Development of Cylindrical Passive Damper using High Damping Rubber

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SUMMARY
Cylindrical passive dampers using high damping rubber were developed for the wood houses. The damper has a pair of rod and cylinder like a common oil damper. But high damping rubber is filled between the rod and cylinder instead of oil. The dampers are installed as K-braces into the post and beam frames of wooden houses. Quasi-static loading test and shaking table tests were conducted to evaluate performances of the K-braced frames with dampers and typical shear walls. Response of the K-braced frames with dampers was almost half of wood frames with nailed plywood shear panels. Response of the K-braced frame with the dampers were simulated by dynamic time-history response analysis using non-linear hysteresis models of the frames with dampers. Results of the response analysis were in accordance with the results of shaking table tests.

Keywords: Seismic, Damper, Wood house, Rubber, Shaking table test, Simulation

1. INTRODUCTION

Earthquake safety of residences is a primary concern to reduce earthquake hazards of people. People must continue their lives after earthquakes occur, so serviceability of residences must be kept after earthquakes. In order to satisfy these people's requirements for residences, earthquake responses of residences should be minimized as possible to keep their serviceability of residences. Seismic damper is a device to resist their inertia forces and reduce seismic responses of the structures. A half of people lives in wooden post and beam constructions in Japan, seismic damper and its installation method for those wooden constructions were developed (Nakao, Yamaguchi and Furuta, 2011). The dampers are installed into the wooden post and beam frames. Quasi-static loading tests of the damper and the wood frames with dampers were conducted. Shaking table tests of the wood frames with dampers were also conducted. Responses of the wood frames with the dampers were simulated by non-linear hysteresis model of the damper. Results of the dynamic response analysis of the frames were compared to the response of them measured in the shaking table tests. The purpose of these tests and analysis is to clarify efficiency of the cylindrical passive dampers for wood constructions against moderate earthquakes.

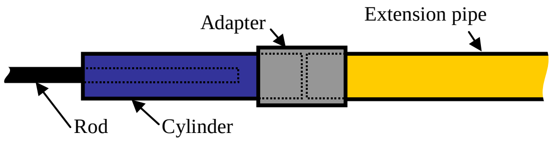
2. DAMPER SYSTEM

2.1. Damper

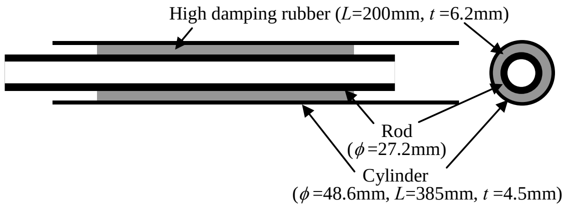
The damper has a pair of rod and cylinder like common oil dampers. But high damping rubber is filled between the rod and cylinder of the dampers instead of oil. Figure 2.1 shows an elevation and a section of the damper. Diameter and length of the damper is 48.6mm and 350mm. Thickness, length and shear modulus of the high damping rubber is 6.2mm, 200mm and 0.8N/mm^2. Table 2.1 indicates specifications of the high damping rubber used for the dampers. The damper is passive and simple to reduce their initial costs. Figure 2.2 shows force-displacement relationships of the dampers using high damping rubber by quasi-static loading tests. The damper is displacement-dependent as wood, stably and more energy absorbing than wood, but less energy absorbing and less velocity-dependent than typical oil dampers.

Table 2.1. Specifications of Rubber

Modulus of rigidity $G(N/mm^2)$	Equivalent viscous damping factor $H_{eq}(\%)$	Fracture shear strain $E_b(\%)$
0.80	22.9	600over



(a) Elevation



(b) Section

Figure 2.1. Cylindrical Damper and Adapter

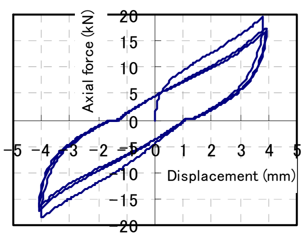
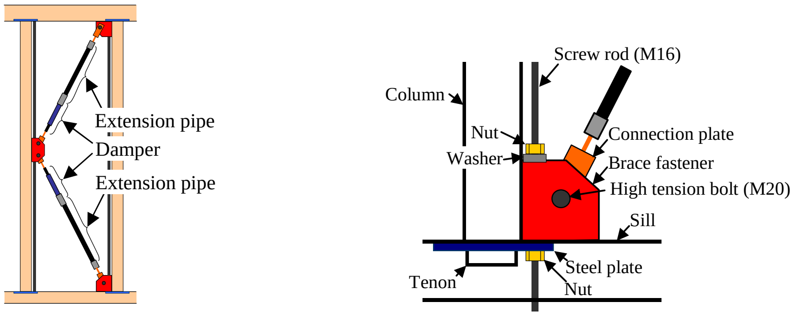


Figure 2.2. Force-Displacement Relationships of a Damper using High Damping Rubber

2.2. Installation of dampers

The damper is connected to an extension pipe, and the extension pipe with damper is installed as braces into a wooden post and beam frame. The type of brace-installation is K-shape. Arrangement of the two braces is shown in Figure 2.3. A pair of threaded rods to tie beams and sills of the wood frame is installed vertically along both sides columns in the wood frame. An extension pipe of the damper is connected to a connection plate that is installed between a pair of ‘brace fastener brackets’. A high-tension bolt is inserted horizontally through a pair of ‘brace fastener brackets’ and a connection plate, those three parts are mutually fastened with a high-tension bolt which makes strong friction between them. A threaded rod is inserted between a pair of ‘brace fastener brackets’, and two nuts are screwed through the rod. The nuts on and bottom of the brackets restrain a vertical motion of the brackets. The brackets are fastened to the columns horizontally and sills/beams vertically with wood screws. A pair of ‘brace fastener brackets’ was also installed at the middle of a column, and connected the column to two braces with dampers. A threaded rod is also inserted between a pair of the middle brackets at the middle of column. Nuts through the rods are put on and under the brackets at the middle of column. Those nuts restrain the vertical motion of the brackets. A steel plate on the sill reinforces the embedding stiffness perpendicular to the grain of the sill.



(a) K shape arrangement of the damper **(b)** Connection of the damper and wood frame

Figure 2.3. Installation of damper and its connection

3. METHOD OF EXPERIMENT

3.1. Test frames

Test frames using wood frames are prepared for the quasi-static loading test and shaking table test. The size of the frames is 910mm width and 2730mm height. Species and dimensions of the sill and columns of the frames are Tsuga (Hem Fir) and 105mm x 105mm, those of the beam are Douglas Fir and 180mm x 105mm. The K-braded damper or typical shear walls are installed in any spaces between two columns in the frame. Nailed plywood shear panels and single wood brace are used as typical shear walls. Table 3.1 shows specification of typical shear walls. Quasi-static loading tests use a wood frame of two spans with three columns. Shaking table test used three wood frames of three spans with four columns; those three wood frames are jointed with a floor. Figure 3.1 shows three wood frames for the shaking table tests. The K-braced damper or typical shear walls are installed in the centre frame of the three wood frames. Two outer frames do not resist to horizontal loads.

Table 3.1. Specifications of Typical Shear Walls

Shear wall	Wall length	Material & connector
Nailed plywood	910mm	Plywood : t=12mm, Japanese cypress Connector : Φ50mm@150mm
Single wood brace	910mm	Wood brace : Hem Fir, 90mm x 45mm Brace fastener : Box type

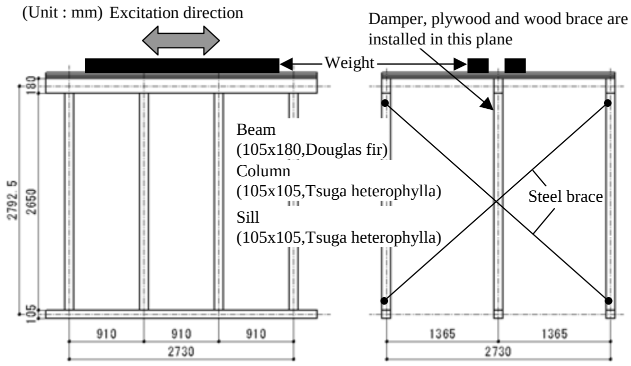


Figure 3.1. Elevations of the Three Wood Frames for Shaking Table Tests

3.2. Quasi-static loading tests

Performance of the damper is evaluated by quasi-static loading tests. A set of K-braced dampers was installed in the frame, and cyclic displacements of 1/300rad, 1/200rad and 1/150rad of the frame height were applied for the frames horizontally. Weight of 8kN was applied on the both side columns of the K-braced frames or typical shear walls respectively. The other 4kN was applied on the rest of columns of the frames respectively.

3.3. Shaking table tests

Performance of the K-braced dampers is also evaluated by shaking table tests. Direction of the shaking is apparel to the test frames. Steel mass of the weight is fastened with volts on the floor of the frames. Total weight of the mass and a upper half of the frame was 24.5kN. Input motions for the shaking table tests were Pulses and JMA Kobe NS motions. Displacements of each input pulse motions were 1mm, 2mm and 3mm respectively. The JMA Kobe NS motion was NS component of the observed acceleration records measured during Jan. 17 1995 Kobe Earthquake at Japan Meteorological Agency Kobe station. BCJ L2 motion is a design ground motion with design spectrum and random phases. This design spectrum is defined in Building Standard Law of Japan. Scaled JMA Kobe NS motions of 10%, 20% and 40% were used for the shaking table tests. Both of JMA Kobe NS and BCJ L2 motions were used in the analysis of combination of dampers and typical shear walls.

4. METHODS OF ANALYSIS

4.1. Dynamic time-history response analysis

Seismic responses of the frames with the dampers were simulated by the computer analysis using schematic model of the frame and non-liner hysteresis model simulating force - displacement relationships of the dampers. Figure 4.1 indicates a schematic model of the frames with dampers. The model of the frames is based on the dimensions of the test frames. Horizontal linear stiffness of the test frames shown in Figure 4.1 were determined based on the quasi-static horizontal loading test of the frames without dampers. Stiffness of two joints in both ends of a damper in Figure 4.1 was determined 30kN/mm by quasi-static loading tests. Total horizontal stiffness of the wood frame was a sum of 80kN/rad horizontal stiffness of frames and 30kN/rad stiffness between the brackets and connection plates. Figure 4.2 shows force - displacement curves of upper and lower dampers of braces in the frames obtained by the quasi-static loading tests. Non-liner hysteresis model of the dampers were determined using peak-oriented tri-linear models. Non-linear hysteresis models of the upper and lower dampers are illustrated in Figure 4.2.

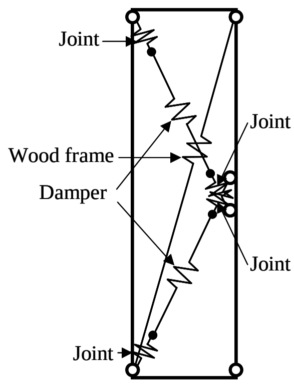
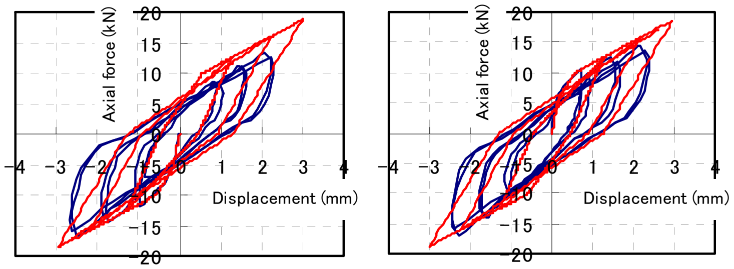


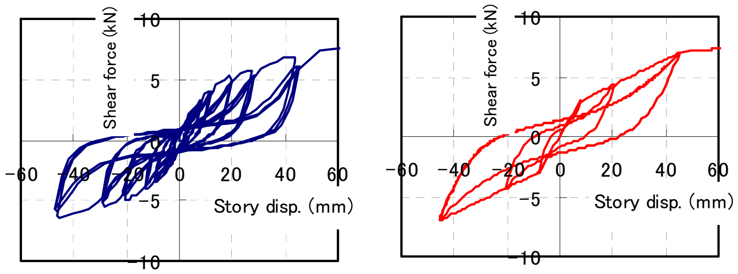
Figure 4.1. Schematic Models of Frame with Dampers for Response Analysis



(a) Upper Damper **(b)** Lower Damper

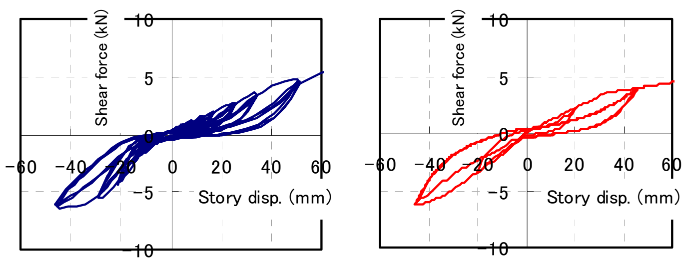
Figure 4.2. Non-linear Hysteresis Models of Dampers for K-braces

In order to simulate seismic responses of the frames with typical shear walls, non-liner hysteresis of the typical shear walls were modelled. Figure 4.3(a) and Figure 4.4 (a) show force - displacement curves of nailed plywood shear panels and single wood braces obtained by the quasi-static loading tests. Non-liner hysteresis of nailed plywood shear panels and single wood braces are modelled using NCL modelling method (Matsunaga, Miyazu and Soda, 2009), which are shown in Figure 4.3(b) and Figure 4.4 (b). Figure 4.5 shows total hysteresis model of the frame with K-braced dampers by push-over analysis using liner stiffness of the frames and joints, and non-liner hysteresis model of the K-braced dampers. Viscous damping for the dynamic time-history response analysis was assumed 5%, which was assumed to be proportional to the tangent stiffness. Weight of the mass of the frame models assumed in response analysis was 24.5kN, which was same as the weight in the shaking table tests.



(a) Quasi Static Loading Test **(b)** Model for Analysis

Figure 4.3. Force-Displacement Relationships and Non-linear Hysteresis Models of Nailed Plywood Panels



(a) Quasi Static Loading Test **(b)** Model for Analysis

Figure 4.4. Force-Displacement Relationships and Non-linear Hysteresis Models of Single Wood Braces

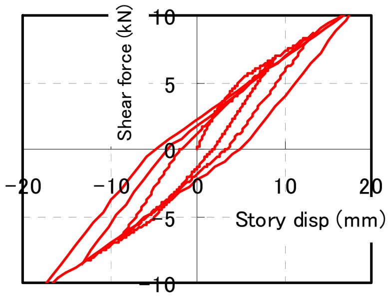


Figure 4.5. Non-linear Hysteresis Model of the Frame with K-braced Dampers by Push Over Analysis

4.2. Analysis of combination of dampers and typical shear walls

Most of wood constructions will use dampers with typical shear walls. The wall length ratio of damper is defined as the ratio of walls length with K-braced dampers to the total wall length of shear resistant walls using K-braced dampers and typical shear walls. Seismic responses of the frames with several wall length ratio using dampers and typical shear walls were analysed. The weights of the frames in analysis were determined based on the design shear strengths of typical shear walls and design seismic shear coefficient. The basic design seismic shear coefficient of buildings in Japan was 0.2. The design shear strengths per wall lengths in meters of nailed plywood panels and double wood braces were 2.5 x 1.96kN and 4.0 x 1.96kN respectively. Eqn. 4.1 shows weight (W) of frames for the analysis. (S) is total design shear strength of shear resistant walls, and (C) is a basic design seismic shear coefficient for buildings in Japan. JMA Kobe NS motion was used for the input motions in the analysis. Input motions were scaled in order to make adjustments the peak linear response acceleration of the frames with typical shear walls to 0.2G. Table 4.1 shows obtained scale factors of input motions for combination analysis.

$$W = \frac{S}{C} \tag{4.1}$$

Table 4.1. Scale Factor of Input Motions for Combination Analysis

Shear wall	JMA Kobe	BCJ L2
Nailed plywood	0.086	0.197
Double wood brace	0.114	0.204

5. RESULTS AND DISSCUSIONS

5.1. Force – displacement relationship of the frame with dampers

Figure 5.1 shows measured shear force - displacement curves of a frame with K-braced dampers obtained by quasi-static loading tests. The peak horizontal displacement of the frame was around 1/150rad of its height. The shear force - displacement relationship was almost linear, and shear strength was 7.6kN at 1/200rad displacement. Shear stiffness of the frame was 0.55kN/mm.

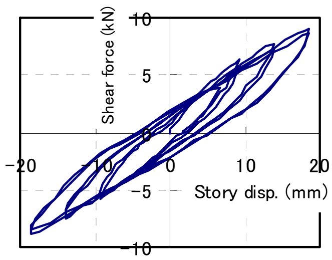
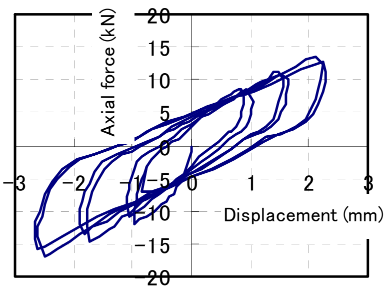


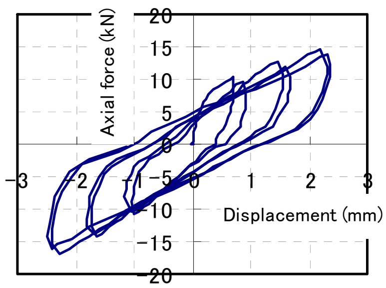
Figure 5.1. Measured Force - Displacement Relationship of a Frame with K-braced Dampers under Quasi-static Loading Test

5.2. Force – displacement relationship of dampers and joints

Figure 5.2.(a) and (b) show force - displacement curves of upper and lower K-braced dampers obtained by quasi-static loading tests of the frame with dampers. Average strength of the upper and lower dampers was 13.1kN at 1/200rad displacement. Then, the average axial displacement of upper and lower dampers was 1.6mm, which was 25% of the rubber thickness. Each damper has two joints at the both ends of the damper. Figure 5.3.(a) and (b) show force - displacement curves of total slips of both end joints obtained by quasi-static loading tests of K-braced dampers. Total stiffness of two end joints was 15kN/mm from these data.

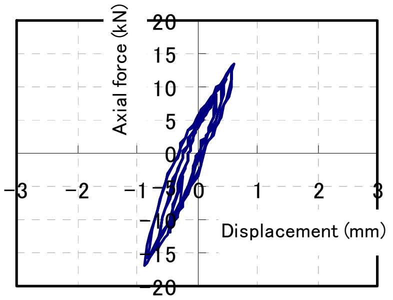


(a) Upper Damper

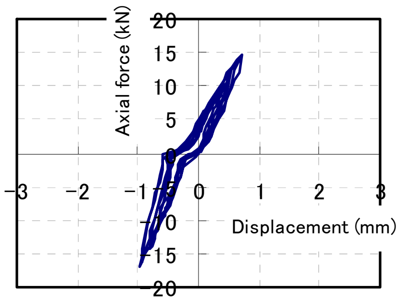


(b) Lower Damper

Figure 5.2. Force - Displacement Relationship of K-braced Dampers under Quasi-static Loading Test



(a) Total Slip of Two End Joints of Upper Damper



(b) Total Slip of Two End Joints of Lower Damper

Figure 5.3. Force - Displacement Relationship of Two Joints under Quasi-static Loading Test

5.3. Response of the frame with dampers and typical shear walls by shaking table test

Damping factor and predominant frequency of the frames with K-braced dampers were 4.4% and 0.28sec by shaking table tests using 3mm pulse motion. Figure 5.4 indicates acceleration - story displacement relationship in the shaking table tests using JMA Kobe NS 40% motion. The peak story displacement was around 20mm, which was 1/140rad of the frame height. Secant shear stiffness of the frames during the peak responses was 0.54kN/mm. Shaking table test of the frame with nailed plywood shear panels were also conducted and provided the peak shear force and story displacement of 9.8kN and 1/60rad during JMA Kobe NS 40% motion. The secant shear stiffness of the frame with nailed plywood panels during the peak responses was 0.21kN/mm, which was a half stiffness of the frames with K-braced dampers. Response of the frames with K-braced dampers was almost half of them with nailed plywood shear panels.

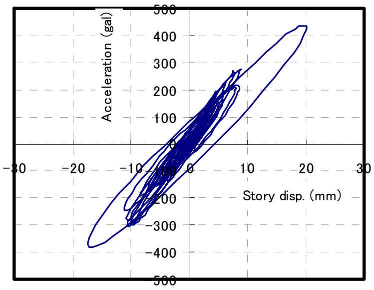


Figure 5.4. Measured Acceleration - Story displacement Relationship of the Frame with K-braced Dampers under Shaking Table Test

5.4. Dynamic time-history response analysis

Response of the modelled frame with K-braced dampers was calculated using a dynamic time-history response analysis program. Scaled JMA Kobe NS motion that was measured on the shaking table during the shaking table tests was used for these dynamic analyses. Calculated response displacements and accelerations by the dynamic analysis are shown in Figure 5.5 and Figure 5.6. Figure 5.5 and Figure 5.6 also show measured response displacements and accelerations obtained from shaking table tests. Figure 5.5 and Figure 5.6 indicate that responses of the frames by the dynamic analysis are in accordance with those of shaking table tests. These results suggest that modelling of the schematic frame models and non-linear hysteresis model of the dampers, assumed stiffness of the joints and viscous damping of the frame were reasonable. In this analysis, all the coefficients and factors for the modelling of frames and dampers were decided using the results of quasi-static loading tests. Quasi-static loading tests of the dampers and frames were efficient for dynamic response analysis of them.

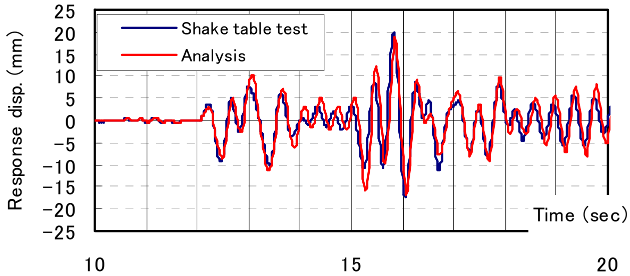


Figure 5.5. Response Displacements of the Frame with K-braced Dampers by Analysis and Shaking Table Test (JMA Kobe NS)

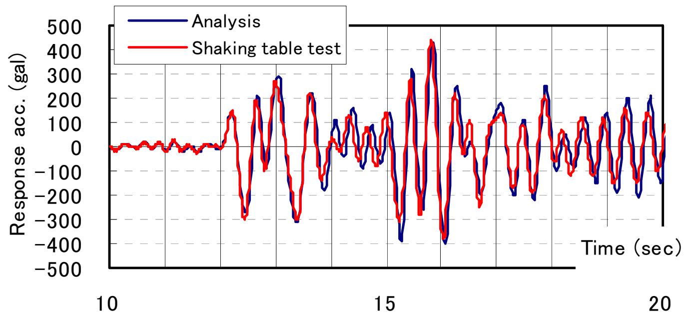
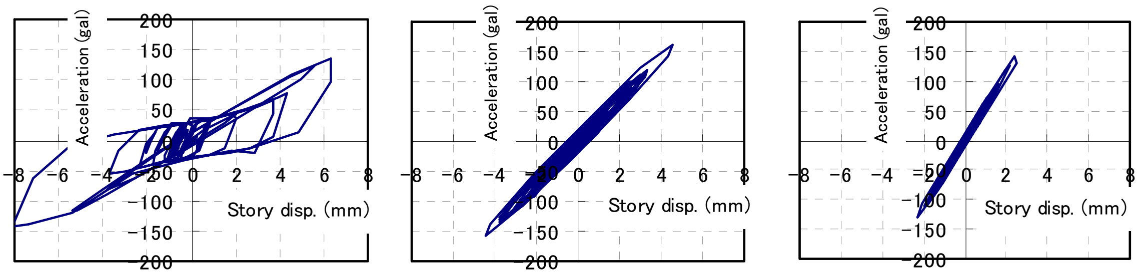


Figure 5.6. Response Accelerations of the Frame with K-braced Dampers by Analysis and Shaking Table Test (JMA Kobe NS)

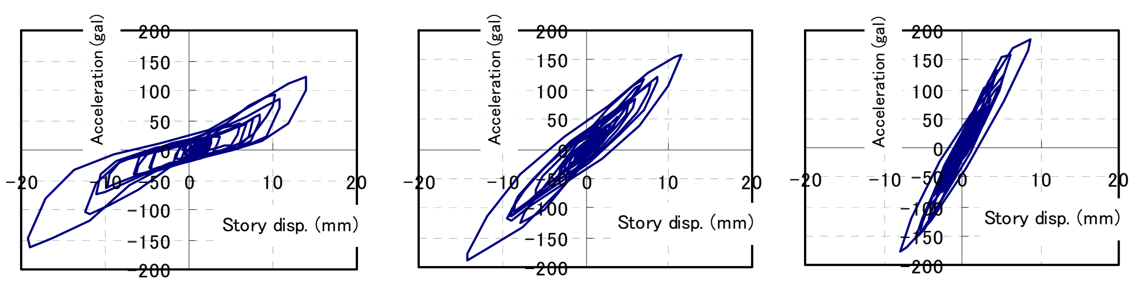
5.5. Effect of the combination of dampers and typical shear walls

Figure 5.7 shows response of the frame with K-braced dampers and/or nailed plywood shear panels under JMA Kobe NS motion. Figure 5.7(a) shows response of the frame with nailed plywood shear panels only. Figure 5.7(c) shows response of the frame with K-braced dampers only. Figure 5.8 also shows response of the frame with K-braced dampers and/or double wood braces under JMA Kobe NS motion. Figure 5.8(a) shows response of the frame with double wood braces only. Figure 5.8(c) shows response of the frame with K-braced dampers only. First and second stiffness (K_1, K_2), weights (W) of the frame and the peak input ground motions (Input) are also shown in Figure5.7 and Figure 5.8. In Figure 5.7 and Figure 5.8, as the wall length ratio of dampers increases, the stiffness of the frame increases and response displacements of the frame decreases.



(a) Wall length ratio of damper=0% (K_1=4.97, K_2=2.86 kN/cm)
(b) Wall length ratio=50% (K_1=9.11, K_2=4.67 kN/cm)
(c) Wall length ratio=100% (K_1=13.25, K_2=6.48 kN/cm)

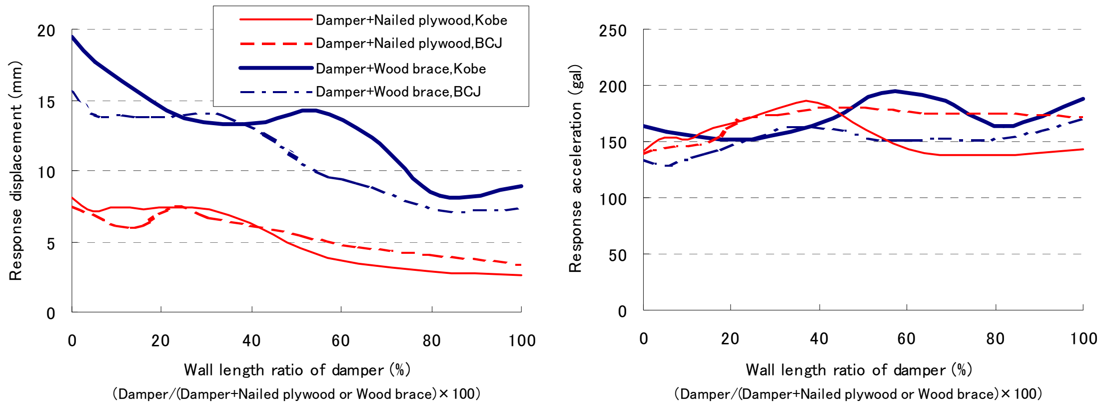
Figure 5.7. Response of the Frame with Dampers and Nailed Plywood Shear Panels under JMA Kobe Motion (W=22.295kN, Input=70.98gal)



(a) Wall length ratio of damper=0% (K_1=3.48, K_2=3.27 kN/cm)
(b) Wall length ratio=50% (K_1=8.37, K_2=4.88 kN/cm)
(c) Wall length ratio=100% (K_1=13.25, K_2=6.48 kN/cm)

Figure 5.8. Response of the Frame with Dampers and Double Wood Braces under JMA Kobe Motion (W=35.672kN, Input=93.34gal)

Figure 5.9 shows relationship between response of the frame and wall length ratio of dampers by JMA Kobe NS and BCJ L2 motions. Figure 5.9(a) shows that as the wall length ratio of dampers increases, the peak response displacements of the frame decrease. Figure 5.9(b) shows that as wall length ratio increases, peak response accelerations of the frame are almost constant. This damper is displacement-dependent as wood, and less velocity-dependent than typical oil dampers. These features of this damper may lead the results of these combination analyses.



(a) Response displacement **(b)** Response Acceleration

Figure 5.9. Relationship between Response of Frame and Wall Length Ratio of Damper

6. CONCUSIONS

Cylindrical passive dampers using high damping rubber were developed for wood houses in Japan. Performance of the wood frames with dampers was evaluated by quasi-static loading tests. Shaking table tests of the frames with dampers and typical shear walls were conducted. Response of the frames with K-braced dampers in the shaking table tests was almost half of them with nailed plywood shear panels. Response of the frames with K-braced dampers was almost half of them with nailed plywood shear panels. Efficiency of this cylindrical passive damper was verified in shaking table tests. Dynamic response analysis of the frames with dampers using the results of the quasi-static loading tests succeeded to predict the response of the frames by shaking table tests. Non-linear hysteresis model of the frame with dampers based on the quasi-static loading tests was efficient for dynamic response analysis of them. Combination of the dampers and typical shear walls were analysed. The results showed as wall length ratio of dampers increased, response displacements of the frame decreased, but response accelerations of the frame were almost constant.

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