Analytical Study on Passively Controlled 2-Story Wooden Frame by Detailed Frame Model

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SUMMARY:
This paper proposes an accurate, member-by-member analytical model for timber structures having energy dissipation walls and/or plywood shear walls. Various member joints are modeled by using nonlinear spring elements whose properties derived from numerous test results, and model's schemes are described in detail. The analyses were found to reproduce both local and global responses obtained from cyclic loading tests and shaking table tests of a variety of one and two-story mult-span timber frames. Moreover, unsteady behavior of slip-hysteretic structure, energy absorption performance and deformation state of energy dissipation wall arranged in 2nd floor are discussed.

Keywords: Frame Analysis, Wooden Structure, Passive Control, Viscoelastic Damper, Structural Plywood

1. INTRODUCTION

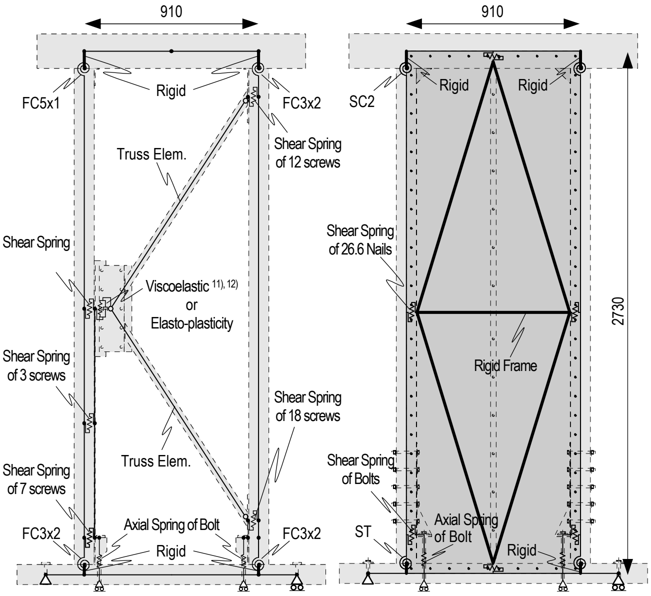
In order to mitigate the earthquake response and damage of wooden houses, an energy dissipation wall was developed (Kasai and Sakata et al. 2005, Appendix 1) and a lot of experimental studies using the wall were carried out, such as dynamic cyclic loading tests of the energy dissipation walls (Matsuda et al. 2008), shaking table tests of 1-story and 2-story wooden frames (Sakata et al. 2007 and Matsuda et al. 2007), and so on. However, analytical studies need to be carried out to develop more effective energy dissipation wall and to propose the design method. In particular, a framed analysis is effective to study their local behavior. Therefore the objective of this study is to propose an accurate, member-by-member analytical model for timber structures having energy dissipation walls and/or plywood shear walls.

To make the model, modeling the joint is important extremely. In this study, various member joints are modeled by using nonlinear spring elements whose properties derived from numerous test results, and model's schemes are described in detail. Also the accuracy of the framed analytical model is confirmed by the comparison between the analytical results and many test results. In addition, unsteady behavior of slip-hysteretic structure, energy absorption performance and deformation state of energy dissipation wall arranged in 2nd floor are discussed.

2. ANALYTICAL FRAME MODEL

2.1. Outline of Analytical Frame Model

Fig. 1(a) illustrates frame model of the energy dissipation wall and the plywood shear wall. Basically linear beam elements which have same condition to the test members, are arranged in the center of the members. The column and horizontal member are connected by the joint elements which consist of three springs: axial spring, shear spring and rotational spring (see Fig. 2). The area between the beam edge and the column edge is assumed rigid and the steel pipe brace is set for truss elements. There



(a) Energy Dissipation (b) Plywood Shear Wall

Figure 1 Detail of Frame Model

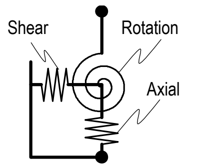


Figure 2 Joint Elem.

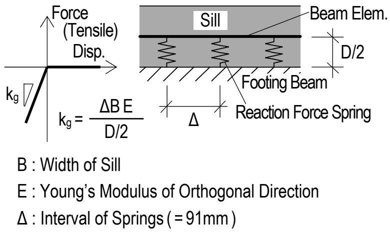
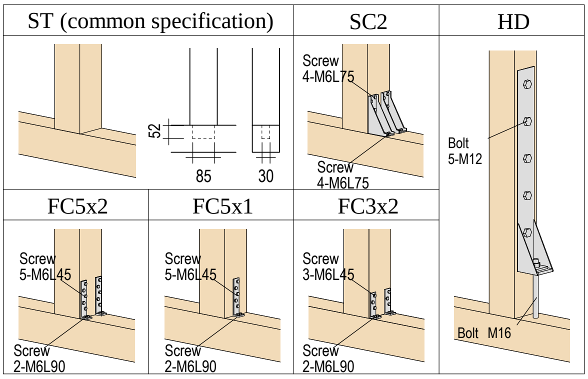


Figure 3 Reaction Force Spring of Sill

Table 1 Joint Types



are reaction springs under the sill (see Fig. 3). Viscoelastic element which was proposed by Kasai et al. (2001, 2002), or elasto-plasticity element are arranged at the point between the intersection of the braces and the steel plate. Basically following equations are used in viscoelastic element.

$$\tau(t) + aD^{\alpha}\tau(t) = G\,[\gamma(t) + bD^{\alpha}\gamma(t)] \tag{2.1}$$

$$a = a_{ref}\lambda^{\alpha} \quad , \quad b = b_{ref}\lambda^{\alpha} \tag{2.2a, b}$$

$$\lambda = \exp[-p_1(\theta - \theta_{ref})/(p_2 + \theta - \theta_{ref})] \tag{2.3}$$

Where D^{α} is operator of fractional derivative, α is order of fractional derivative. a, b and G are parameter to depend on frequency, a_{ref} and b_{ref} are parameter to depend on temperature.

There are two types of joint element: FC3x2, FC5x1 (see Table 1). The L-type metal includes "FC5" and "FC3" which indicate the number of screws on the column. "x1" and "x2" indicate the number of the metals. Detail of setting the each spring will be described in section 3.2. The shear springs between the two nodes are set depending on shear performance of per screw which is set from the test of the joint, because the steel plate is screwed on column by a number of screws. Also the axial springs of bolt are set from the test of joint.

Fig. 1(b) illustrates frame model of the plywood shear wall. Basically constructing method of the exterior frame is same as energy dissipation wall. Therefore linear beam elements which have same condition to the test members, are arranged in the center of the members. Each beam elements are connected by the joint elements which consist of three springs. There are two types of joint element: ST and SC2 (see Table 1). There are shear springs and axial springs of the bolts. The effect of the nails is concentrated to four shear springs using the shear property of a nail and the sheeted wall theory (Murakami et al. 1999).

2.2. Method of Concentrating Nail Spring

Murakami and Inayama have proposed a method to calculate the shear performance of plywood shear wall from relationship between shear force of nail and displacement of nail (Murakami et al. 1999). The method assumes the nail behavior to be able to separate to mode X and mode Y (see Fig. 4). The concentrating method which will be proposed here is based on the same idea.

Considering that the center of Fig. 4 (mode X) is separated up and down, the effect of nails of upper side is concentrated to point U in Fig. 5. Similarly the effect of lower side is concentrated to point D. The scale factors of up and down are obtained from equation (2.4).

$$m_U = \sum y(i_u)^2 / H_U{}^2 \quad , \quad m_D = \sum y(i_D)^2 / H_D{}^2 \qquad (2.4a, b)$$

Where H_U and H_D are distance of each point to neutral axis, i_U and i_D are number of nail, y is distance of each nail to neutral axis. Similarly considering the mode Y, the scale factors of right and left are obtained from equation (2.5).

$$m_L = \sum x(i_L)^2 / L_L{}^2 \quad , \quad m_R = \sum x(i_R)^2 / L_R{}^2 \qquad (2.5a, b)$$

The four scale factors are multiplied by the relationship between shear force of nail and displacement of nail (see Fig. 5), the four springs are connected by the rigid member. It was confirmed that the concentrated model behaves similarly to detailed model and also real structure (Matsuda et al. 2010).

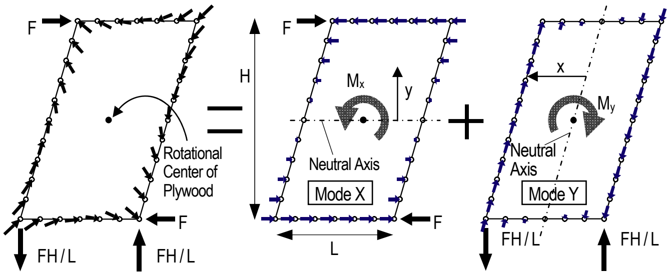


Figure 4 Force Acting on Frame (Elastic)

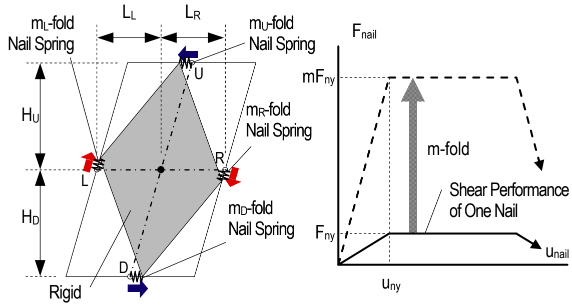


Figure 5 Outline of Concentrating Nail Spring

3. CONFIGURATION OF SPRING

3.1. Hysteresis Rule

Fig. 6 illustrates hysteresis rule of Joint. After arriving at the elastic limit, the force increases gradually, and the envelope curve is calculated by Equation (3.1).

$$P = \frac{(k_0 - k_p)(u - u_a)}{\left(1 + \left|k_0 (u - u_a)/P_0\right|^n\right)^{1/n}} + k_p (u - u_a) + P_a \qquad (u > u_a) \qquad (3.1a, b)$$

Where P_0 is constant number which is obtained by substituting P_b and u_b into P and u. n is coefficient to decide the shape of the curve.

To duplicate the pinched hysteresis having slippage specific to wooden structure, the hysteresis rule is able to change the slip stiffness depending on maximum displacement (see Fig. 6). This hysteretic rule is applied to the six springs: axial, rotational and shear springs of the joint, and shear springs of the screw, bolt and nail.

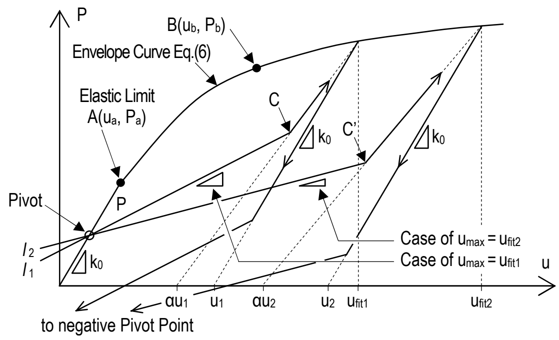


Figure 6 Hysteresis Rule of Joint

3.2. Joint Spring between Column and Horizontal Member

In order to model the property of the joint spring, a lot of joint test were carried out (Sakata et al. 2009). Fig. 7-8 show the modelization of the many kinds of joint. The envelop curves of model are fitted to the average of more than three test results. The models correspond to test results including their cyclic behavior.

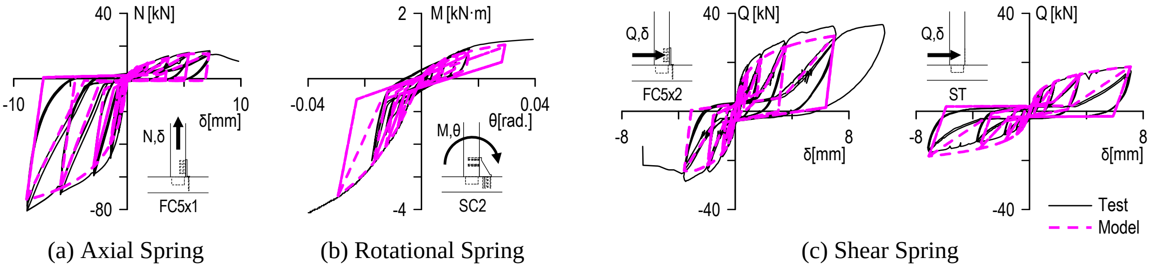


Figure 7 Modelization Example of Joint between Column and Horizontal Member

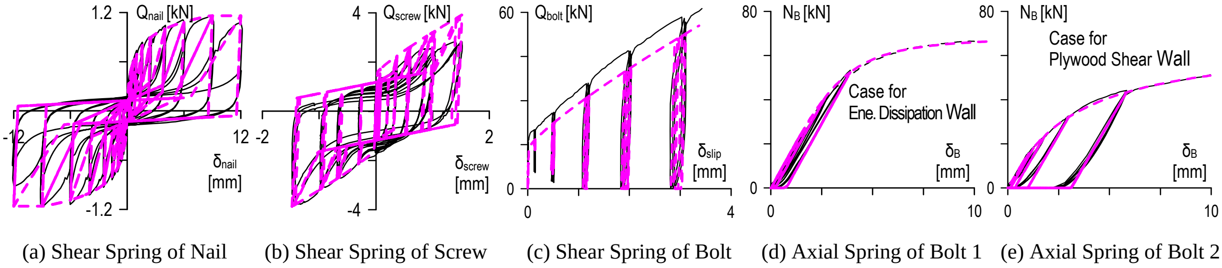


Figure 8 Modelization Example of the Other Joint

Test Model

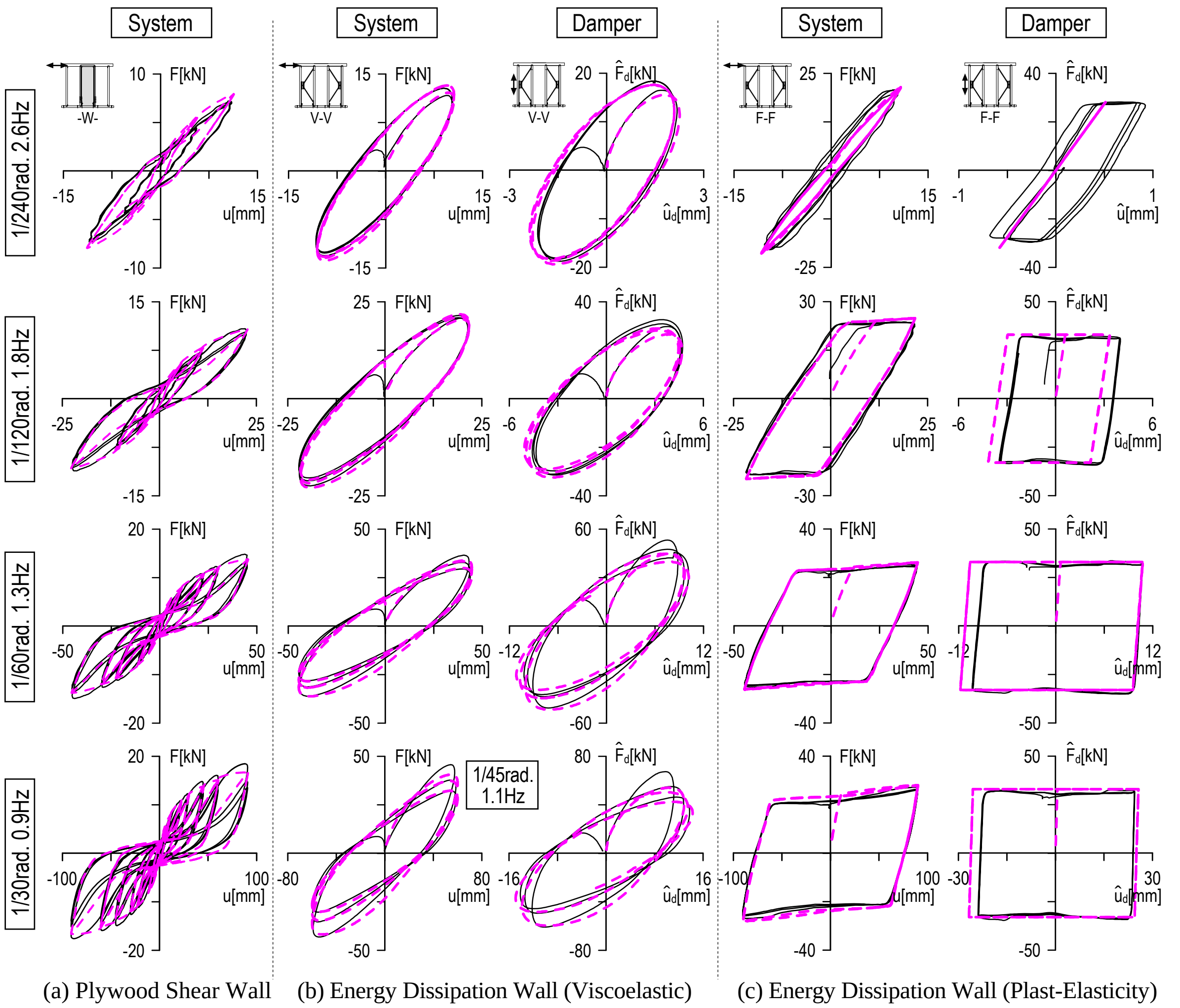


Figure 9 Comparison of Test and Analysis of Cyclic Loading

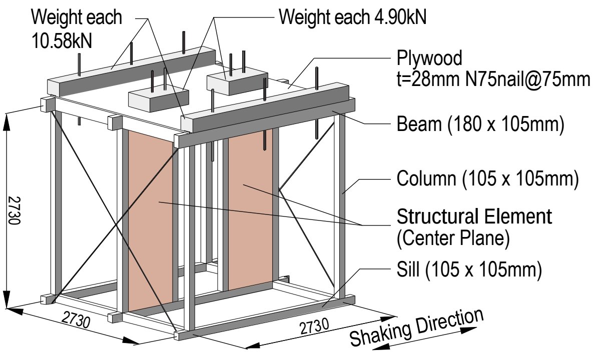
Test Model

4. COMPARISON BETWEEN TEST AND ANARYSIS

The letters of the model name indicate the kind of structural element, W means wood panel, V means viscoelastic damper, F means friction damper, - means no wall and / means border of between 1st and 2nd floor.

4.1. Cyclic Loading Test

As for cyclic loading test of energy dissipation wall and plywood shear wall, Fig. 9 illustrates the comparison of test results (Matsuda et al. 2008) and analytical results. In the case of plywood shear wall, the analysis result duplicates not only strength but also slip behavior. In the case of energy dissipation wall, in both viscoelastic damper and elasto-plasticity damper, system hysteresis and damper hysteresis, analytical results correspond to test results with high accuracy.



(a) 1-Story Wooden Frame (Left)
(b) 2-Story Wooden Frame (Right)

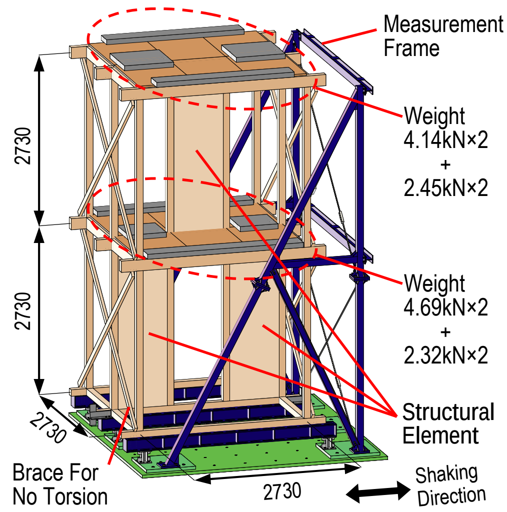


Figure 10 Shake Table Test of Wood Frame with Damper

4.2. Shaking Table Test

In order to confirm the accuracy of seismic response, the comparison of shake table test and seismic response analysis will be discussed. Fig. 10 indicates the test specimen. Only center plane of the specimen is substituted to frame model since four-cornered columns hardly have horizontal force. Stiffness proportional damping 0.5% is used. Acceleration record which was measured on the specimen's sill during shake table test is used for the analysis and the records have been adjusted to JMA-Kobe 0.6g. Time step Δt is 0.001 sec and total analysis time is 10 sec (10,000step).

4.2.1. Shaking Table Test of 1-Story Wooden Frame

Fig. 11 show the comparison of test result and analytical result. As for W-W, although the maximum displacement corresponds each other, there is large error in the positive side. The reason is that the effect of large deformation of the negative side on positive side is not considered in this analysis. However the analytical result is similar to test result in both system and damper hysteresis, and the error in the maximum displacement is within 15%.

4.2.2. Shaking Table Test of 2-Story Wooden Frame

Fig. 12 shows the comparison of test result and analytical result in both global and damper behavior. As for -1.6W-/W-W, there is large error in the positive side as well as W-W of Fig. 11. In the case of specimens which have energy dissipation wall in each floor, the test results and analysis results correspond each other with high accuracy.

Fig. 13 shows the comparison of test result and analytical result of local behavior. The rotational angle of local behavior shown in upper stage of Fig. 13 is duplicated with high accuracy since the rotation angle tends to follow story drift angle. In the case of center capital of 1st floor, rotational

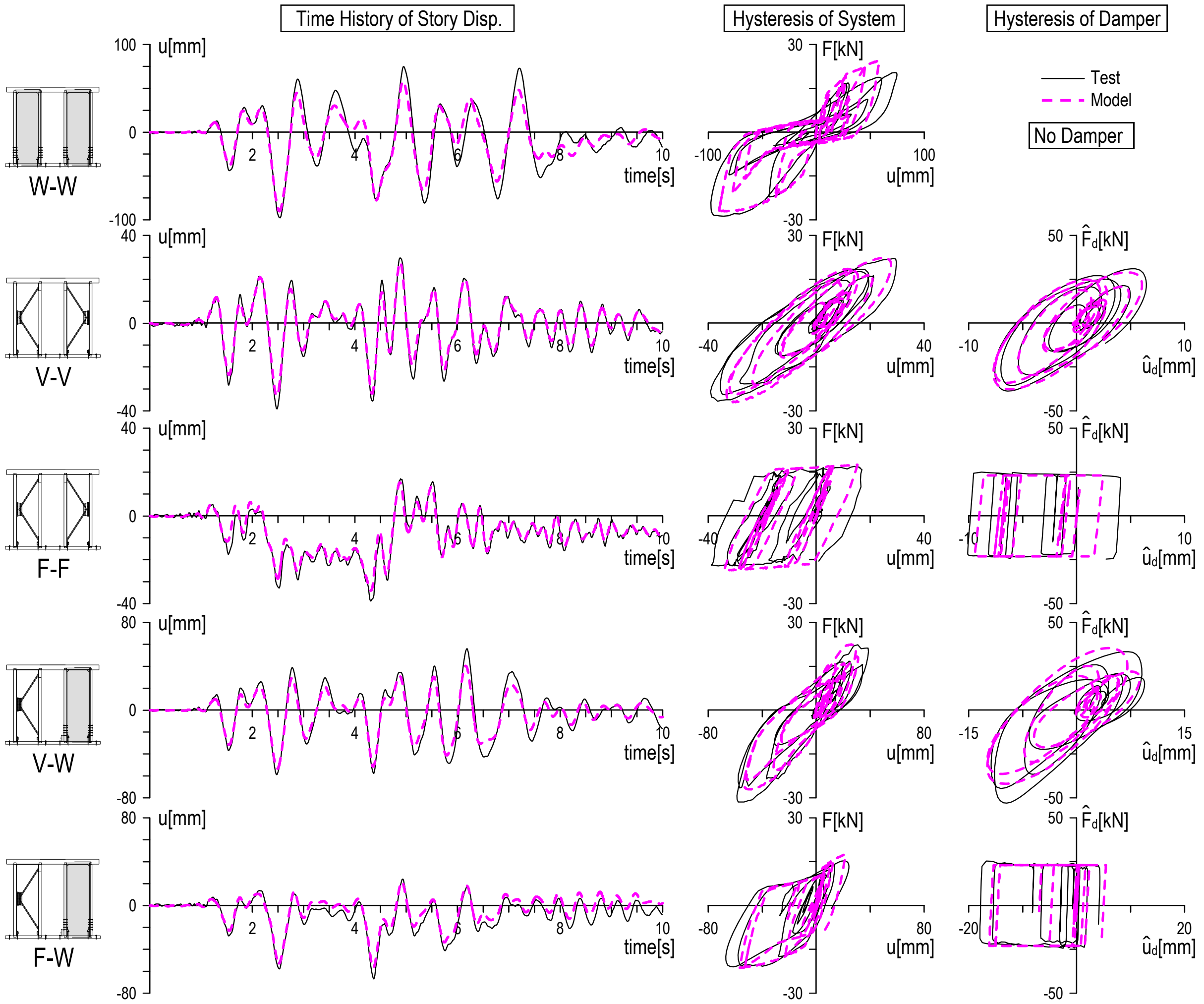


Figure 11 Comparison of Test and Analysis of Global Behavior (1-Story Frame, JMAKobe0.6g)

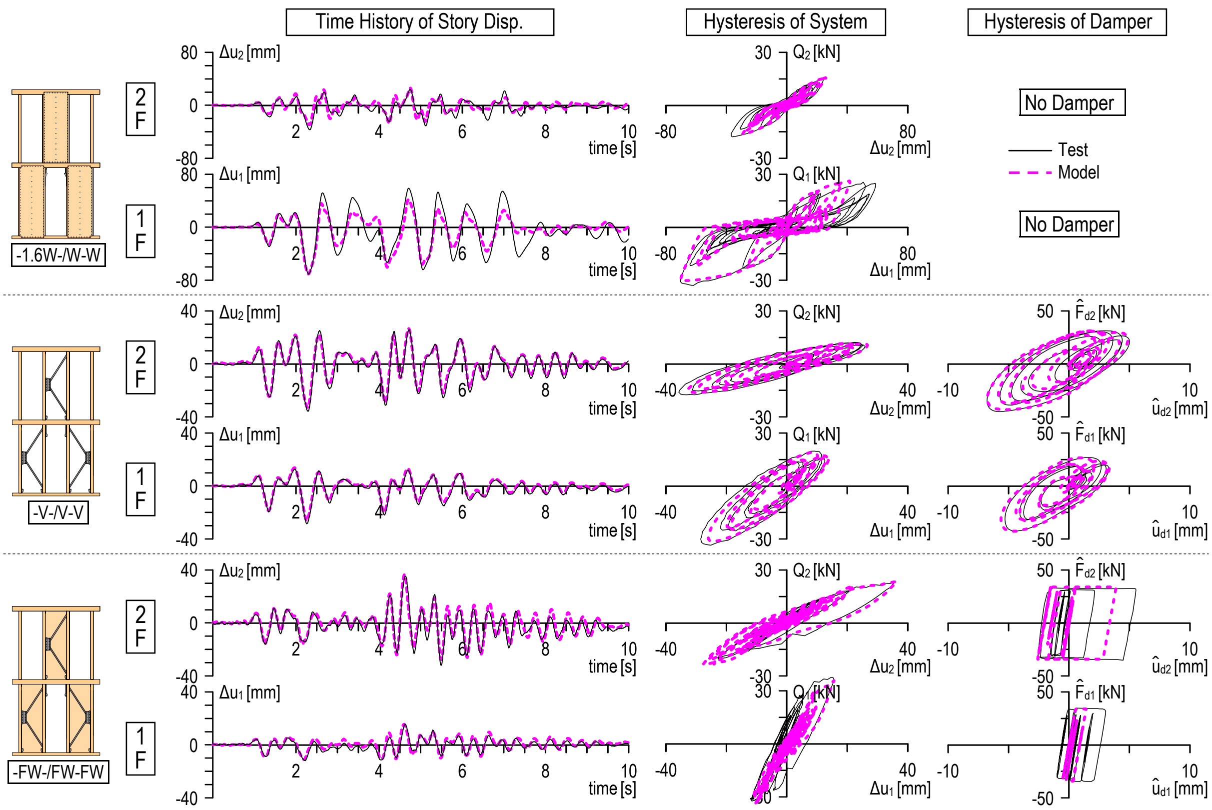
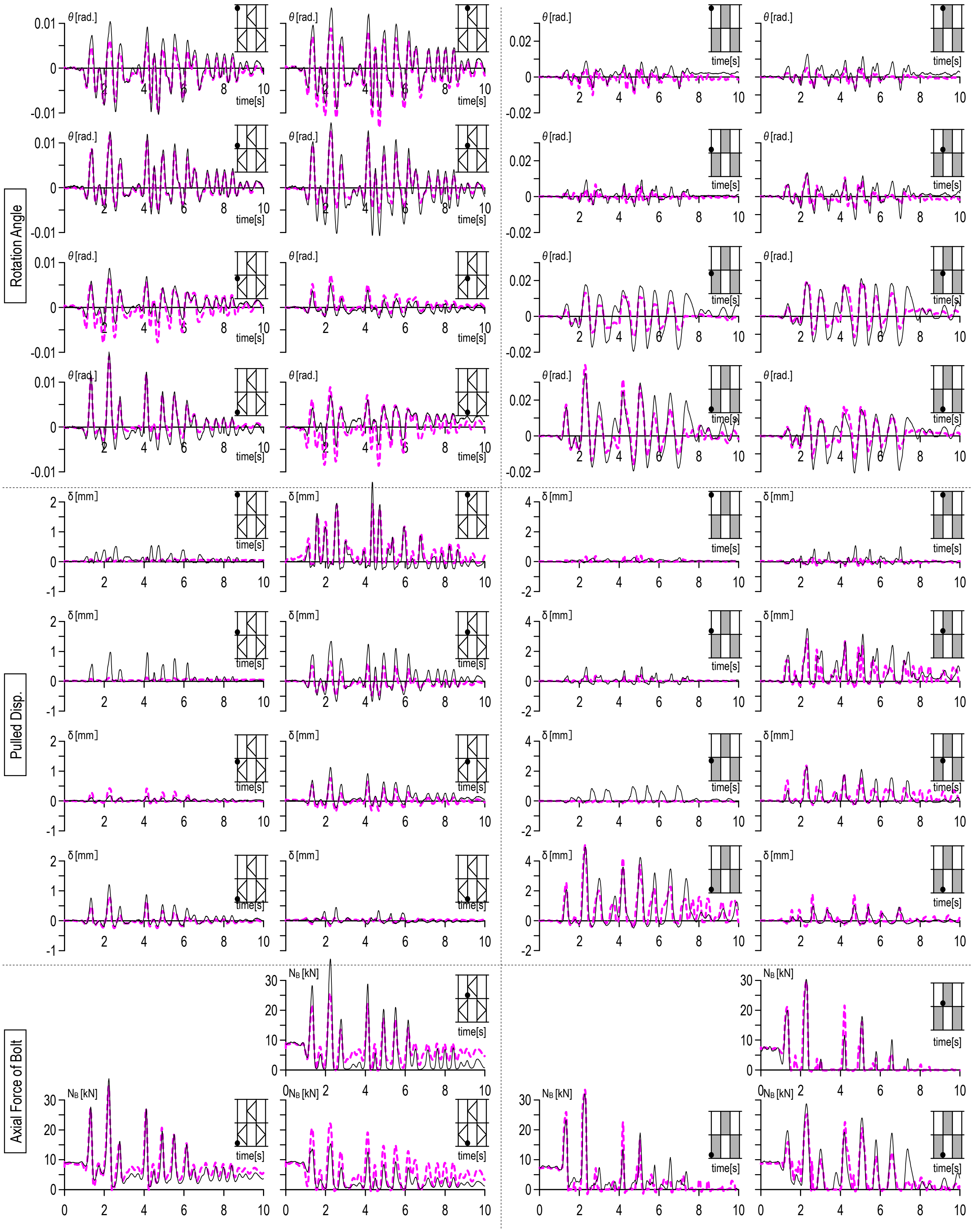


Figure 12 Comparison of Test and Analysis of Global Behavior (2-Story Frame, JMAKobe0.6g)



(a) –V-/V-V (Energy Dissipation Wall)　　　(b) –1.6W-/W-W (Plywood Shear Wall)

Figure 13 Comparison of Test and Analysis of Local Behavior (2-Story Frame, JMAKobe0.6g)

resistance is strong since the joint has two metals (FC3x2 and holddown bolt) in both sides, therefore the rotational angle is smaller than the other joints. The analysis result is able to duplicate this phenomenon. In the case of axial displacement shown in center stage of Fig. 13, the analytical displacement of capital part is smaller than the test result. Since the analysis is not able to duplicate axial displacement which the rotation provokes. However the other feature is similar between the analysis and the test. In the case of also axial force of bolt shown in lower stage of Fig. 13, the analytical result duplicates the test result nearly. In particular, the analysis result is able to duplicate axial force of bolt caused by rotation. As observed above, the frame model is able to duplicate the shake table test of 2-story timber frame in terms of not only global behavior but also local behavior with a high degree of accuracy.

5. EFFECT OF LAYOUT OF WALLS

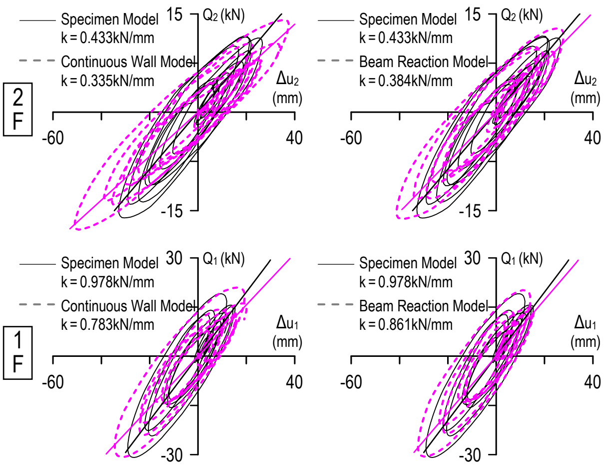
5.1. Examination Object

Although the check configuration of structural wall was adopted to the specimen for the shake table test, vertically continuous configuration of structural wall is often adopted to the real houses. In addition, in the case of seismic retrofit or not continuous column vertically, the reaction force of the holddown bolt of 2nd floor is obtained from a just below beam. Therefore the energy absorption performance of these cases will be estimated by using the detailed frame model. In sequence, these model are called Specimen Model, Continuous Wall Model and Beam Reaction Model.

5.2. Comparison of Global and Local Behavior

As for the specimen which has viscoelastic damper, Fig. 14 shows the relationship between story shear force Q and story drift Δu in each model. The stiffness of Continuous Wall Model decreases about 20% from Specimen Model in each floor and maximum deformation of 2nd floor increases about 50% from Specimen Model. The stiffness of Beam Reaction Model decreases about 8% from Specimen Model in each floor and maximum deformation of 2nd floor increases about 25% from Specimen Model. Axial force distribution of column and relative displacement of joint at peak strength of 1st floor are shown in Fig. 15. When the 1st floor reached a maximum strength, 2nd floor almost reached a maximum strength since the contribution of 1st deformation mode was extremely high.

In the case of Fig. 15 (b) Continuous Wall Model, the axial force of 1st floor column increases because the axial force of 2nd floor column is transferred to just below column. Therefore the method to select metal type has been established to consider the configuration of structural wall by Japanese building standard low. Meanwhile, there is no rule to consider the configuration of energy dissipation wall. A method to select specification of the joint considering the configuration of energy dissipation wall should be discussed.



(a) vs Continuous Wall Model (b) vs Beam Reaction Model

Figure 14 $Q-\Delta u$ Relationships of Each Model

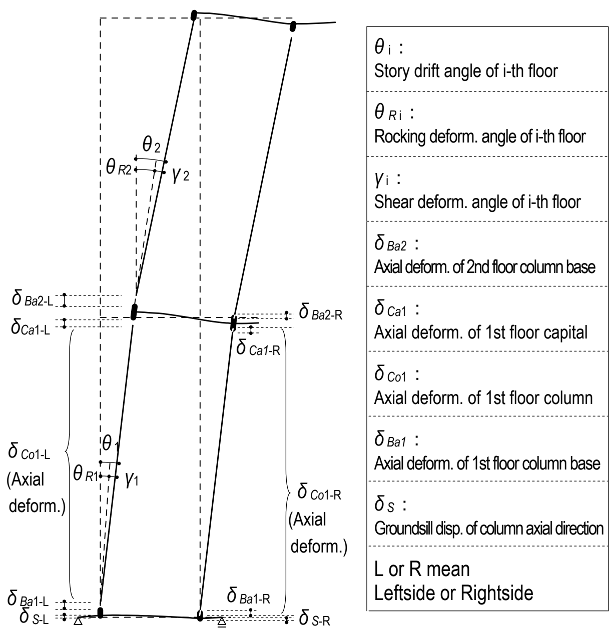
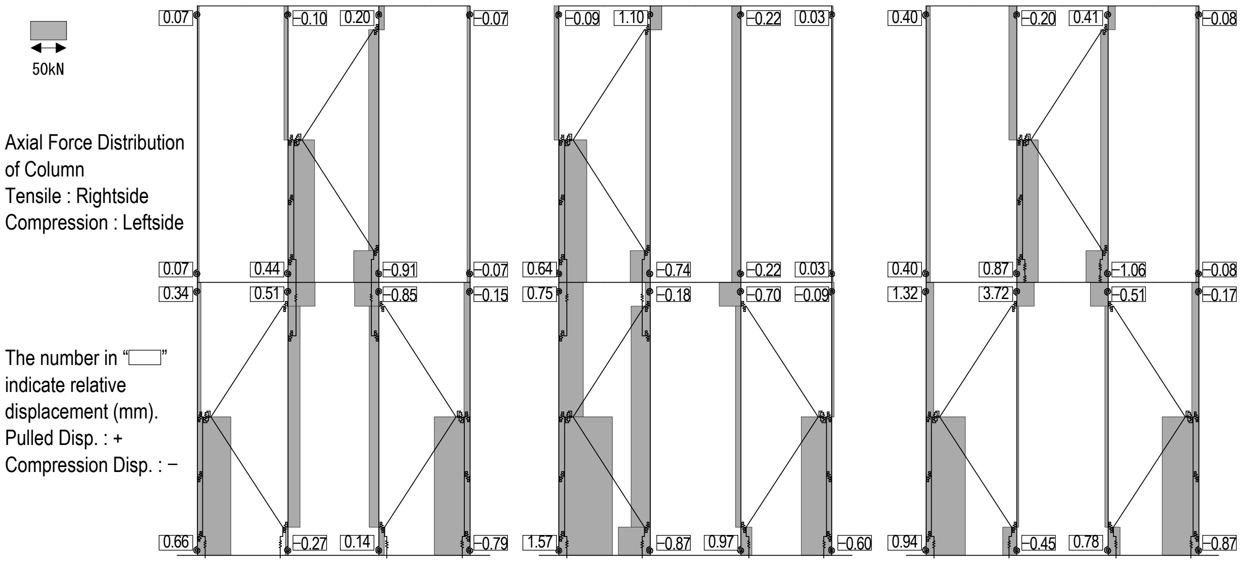


Figure 16 Deformed State and Definition of Symbol



(a) Specimen Model (b) Continuous Wall Model (c) Beam Reaction Model

Figure 15 Axial Force Distribution of Column and Relative Displacement of Joint at Peak Strength of 1st Floor

In the case of Fig. 15 (c) Beam Reaction Model, at the capital of leftside center column of 1st floor, axial tension force is increasing, and as a result, relative displacement is increasing at the point. Because 2nd floor column and 1st floor beam are connected solidly, the beam is bending and the deformation is concentrated at the 1st floor capital which has weak connection relatively.

5.3. Proportion of Local Deformation

The deformed state and definition of symbol are illustrated in Fig. 16. Rocking distortion angle of each floor θ_{R1} and θ_{R2} are calculated by Eq. (1) and (2).

$$\theta_{R1} = \frac{(\delta_{S-L} - \delta_{S-R}) + (\delta_{Ba1-L} - \delta_{Ba1-R})}{L} \quad (5.1)$$

$$\theta_{R2} = \theta_{R1} + \frac{(\delta_{Co1-L} - \delta_{Co1-R}) + (\delta_{Ca1-L} - \delta_{Ca1-R}) + (\delta_{Ba2-L} - \delta_{Ba2-R})}{L} \quad (5.2)$$

Where, 1st parenthesis of Eq. (5.1) is contribution of bending deformation of groundsill, 2nd parenthesis of Eq. (5.1) is contribution of axial deformation of 1st floor column base, 1st parenthesis of Eq. (5.2) is contribution of axial deformation of 1st floor column, 2nd parenthesis of Eq. (5.2) is contribution of axial deformation of 1st floor capital, 3rd parenthesis of Eq. (5.2) is contribution of axial deformation of 2nd floor column base.

Assuming this energy dissipation wall is composed of series system of 3 springs, spring of rocking deformation, spring of damper deformation and the other spring, the contribution of each springs at peak story drift of 1st floor are listed in Table 2. The contribution of rocking deformation is calculated by Eq. (5.1) and (5.2). The contribution of damper deformation is obtained from ratio of 3 times of damper deformation to story drift. The other contribution is obtained from subtract the two contributions from 1.

In the case of using viscoelastic damper, the contribution of damper deformation in 1st floor of Specimen Model is the highest. As for 2nd floor of Specimen Model, the contribution of damper deformation is lower than 1st floor, however higher than the other model. It is confirmed that the check configuration of energy dissipation wall is effective for energy absorption performance. It is confirmed that controlling the rocking deformation is very significant for this energy dissipation wall since the contribution of the other deformation is almost equal and relatively small in all models. In the case of using friction damper, contribution of damper deformation is higher than same model of using viscoelastic damper. Since the damper force was low by the damper slipped and the other deformation.

Table 2 Proportion of Local Deformation to Story Drift (Unit: %)

		Energy Dissipation Wall Using Viscoelastic Damper									Energy Dissipation Wall Using Friction Damper								
		Specimen Model			Continuous Wall Model			Beam Reaction Model			Specimen Model			Continuous Wall Model			Beam Reaction Model		
		1F-L	1F-R	2F-C	1F-L	1F-R	2F-C	1F-L	1F-R	2F-C	1F-L	1F-R	2F-C	1F-L	1F-R	2F-C	1F-L	1F-R	2F-C
Rocking Deform.	Bending Deform. of Groundsill	9.2	2.6	-1.0	11.8	3.3	9.0	9.6	3.6	-2.4	9.0	2.9	-0.9	6.0	1.2	-1.1	6.9	2.4	-1.7
	Axial Def. of 1st Floor Column Base	10.5	10.5	-4.1	23.8	15.3	18.2	13.9	16.6	-10.6	8.5	8.5	-3.0	13.6	6.6	14.1	9.0	9.1	-6.6
	Axial Def. of 1st Floor Column			5.0			7.4			0.6			3.1			3.9			1.1
	Axial Def. of 1st Floor Capital			13.7			6.9			36.4			8.1			2.0			22.1
	Axial Def. of 2nd Floor Column Base			13.6			10.3			16.6			8.3			4.0			12.6
Shear Deform.	Damper Deformation	63.0	60.3	55.3	49.7	56.1	36.3	61.2	54.9	45.3	69.5	65.9	74.5	79.7	85.9	67.7	80.3	75.7	65.8
	Other	17.2	26.6	17.6	14.6	25.2	11.9	15.2	24.9	14.1	13.0	22.8	9.9	0.7	6.3	9.4	3.7	12.9	6.6
Total		100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

6. CONCLUSIONS

Accurate, framed analytical models for the wooden energy dissipation wall with damper and plywood shear wall were proposed. In addition, case study was carried out using the frame model. Major finding are

- Framed analytical models of energy dissipation wall and/or plywood shear wall were constructed by using many kinds of nonlinear springs whose properties are derived from the test results of the joint. The joint spring between column and horizontal member consists of three types of spring, axial, rotational and shear spring.
- The frame models were able to duplicate not only global behavior but also local behavior with a high degree of accuracy in many kinds of test.
- It is confirmed that the check configuration of energy dissipation wall is effective for energy absorption performance. And it is confirmed that controlling the rocking deformation is very significant for this energy dissipation wall.

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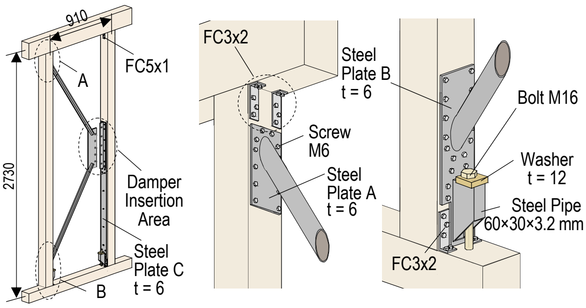
APPENDIX 1: Outline of Energy Dissipation Wall

The feature of K-brace energy dissipation wall is shown below (Fig. A1). When the wall deforms, there is vertical deformation between the brace and the steel plate and the damper is inserted in the place. The wall is classified in to a series of so-called shear link type. In order to reduce the effect of the column's bending, the edge of the brace is fixed near the joint of the column and horizontal member. FC3x2 (Table 1) and holddown bolt are allocated in the joint of the column and horizontal member. Energy absorption capacity is increased as much as possible by allocating the bolt closer to the column, and integrating the steel plate C into the hold-down metal.



(a) Overview (b) Detail of Part A (c) Detail of Part B

Figure A1 Detail of Energy Dissipation Wall