having idealized spectrum and four real waves whose peak ground velocity (PGV) is scaled to 50cm/s are used. Pseudo acceleration spectra are shown in Fig. 14(b), (c).



(a) Analysis model (b) Hysteresis loop under steady state condition (1/120rad, 1.8Hz)

Fig. 13 – Analysis model of energy dissipation wall with velocity-dependent damper [15]

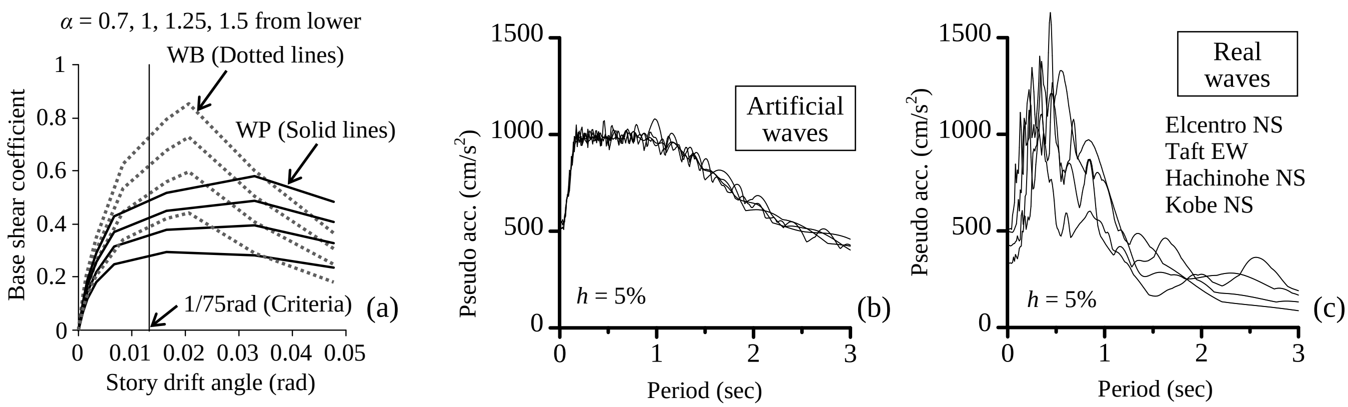


Fig. 14 – Relation between base shear coefficient and story drift angle (a)
and response spectra of input motions(b),(c)

5.5 Analysis results

Analysis results of maximum story drift of various combination of wooden shear walls and energy dissipation walls(WP+VE, WB+VE, WP+ST and WB+ST) are shown in Fig. 15. Vertical axis shows wall amount (P_f/Q) ranging from 0.7 to 1.5. White symbols show average of maximum response of models without energy dissipation walls, and black symbols show that with energy dissipation walls. If average response is close to 36mm (=1/75rad), proposed design method has good accuracy. The range of maximum to minimum response is also demonstrated in the figure.

In almost all cases, average of maximum response does not exceed criteria (=1/75rad). As for models without energy dissipation walls, larger P_f/Q than 1.0 seem necessary to prevent collapse. Even if P_f/Q is 1.5, the response possibly exceeds 46mm (=1/60rad). Therefore, it is difficult to prevent damage without energy dissipation walls.

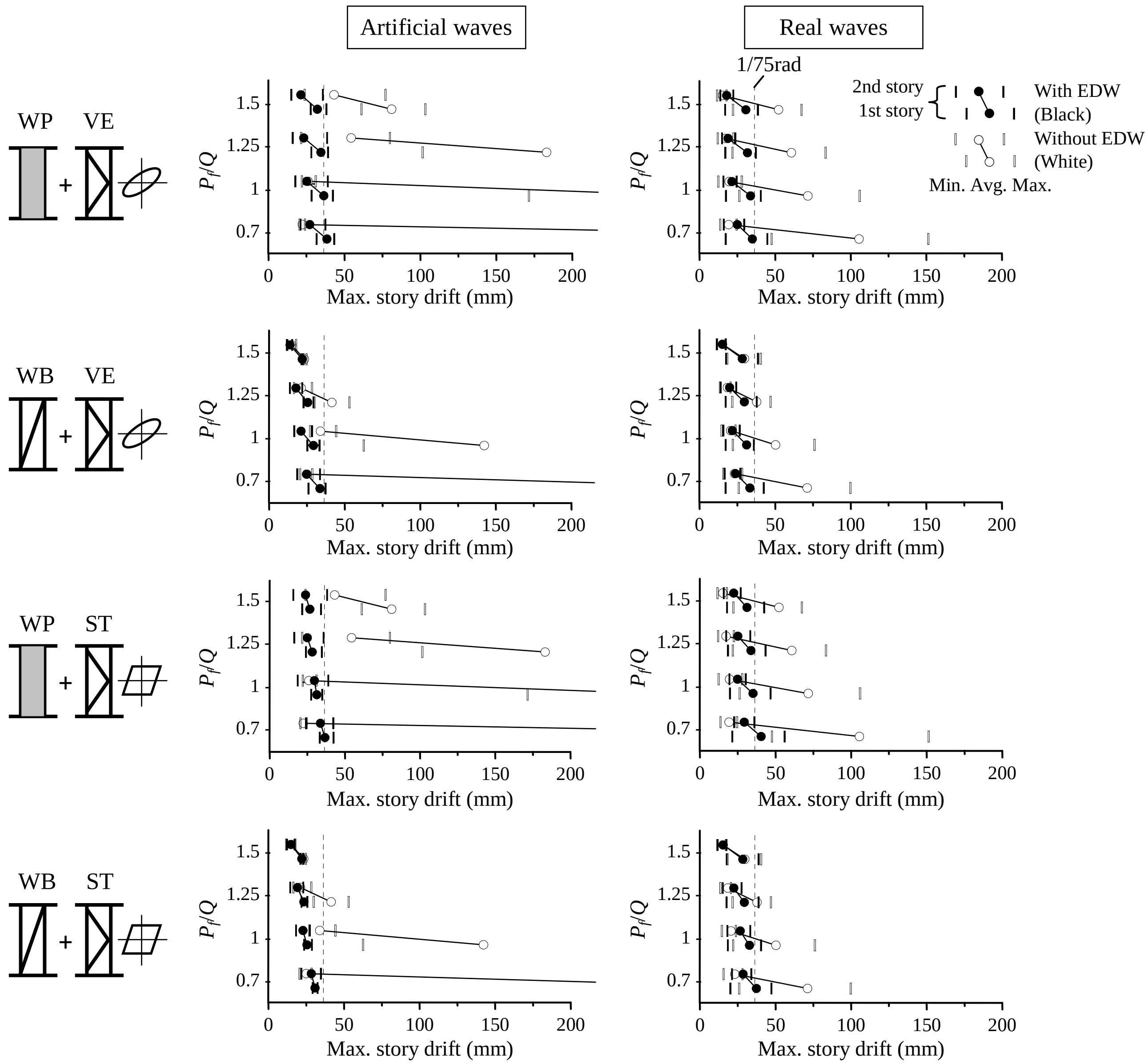


Fig. 15 – Results of time history analysis using models designed by proposed method

6. Conclusions

Behaviors of wooden frame, energy dissipation wall and passively controlled wooden frame were discussed, and seismic design method of passively controlled wooden house was also proposed. While conventional wooden structure is not likely to maintain original performance after severe earthquake, the one provided with energy dissipation walls are expected to protect the safety not only in main shock but in aftershocks. The passively controlled system can contribute to enhancement of property-retention capability of wooden detached houses.

The authors are preparing for publishing design manual for small buildings with passive control devices.

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