EXPERIMENTAL STUDY ON DYNAMIC BEHAVIOR OF WOODEN FRAMES WITH PASSIVE CONTROL SYSTEM AND INNER-AND-OUTER WALLS USING SHAKING TABLE

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ABSTRACT :

In Japan there are 10 million inadequate wooden houses against building standard law and most of them (approximately 90 percent) are composed of conventional post-and-beam. Passive control schemes to mitigate their seismic damage are important. In order to reduce seismic response and damage of wooden houses effectively, a series of so-called shear-link-type passive control systems, which include both velocity- and deformation-dependent dampers were proposed. A number of shaking table tests of the full-scale two-story wooden frame specimens were carried out and the dynamic behavior of the specimen having only structural elements were figured out. However nonstructural element is had to consider when passive control system is applied to wood frames. In this study, a number of shaking table tests of the full-scale two-story wooden frame specimens with inner and outer walls were carried out. Gypsum board, ceramic siding and mortar were used as inner and outer walls. The amount of inner and outer walls of the specimens is determined by the amount of inner and outer walls of real house. The performance of the specimens is discussed by referring to story drifts, story shear forces with a focus on behavior of inner and outer walls. The dynamic property of the structures such as equivalent first eigenfrequency is also discussed.

KEYWORDS: shaking table test, two-stories wooden-frame, inner-and-outer wall, passive control, viscoelastic damper, friction damper

1. INTRODUCTION

In the Hanshin-Awaji (Kobe) Earthquake that occurred in 1995, the number of collapses or seriously damaged of wooden houses were approximately 250,000. It is said that approximately 10 million wooden houses are insufficient for earthquake resistant in Japan, and those houses need to be reinforced immediately. Moreover, to design new wooden houses to be resistant to earthquakes, it is important to investigate rational methods applying the passive control to wooden houses.

In order to mitigate the damage of wooden houses and seismic response, dynamic cyclic loading tests for wooden frames with passive controls[1), 2)] and shaking table tests for one-story wooden frames that corresponded to mass for two-story were carried out[3)]. And shaking table tests for two-story wooden frames (figure 1(a)) were also carried out[4)]. In this way, a number of shaking table tests of the full-scale wooden frame specimens were carried out and the dynamic behavior of the specimen having only structural elements were figured out. However nonstructural element is had to consider when passive control system is applied to wood frames. There are a lot of influences of nonstructural element and it's contemplated that the most is inner and outer wall. Therefore the inner and outer walls were adopted as nonstructural element. In this study, a number of shaking table tests of the full-scale two-story wooden frame specimens with inner and outer walls were undertaken (figure 1(b)). The objective of this study is to figure out the dynamic behavior of these specimens by shaking table tests.

(a) Only Structural Elemenet (b) Having Nonstructural Element

Figure 1 Experimental Overview

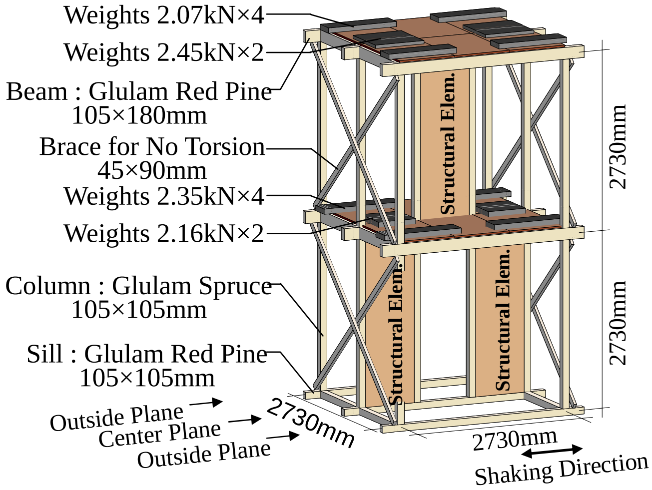


Figure 2 Building Frame of Structural Element

2. OUTLINE OF SHAKING TABLE TEST

2.1. Specimen Concept

Figure 2 illustrates the building frame of the structural element. The specimen is composed of conventional post-and-beam and has a configuration of piled-up two cubes with 2730mm length on each side. The wooden frame has glulam spruce timber for the post (105×105mm), glulam red pine timber for the groundsill (105×105mm), glulam red pine timber for the beam (180×105mm), and structural plywood for the floor slabs (thickness of 28mm).

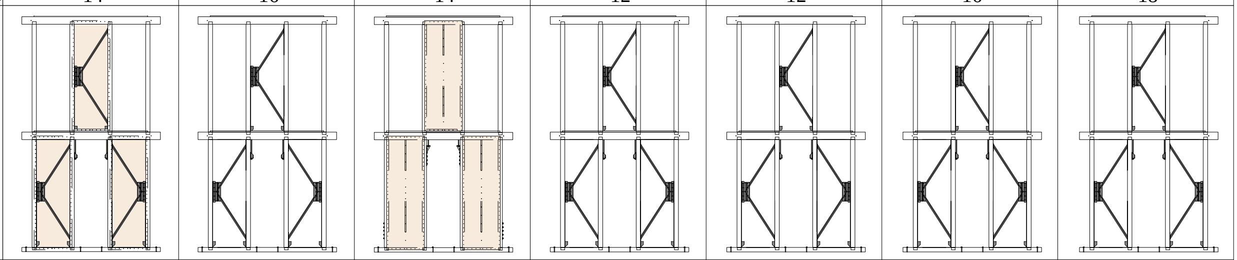
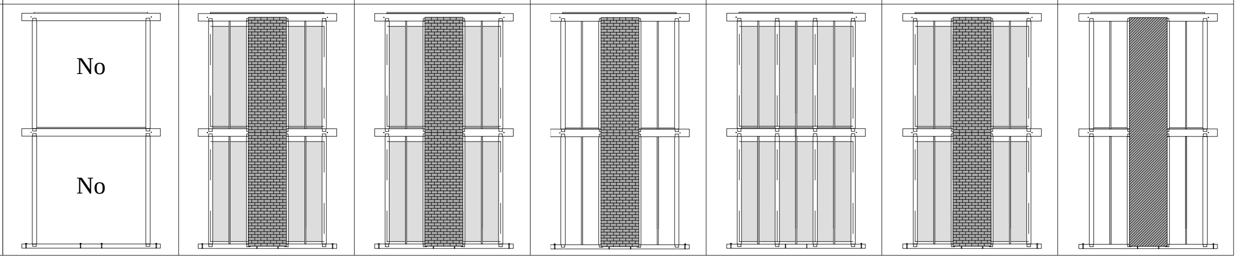
The seismic resistant frame is allocated in the center plane in the shaking direction, and the nonstructural element is allocated in the outside planes. The weight of the specimen is determined so that the two structural elements of the wall-strength-factor 2 have the resistance equivalent to the design lateral force for one story. Design lateral force for one story is obtained as a product of the weight of the specimen and the standard base shear coefficient (= 0.2). Here, the bracing-unit-multiplier is defined as the value of the lateral force corresponding to the 1/120rad. story drift angle deformation of 1m structural element divided by 1.96kN (= shear force which 1m wall can resist). The mass ratio of the 2nd floor to the 1st floor is 0.9, assuming the heavy roof and house where the area of the 1st floor is equal to that of the 2nd floor. The weights over the structural element have an effect on the pull-out of the post of the structural element. Therefore, the weights over the structural element are determined so that permanent axial load of the post of structural element is approximately equal to the dead load of the post of real houses. In the plane orthogonal to the shaking direction, the wood braces are set up to prevent torsion.

2.2. Parameter of Specimen

Specimen parameter is listed in Table 1. The wall-quantity in Table 1 is represented by the product of the bracing-unit-multiplier of structural element and the length. The seismic resistant frame is allocated in the center plane, and the nonstructural element is allocated in the outside planes. The shear link type "K-brace" is used as passive control system. For wood panel of the 2nd floor, the wall is represented by the value considering the strength-factor at the adjustment since stiffness and strength by the number of nails obtained by Murakami and Inayama's equations were changed [5]. In addition, the letters of W means wood panel, V means viscoelastic damper, F means friction damper, S means siding, G means gypsum board, and M means mortar. The structural elements are arranged in center plane and the nonstructural elements are arranged in outside planes.

Table 1 Parameter of Specimens

WQ means "Wall-Quantity"

No.		1	2	3	4			5
Name		-FW-/FW-FW	-F-/F-F(S+G)	-1.2W-/W-W(S+G)	-V-/V-V(S)	-V-/V-V(G)	-V-/V-V(G+S)	-V-/V-V(M)
Center Plane	2nd Floor	F + W	Friction Damper	Wood Panel	Viscoelastic Damper	Viscoelastic Damper	Viscoelastic Damper	Viscoelastic Damper
		WQ = (6+3.6)×0.91	WQ = 6×0.91	WQ = 3.6×0.91	WQ = 5×0.91	WQ = 5×0.91	WQ = 5×0.91	WQ = 5×0.91
	1st Floor	F + W	Friction Damper	Wood Panel	Viscoelastic Damper	Viscoelastic Damper	Viscoelastic Damper	Viscoelastic Damper
		WQ = (6+3)×0.91×2	WQ = 6×0.91×2	WQ = 3×0.91×2	WQ = 5×0.91×2	WQ = 5×0.91×2	WQ = 5×0.91×2	WQ = 5×0.91×2
Outer Plane	Innner	-	Gypsum Board	Gypsum Board	-	Gypsum Board	Gypsum Board	-
	Outor	-	Ceramic Siding	Ceramic Siding	Ceramic Siding	-	Ceramic Siding	Mortar
Last Schedule		14	16	14	12	12	16	18
Center Plane								
Outside Plane								

2.3. Measurement and Vibration Scheme

Figure 3 illustrates the measurement. Laser displacement sensors on the measurement frame built in the shaking table were used to measure the relative displacement of the specimen to the shaking table, and story drifts u_1, u_2 are calculated by using Equation 2.1. There are acceleration sensors at the specimen's groundsill, beams on the 1st floor and the 2nd floor, and the story lateral force, F_1 and F_2, are calculated by using Equation 2.2. The calculation of the story lateral force is found to be correct since Equation 2.3 was verified by using the data of the shear-type load-cell arranged under the basement.

$$u_2 = d_2 - d_1 \qquad u_1 = d_1 - d_0 \tag{2.1}$$

$$F_2 = m_2 \times a_2 \qquad F_1 = F_2 + m_1 \times a_1 \tag{2.2}$$

$$F_1 + m_0 \times a_0 = \sum F_{load} \tag{2.3}$$

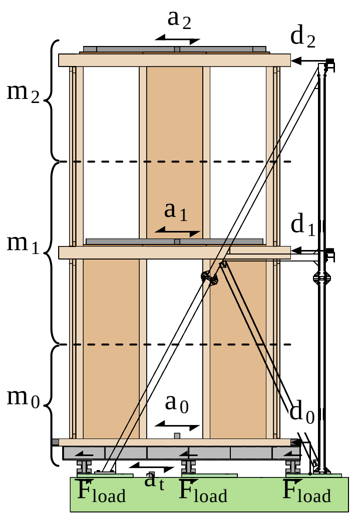


Figure 3 Measurement

Table 2 Vibration Scheme

No.	Name	Maximum Acc.(g)
1	W1	0.1
2	Taft-0.2g	0.2
3	W2	0.1
4	Kobe0.2g	0.2
5	W3	0.1
6	Kobe0.6g	0.6
7	W4	0.1
8	Kobe0.2g(2nd)	0.2
9	W5	0.1
Bolt The Joint Again		
10	W6	0.1
11	Kobe0.83g	0.83
12	W7	0.1
13	Kobe0.83g(2nd)	0.83
14	W8	0.1
15	Kobe1.08g	1.08
16	W9	0.1
17	Kobe1.08g(2nd)	1.08
18	W10	0.1

Vibration scheme is listed in Table 2. For all earthquakes, the coefficient of variation of the displacement response spectrum and the pseudo-acceleration response spectrum obtained from the acceleration at the specimen's groundsill against target spectrum was checked to be within 5% for the natural period from 0.1 to 10.0 second. The eigenfrequency of specimens was measured in subjected to whitenoise which has maximum acceleration 0.1g before or after earthquakes. All specimens were not carried out all earthquakes since each specimens have different strength. The last vibration scheme number is indicated on table 1. The specimens of frame number 4 (table 1) were carried out according to -V-/V-V(S), -V-/V-V(G), -V-/V-V(S+G).

2.4. Amount and Sort of Inner and Outer Walls

Amount of inner and outer walls which are arranged in real house are investigated in order to determine amount of inner and outer walls which are arranged in the specimens. Here is the procedure to determine amount of inner and outer walls.

Regarding the weight of specimen, the 1st floor is 18.8kN and the 2nd floor is 16.8kN. Regarding the weight per unit area which is assumed to calculate necessary wall-quantity, the 1st floor is 1.67kN/m^2 and the 2nd floor is 1.44kN/m^2. The floor area of the specimens correspond to 11.5m^2 1st floor and 2nd floor alike because of dividing the weight of the 1st and 2nd floor by per unit area. According to the investigation of four real houses using the opening reduction coefficient K_0, amount of inner and outer walls per unit area is generally equal and the average is listed in table 3(a). Multiplying the value of table 3(a) by 11.5m^2 corresponding to floor area of specimens gives the value of table 3(b). Therefore, the 1st floor and 2nd floor alike, 6P inner walls and 2P outer walls are arranged in each floor of the specimens.

Table 3 Amount of Inner and Outer Walls (Average)

(a) Per 1m^2

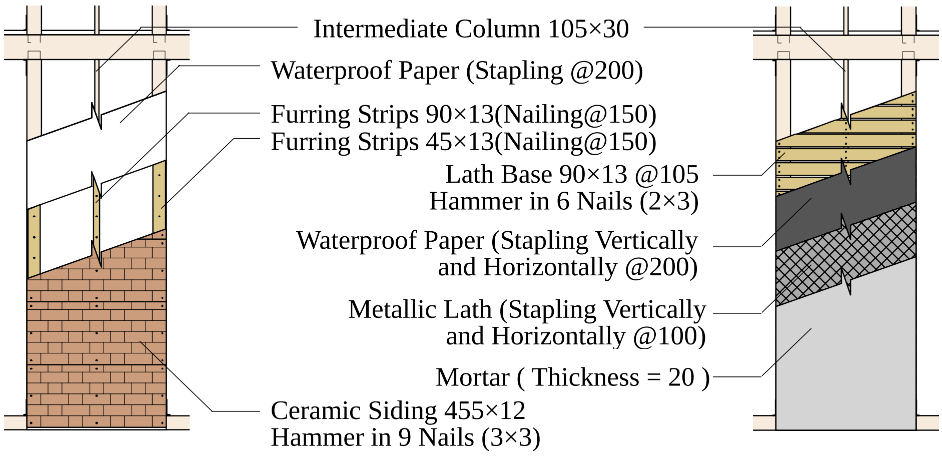
	Inner Wall	Outer Wall
1st Floor	0.443	0.144
2nd Floor	0.515	0.171

(b) Per 11.5m^2

	Inner Wall	Outer Wall
1st Floor	5.10	1.66
2nd Floor	5.92	1.97

Unit : P (= 910mm)

(1) Inner Wall
The gypsum board was used. The size is 910×2420× 12mm. The gypsum boards are screwed to the column and the intermediate column at 150mm intervals.
(2) Outer Wall
The details of outer walls are illustrated to figure 4 and used staple is illustrated to figure 5. There are a lot of construction methods of outer walls, the commonest construction method is adopted. The ceramic siding walls are composed of ventilatory method by arranging the furring strips vertically. The mortar walls were given a first coat on March 8th, were given a final coat on March 14th and shaking table test of the specimen applied mortar walls are carried out on April 9th. In the case of using inner walls or outer walls, L type joint metal (figure 6) is arranged in the junction of column with horizontal member.



(a) Ceramic Siding (b) Mortar

Figure 4 Details of Outer Walls

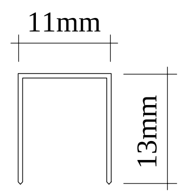


Figure 5 Used Staple

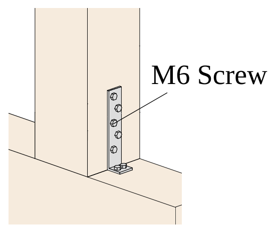


Figure 6 L Type Joint Metal

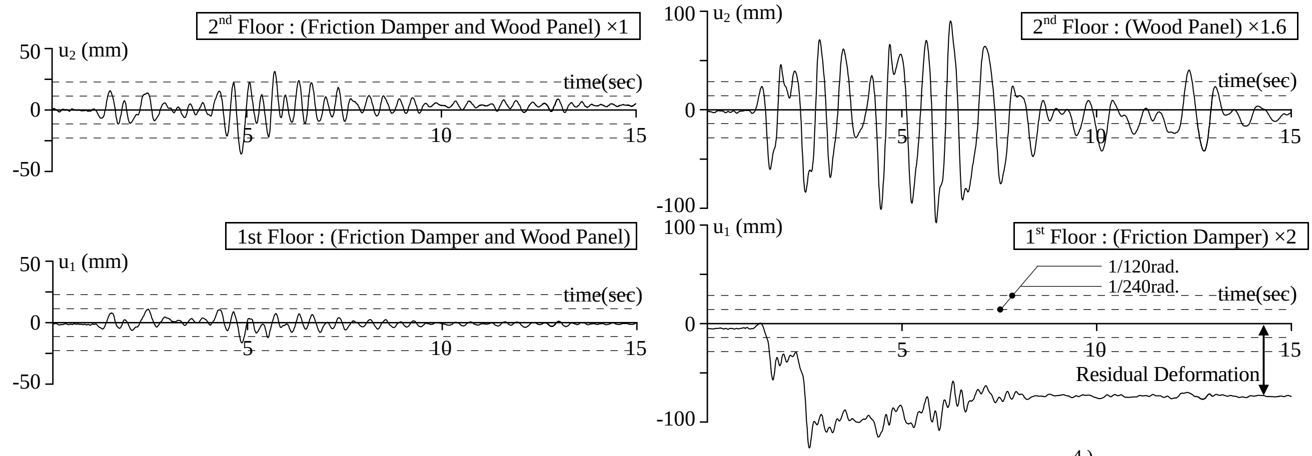
3. TEST RESULTS AND COMSIDERATION

3.1. Time History of Story Drift

Figure 7(a) indicates the time history of story drift in case -FW-/FW-FW was subjected to Kobe0.83g. And for comparison, figure 7(b) indicates the time history of story drift in case -1.6W-/F-F which is included in the reference [4)] was subjected to same earthquake.

In the case of -1.6W-/F-F, the 1st floor with only friction damper had residual story drift angle of approximately 1/45rad. and the 2nd floor with only wood panel had long natural period because of the heavy damage. On the other hand, in the case of -FW-/FW-FW, although the 1st floor has story drift angle of approximately 1/90rad., the floor has little residual story drift and stable natural period.

In the case of no elasticity element, there is a high possibility that the floor with only friction damper has residual story drift because the secondary stiffness of friction damper is low. It is possible to confirm that the wood panel serves as elasticity element effectively.

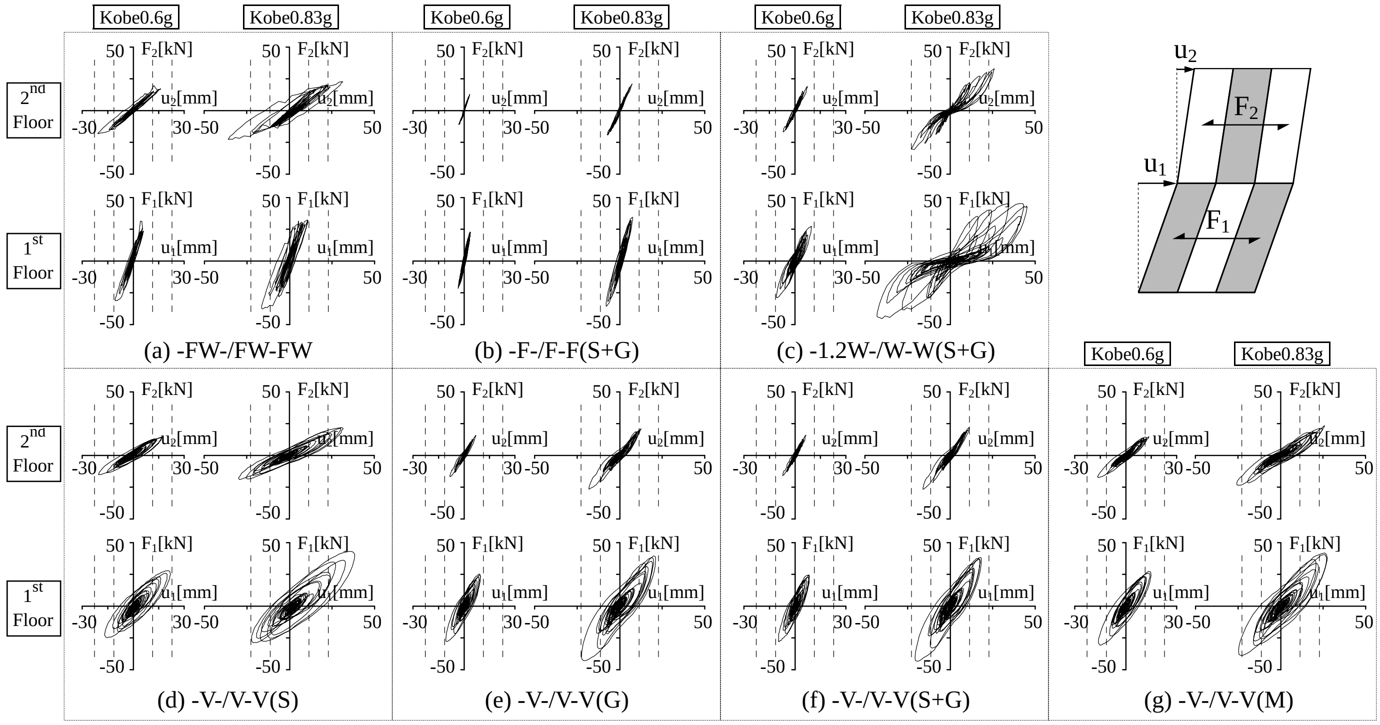


(a) -FW-/FW-FW (b) -1.6W-/F-F 4)

Figure 7 Time History of Story Drift (Kobe0.83g)

3.2. Relationships Between Lateral Force and Displacement

In case the specimens were subjected to Kobe0.6g and Kobe0.83g, the relationships between lateral force and displacement are illustrated in figure 8. -FW-/FW-FW behaved with elasto-plastic hysteresis when it is subjected to Kobe0.6g. However -F-/F-F(S+G) behaved with elastic hysteresis when it is subjected to Kobe0.6g



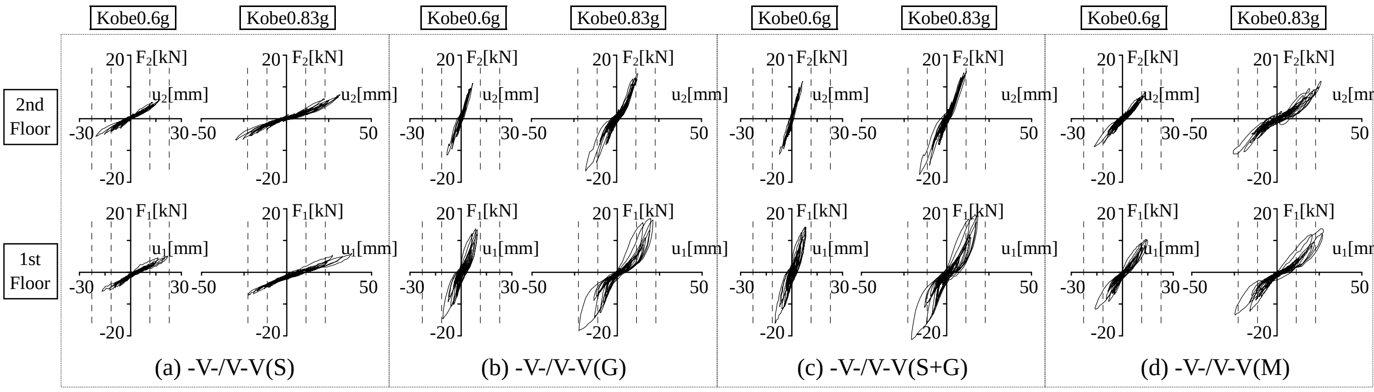
Broken lines indicate displacement of 1/240rad. and 1/120rad.

Figure 8 Relationships Between Lateral Force and Displacement because of high initial stiffness. When -1.2W-/W-W(S+G) was subjected to Kobe0.83g, it behaved with pinched hysteresis having slippage after nails came off structural plywood. The hysteresis of the specimens with viscoelastic damper formed the ellipsoid.

3.3. Relationships Between Lateral Force and Displacement of Outside Planes

When the center plane has K-brace, the lateral force which the center plane bears approximately equal to third part of damper force[3)]. Subtracting the third part of damper force from lateral force of figure 8, it is possible to calculate the lateral force which the outside planes bear. Figure 9 illustrates the relationships between lateral force of outside planes and displacement.

-V-/V-V(S) which has only ceramic siding in outside planes behaved with elastic hysteresis if the story drift angle was over 1/120rad. On the other hand, -V-/V-V(G) which has only gypsum board in outside planes behaved with high initial stiffness, however it behaved with pinched hysteresis having slippage due to the screws dug into the gypsum board before the story drift angle was 1/240rad. -V-/V-V(M) which has only mortar in outside planes also behaved with higher initial stiffness than ceramic siding, however it behaved with pinched hysteresis having slippage due to the staple came off the lath base in small deformation before the story drift angle was 1/240rad.



Broken lines indicate displacement of 1/240rad. and 1/120rad.

Figure 9 Relationships Between Lateral Force of Outside Planes and Displacement

3.4. Variation of First Eigenfrequency

The variation of first eigenfrequency is illustrated in figure 10. The value was evaluated by whitenoise. When -V-/V-V(S) and -V-/V-V(M) are compared, -V-/V-V(M) slightly had higher than -V-/V-V(S) at first. However the two were approximately equal after Kobe0.6g. In spite of -1.2W-/W-W(S+G) had high value at first because of gypsum board, the more it was shaken, the more the value dropped away. In particular, after Kobe0.83g the value dropped away considerably. In the case of the specimen with friction damper, the value didn't drop so much, because the damper has high stiffness. In the case of -V-/V-V(G) and -V-/V-V(S+G), the value gradually dropped away because gypsum board had damage in small deformation. However they had higher value than the specimens which have only outer walls. Therefore the influence of inner walls is larger than that of outer walls, regarding real house.

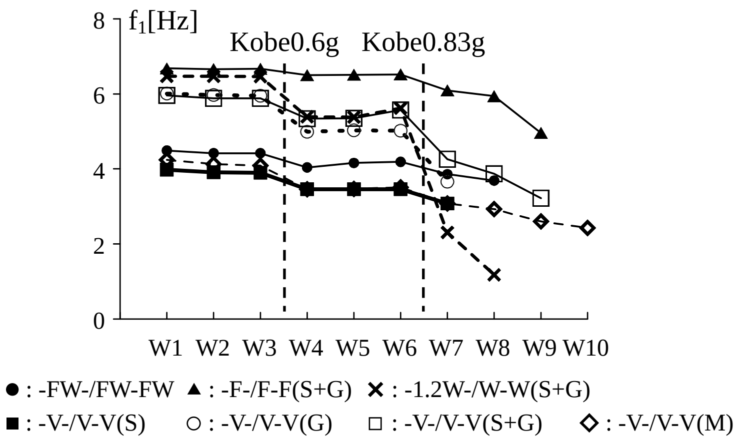


Figure 10 Variation of First Eigenfrequency

4. CONCLUSIONS

A number of shaking table tests of the full-scale two-story wooden frame specimens with inner and outer walls were carried out. Major finding are

1) In the case of the friction damper, it is possible to reduce the residual story drift by combining with the wood panel as elasticity element.

2) The difference of hysteresis of between gypsum board, ceramic siding and mortar are figured out. The walls with only ceramic siding behave with elastic hysteresis if the story drift angle is over 1/120rad. The walls with only gypsum board or mortar behave with pinched hysteresis before the story drift angle is 1/240rad.

3) The influence of inner walls is larger than that of outer walls, regarding real house. And in this experiment, the specimen which has gypsum board in outside planes behaved with eigenfrequency over 6Hz at first

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