Development of a passive damper device with high damping rubber for wooden houses

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ABSTRACT: A new passive damper device which includes high damping rubber has been developed. To investigate the performance of the new damper device, static shear loading test, shaking table test and earthquake response analysis were conducted. On the static shear loading test, wood frame with the new damper device showed stable hysteresis without a decline of stiffness under repeated cyclic lateral loads. It was found that the shear force of wood frame with the damper device at 0.5% of drift is 3.52kN which is corresponding to 79% of the one with nailed plywood. From the shaking table test of wood frame with single damper device in addition to single nailed plywood or double wood braces, it was found that addition of the damper device reduced maximum response drift by approximately 50%, while no remarkable increase of maximum shear force was detected due to the stable damping effect of the damper device. The result of earthquake response analysis showed that replacing optimum number of nailed plywood or wood brace by the damper device decreases response drift by from 20% to 30%. The new developed damper device has stable force-displacement relationship even under repeated cyclic loads. However shear stiffness of wood frame with the damper device is relatively low compared to the one with nailed plywood or wood brace, replacing some plywood or wood brace by the optimum number of the damper device is able to reduce earthquake response of wooden houses effectively.

KEY WORDS: Passive damper; High damping rubber; Wooden house; Shaking table test; Earthquake response analysis.

1 INTRODUCTION

Damper devices are able to absorb vibration energy efficiently, thus they are used in buildings to decrease earthquake or wind responses. Now a day, damper devices have come to be installed to wooden houses as well as high-rise buildings to reduce damage and repairing cost after a severe earthquake. Installing conventional shear resisting elements, such as nailed plywood and wood braces, can reduce response displacement, however, it may increase shear force which a building carries. A damper device is able to reduce response displacement of a building, while shear force does not increase so much due to its high damping. Therefore, it is valid to adopt damper devices to reduce damage on wooden houses. However, the cost of existing damper devices are much higher comparing to constructing cost of wooden houses, it is needed to develop a low-cost and reliable damper device.

From the expressed reason, a new passive damper device for wooden houses has been developed. The new damper device includes high damping rubber which had been developed for laminated rubbers used as base isolation. Adopting high damping rubber realized low cost and high reliability. Authors had already developed a simplified passive damper which includes high damping rubber [1], [2]. The mechanism of the new developed device is more complicated but it has higher performance.

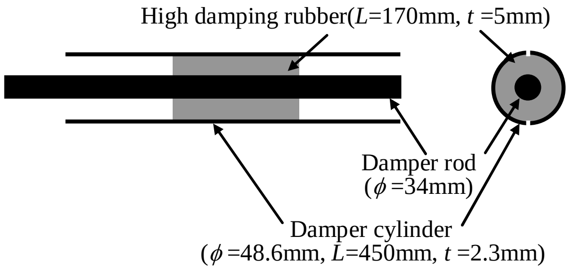


Figure 1. Structure of the damper device

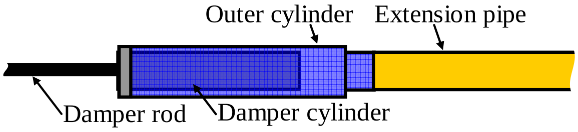
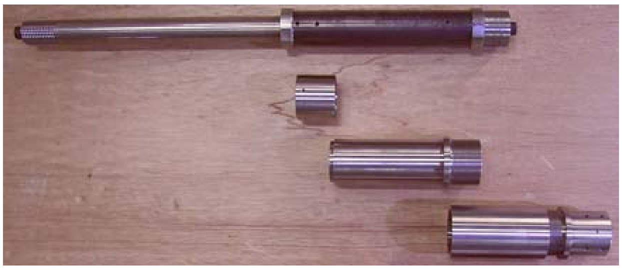


Figure 2. Assembled damper device



Picture 1. New developed damper device and outer cylinders

2 OUTLINE OF THE NEW DEVELOPED DAMPER DEVICE

The new developed damper device, as shown in Figure 1, consists of a steel damper cylinder, a steel damper rod and a high damping rubber. The diameter, thickness and length of the damper cylinder are 48.6mm, 2.3mm and 450mm respectively. The damper rod whose diameter is 34mm is fixed inside the damper cylinder with the high damping rubber with 5mm in thickness and 170mm in length.

Moreover, the additional outer cylinder is attached to the end of the damper cylinder to transfer subjected compressive force to the end of the damper cylinder directly. The assembled damper device is shown in Figure 2 and Picture 1.

The high damping rubber had been developed for laminated rubbers used as base isolation, therefore it has high reliability. It was manufactured to produce 0.8N/mm^2 of shear stiffness when its shear strain reaches to 100%. Table 1 shows the property of the high damping rubber. Therefore, 5mm of relative displacement between the damper cylinder and the damper rod is expected along longitudinal direction under 14.5kN of axial force.

The damper device is able to be installed to wood frame diagonally as shown in Picture 2. To adjust the length of the damper to the diagonal of wood frame, steel extension pipe is connected to the end of the outer cylinder.

The ends of the damper rod and the extension pipe are connected to fasteners which are installed to the inside corner of wood frame with wood screws. Picture 3 shows the corner of wood frame with the fastener.

Table 1. Property of the high damping rubber

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

Picture 2. Setup of the damper device

Picture 3. A fastener installed to the corner of wood frame

3 STATIC SHEAR LOADING TEST

3.1 *Outline of Static Shear Loading Test*

Static shear loading test was conducted to have basic properties of the damper device itself and wood frame with the damper device as well as conventional shear resisting elements such as nailed plywood and wood brace. Table 2 shows the specimens and its specification. No vertical load was applied to those specimens, while the uplift of the beam of the specimen was restricted by liner guides as shown in Figure 3.

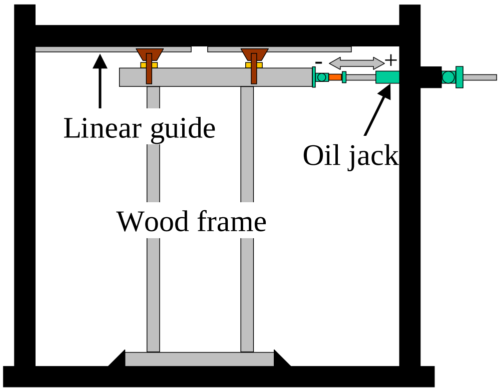
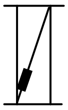
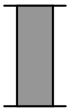
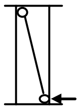


Figure 3. Loading apparatus

Table 2. Specifications of specimen for static loading

Damper	Nailed plywood	Wood brace
		 Fastener
High damping rubber G = 0.8N/mm^2 L = 170mm t = 5mm	Plywood size:2730mmx910mm t=9mm Nail : N50@150mm	Brace size:105mmx45mm Tsuga heterophylla Fastener : 
Wood frame : 910mm x 2792.5mm Column, Sill : 105mmx105mm, Tsuga heterophylla Beam : 105x180, Dugrus fur		

3.2 *Results of Static Shear Loading Test*

Figure 4 shows the relationship between axial repeated cyclic force and displacement of the damper device itself. Due to a limitation of the loading system, the applied axial force was up to approximately 20kN. The hysteresis shows stable characteristics without a decline of stiffness under repeated cyclic force. Axial force obtained from the test at 5mm of displacement, which is corresponding to 100% of shear strain of the high damping rubber, was approximately 20kN. It is higher than the designed axial force by approximately 40%.

Shear force-drift relationship of wood frame with the damper device is shown in Figure 5. Since slippage between the end of the damper device and the fastener was occurred around 3kN of shear force, discontinuous curve was obtained.

Energy dissipation due to hysteresis before the slippage is relatively small compared to the damper device itself as shown in Figure 4, it is considered that the embedment of the surface of wood caused by the fastener was relatively large. Shear force at approximately 1% of drift was 5.4kN.

As for wood frames with nailed plywood and a wood brace, the relationships between shear force and drift are shown in Figure 6 and Figure 7 respectively. In these tests, according to the loading protocol using in Japan, a final half cycle load was applied after some repeated cyclic loads. Maximum shear force of wood frame with nailed plywood was 9.4kN at 3.5% of drift, while the one with a wood brace was 4.9kN at 2.5% of drift when compressive force was applied to the wood brace and buckling of the wood brace was occurred. Especially for plywood, a decline of stiffness under repeated cyclic loads was notable compared to the results of the damper device and wood brace.

Table 3 shows shear forces at 0.5% and 1% of drift of wood frame with the damper device, nailed plywood and a wood brace. It is found that the shear force of wood frame with the damper device at 0.5% of drift is corresponding to 79% of the one with nailed plywood, however, the shear force of wood frame with the damper device at 1% of drift is almost the same level as the one with nailed plywood.

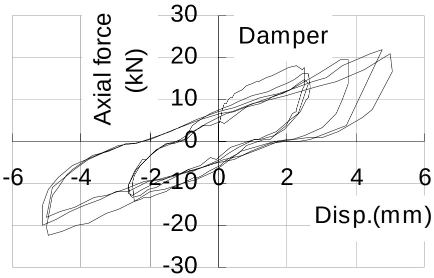


Figure 4. Axial force-disp. relationship of the damper itself

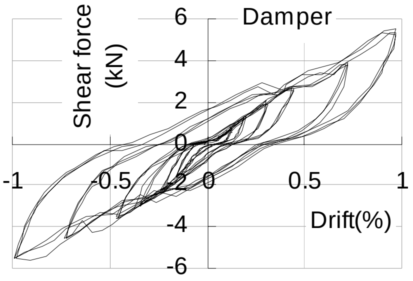


Figure 5. Shear force-drift relationship of wood frame with the damper device

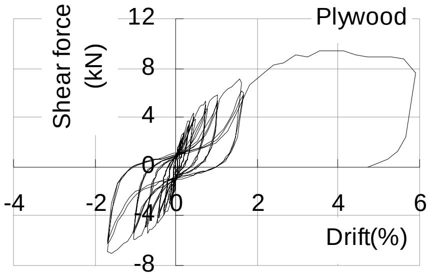


Figure 6. Shear force-drift relationship of wood frame with nailed plywood

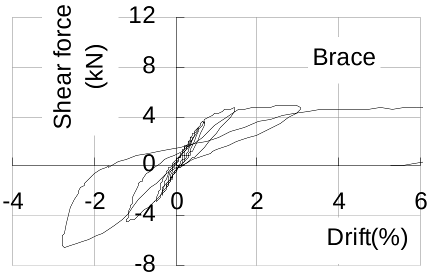


Figure 7. Shear force-drift relationship of wood frame with a wood brace

Table 3. Shear forces at 0.5% and 1% of drift and secant stiffness from static shear loading test

	Shear force at 0.5% of drift (kN)	Secant stiffness at 0.5% of drift (kN/mm)	Shear force at 1% of drift (kN)
Damper	3.52	0.25	5.48
Nailed plywood	4.43	0.32	5.88
Wood brace	2.83	0.20	4.29

4 SHAKING TABLE TEST

4.1 Outline of shaking table test

Shaking table test of a wood frame specimen that has the diagonal damper device, nailed plywood and double wood braces was conducted. Figure 8 and Picture 4 indicate the specimen for the shaking table test, which has three vertical planes at an equal distance of 1365mm. Each vertical plane has four columns at an equal distance of 910mm and the height of the specimen is 2792.5mm.

Shear resisting elements, such as the damper device, nailed plywood and double wood braces as shown in Table 4, were installed in the center of vertical plane. Since the specimen was loaded with the weight of approximately 20kN, the total weight that affects lateral load was 24.5kN.

For the specimen with each shear resisting element, 10%, 20% and 40% of JMA Kobe record was input along one direction only. Time history of acceleration of JMA Kobe 100% is shown in Figure 9, where the maximum acceleration is 821gal. Figure 10 shows response spectrum of JMA Kobe 100%. Before the JMA Kobe input, to have the natural period and the damping property, small random wave and impulse wave were input to the specimen.

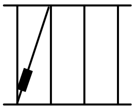
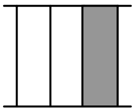
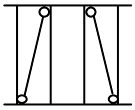
4.2 Results of shaking table test

Table 5 shows natural periods and equivalent viscous damping factors. They were calculated from the responses of impulse and JMA Kobe 40%. The natural period of the specimen with the damper device is longer than the one with nailed plywood by 38% since the stiffness of the wood frame with the damper device is lower than the one with nailed plywood as shown in Table 3. Though the stiffness of wood frame with a single wood brace is 64% of the one with nailed plywood on the static shear loading test, the natural period of the specimen with double wood braces is equal to the one with nailed plywood since the specimen on the shaking table test has two wood braces. The equivalent viscous damping factor of the specimen with the damper device is lower than the one with nailed plywood by 13%.

Figures 11, 12 and 13 show the relationship between shear force and drift of the specimen with the damper device, plywood and wood braces respectively. The record of the specimen with the damper device is under JMA Kobe 20%, on the other hand, the ones with nailed plywood and double wood braces are under JMA Kobe 40%. Though the decline of stiffness was occurred on the specimen with nailed plywood and the one with double wood braces under repeated lateral load, the hysteresis of the specimen with the damper device showed stable hysteresis. Table 6 shows a list of maximum shear forces and maximum drifts. The maximum forces are higher than those of static shear loading test at the same drift. The maximum shear force of wood frame with the damper device on shaking table test is 25% higher than that on static shear loading test due to the rate of loading of the high damping rubber.

Table 7 shows test results of a wood frame specimen which has the damper device in addition to nailed plywood and wood braces. From the results, it is found that addition of the damper device reduced maximum response drift by approximately 50%, while no remarkable increase of maximum shear force was detected.

Table 4. Shear resisting elements in shaking table test specimen

Damper	Nailed plywood	Double wood brace
		
High damping rubber G = 0.8N/mm^2 L = 170mm t = 5mm	Plywood size:2730mmx910mm t=9mm Nail : N50@150mm	Braces size:105mmx45mm Tsuga heterophylla

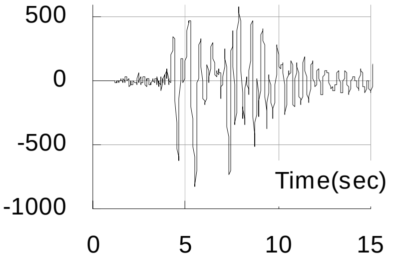


Figure 9. Time history of JAM Kobe 100%

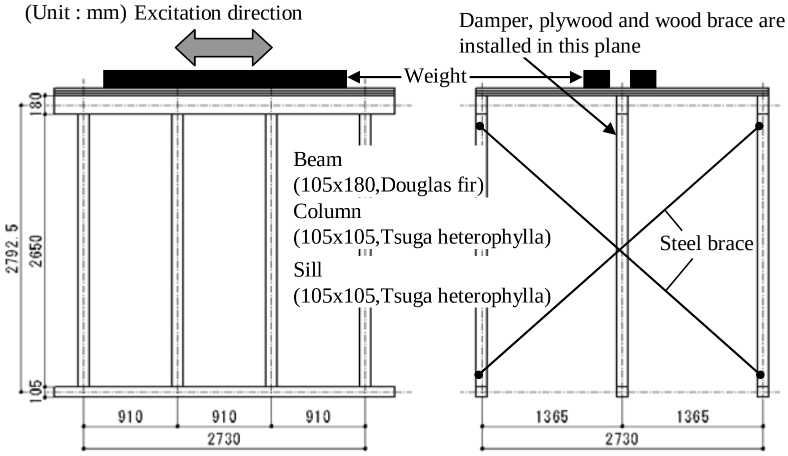


Figure 8. Specimen and weights for shaking table test

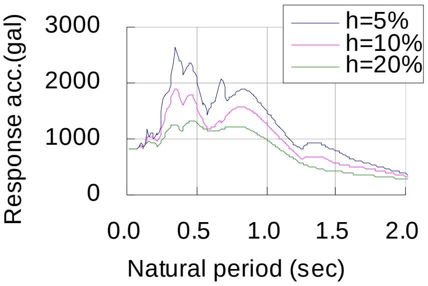


Figure 10. Acceleration response spectrum of JAM Kobe 100%

Picture 4. Wood frame specimen for shaking table test

Table 5. Dynamic characteristics of specimen

	Natural period (Sec)	Equivalent viscous damping factor
Damper	0.51	17.6
Nailed plywood	0.37	20.3
Double wood brace	0.37	13.4

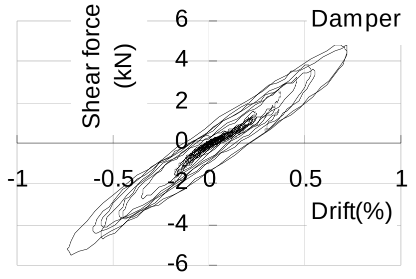


Figure 11. Shear force-drift relationship of damper specimen under JMA Kobe 20%

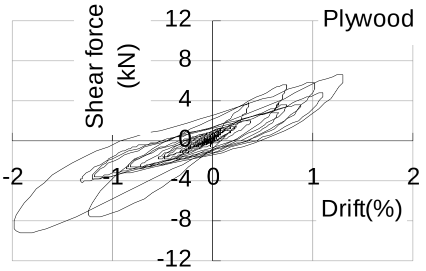


Figure 12. Shear force-drift relationship of plywood specimen under JMA Kobe 40%

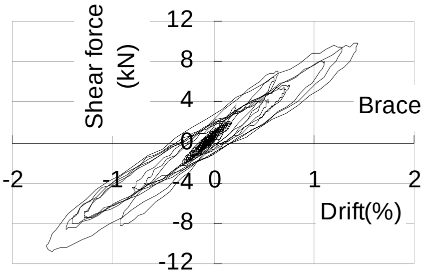


Figure 13. Shear force-drift relationship of double wood brace specimen under JMA Kobe 40%

Table 6. Summary of maximum shear force and drift

	Maximum shear force (kN)	Maximum drift (%)
Damper (JMA Kobe 20%)	5.47	0.73
Nailed plywood (JMA Kobe 40%)	9.16	1.98
Double wood brace (JMA Kobe 40%)	10.71	1.65

Table 7. Maximum shear force and drift of wood frame with plywood/brace and additional damper

	Maximum shear force (kN)	Maximum drift (%)
Nailed plywood+ Damper (JMA Kobe 40%)	10.59	1.03
Double wood braces + Damper (JMA Kobe 40%)	10.58	0.73

5 EARTHQUAKE RESPONSE ANALYSIS

5.1 Summary of analysis

Numerical analysis was conducted to evaluate the damping effect of the damper device in addition to nailed plywood or wood brace in wood frame.

For simplicity, single-mass system was adopted for this analysis. Weight of single mass is 24.5kN, which is equal to the weight of the shaking table test specimen.

Hysteresis models of the shaking table test specimens were set as shown in Figures 14, 15 and 16. Bi-liner model was adopted for the damper model, while Bi-linear-plus-Slip model was adopted for nailed plywood model and wood brace model considering the hysteresis of each case on the static loading test and the shaking table test. Table 8 shows property of the each hysteresis model. The initial stiffness, the second stiffness and the yield drift were calibrated to fit the hysteresis model to the result of the shaking table test. The initial stiffness and the second stiffness of the models also fit the result of the static loading test as shown in Figures 17, 18 and 19. Shear force of the nailed plywood model is lower than the one of static shear loading test since pinching behavior as decline of stiffness of the specimen with nailed plywood was observed under smaller but multi-cyclic input such as JMA Kobe 10% and 20% before the input of JMA Kobe 40%. Adopting the hysteresis models which have the properties as shown in Table 8, the result of the analysis under JAM Kobe wave showed good agreement with the result of the shaking table test as shown in Figures 20, 21 and 22. In addition, the hysteresis models also showed good agreement with the shaking table test result of the wood frame which has additional damper device to nailed plywood and wood brace as shown in Figures 23 and 24.

To understand the effect of the damper device in ordinary wooden house, time history response analysis of wood frame with both nailed plywood and the damper device was conducted. As shown in Table 9, eleven cases of analysis were performed. For wood brace, the same analysis as the case of plywood was also conducted. In every model, since total initial stiffness is the same, the difference of the response drift or the shear force among these models is considered to be

Table 8. Property of hysteresis models

	Initial stiffness (kN/mm)	Second stiffness (kN/mm)	Yield drift (%)	Damping ratio (%)	Natural period (sec)
Damper	0.358	0.215	0.10	6.56	0.54
Nailed plywood	0.358	0.161	0.25	6.00	0.54
Double wood brace	0.537	0.161	0.35	3.00	0.44

due to the difference of hysteresis model. For damping ratio, 6% was used for the case of the damper device and nailed plywood, while 3% was for the case of the damper device and the wood brace.

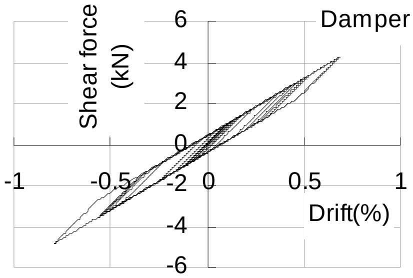


Figure 14. Hysteresis model for wood frame with the damper device

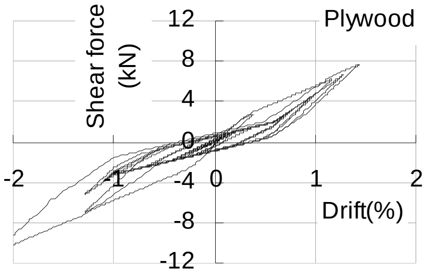


Figure 15. Hysteresis model for wood frame with nailed plywood

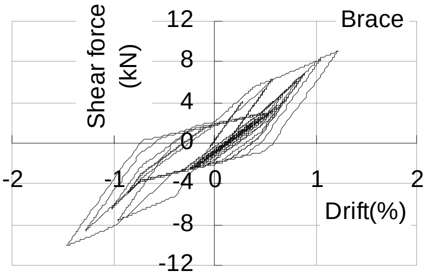


Figure 16. Hysteresis model for wood frame with wood braces

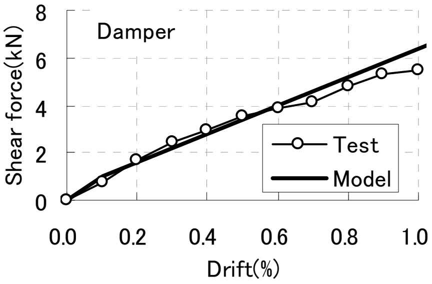


Figure 17. Skeleton curves of static shear loading test and analysis model of wood frame with the damper device

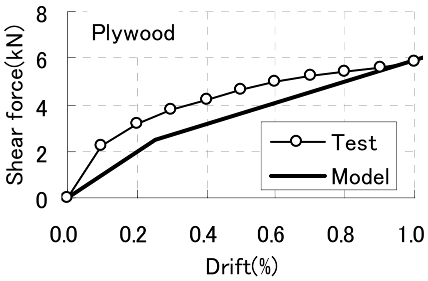


Figure 18. Skeleton curves of static shear loading test and analysis model of wood frame with nailed plywood

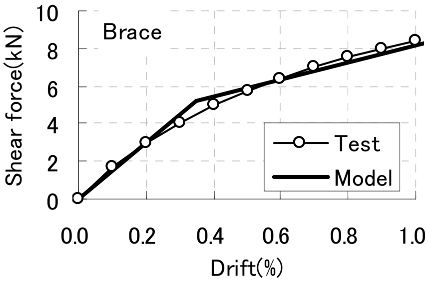


Figure 19. Skeleton curves of static shear loading test and analysis model of wood frame with wood braces

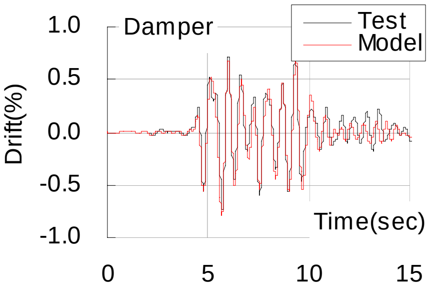


Figure 20. Time history of drift of analysis model with the damper device under JMA Kobe 20%

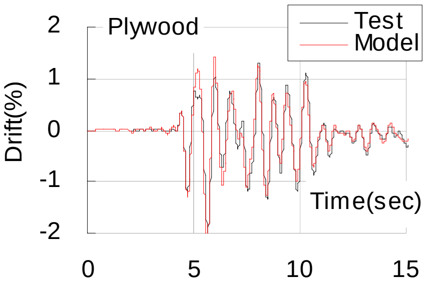


Figure 21. Time history of drift of analysis model with nailed plywood under JMA Kobe 40%

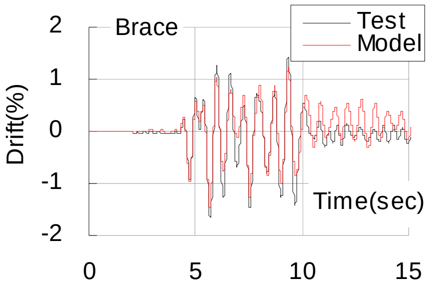


Figure 22. Time history of drift of analysis model with wood brace under JMA Kobe 40%

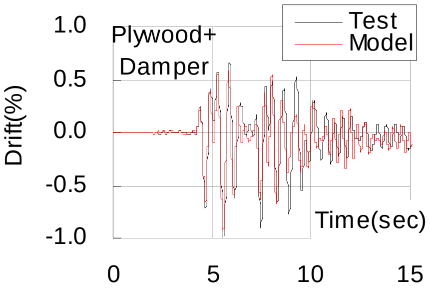


Figure 23. Time history of drift of analysis model with the damper device in addition to nailed plywood under JMA Kobe 40%

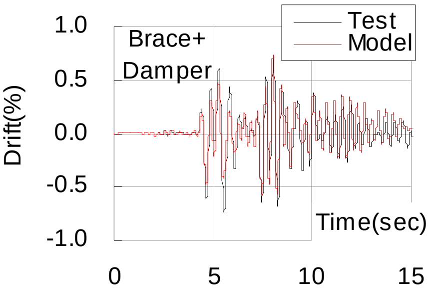


Figure 24. Time history of drift of analysis model with the damper device in addition to wood braces under JMA Kobe 40%

Table 9. Analysis cases

Ratio	Initial stiffness (kN/mm)		
	Plywood or Wood brace	Damper	Total
10:0	0.358	0	0.358
9:1	0.322	0.036	0.358
8:2	0.286	0.072	0.358
7:3	0.251	0.107	0.358
6:4	0.215	0.143	0.358
5:5	0.179	0.179	0.358
4:6	0.143	0.215	0.358
3:7	0.107	0.251	0.358
2:8	0.072	0.286	0.358
1:9	0.036	0.322	0.358
0:10	0	0.358	0.358

5.2 Result of analysis

Figures 25 and 26 shows maximum response drift and shear force of wood frame with both the damper device and nailed plywood under JMA Kobe 40%. Maximum response drift at the ratio of 10:0 is the largest while the ones of 7:3 and 6:4 are the smallest among these eleven cases. The smallest drift is 79% of the largest drift, therefore replacing 30% or 40% of nailed plywood by the damper device decreases drift by 21%. On the other hand, maximum shear force at the ratio of 0:10 is the largest while the ones of 7:3 and 6:4 are the smallest. It was found that a decrease in shear force due to the replaced damper device is 10%.

In the case of wood brace, as shown in Figures 27 and 28, maximum response drift at the ratio of 6:4 is the smallest. A decrease in response drift due to replacing wood brace by the damper device is 28%. For maximum shear force, the one at the ratio of 10:0 is the smallest, while the one at the ratio of 0:10 is the largest. Therefore, replacing wood brace by the damper device increases shear force in this case.

From the analysis, it is found that the optimum number of damper devices exists for every wooden house. Because damper device has stable hysteresis though its shear stiffness is low, using the damper devices as subsidiary shear resisting element is effective to reduce earthquake response of ordinary wooden houses.

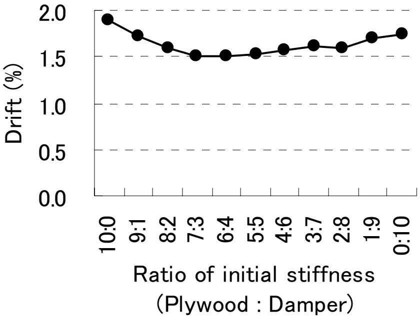


Figure 25. Maximum response drift in the case of a combination of nailed plywood and the damper device

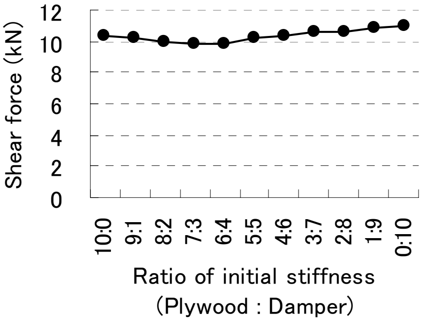


Figure 26. Maximum shear force in the case of a combination of nailed plywood and the damper device

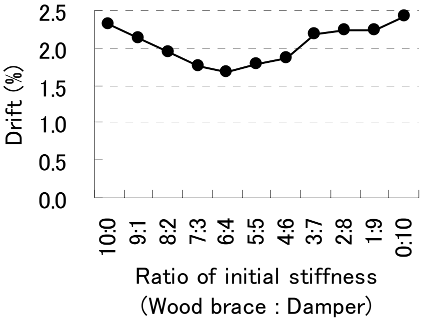


Figure 27. Maximum response drift in the case of a combination of wood brace and the damper device

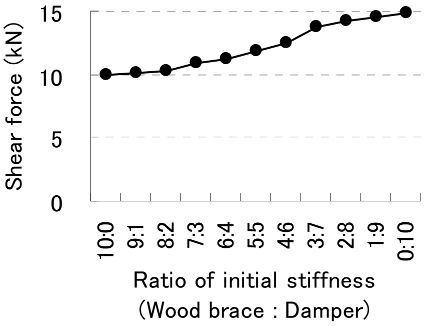


Figure 28. Maximum shear force in the case of a combination of wood brace and the damper device

6 CONCLUSIONS

A new passive damper device which includes high damping rubber has been developed. To investigate the performance of the new damper device, static shear loading test, shaking table test and earthquake response analysis were conducted.

On the static shear loading test, wood frame with the new damper device showed stable hysteresis without a decline of stiffness under repeated cyclic lateral loads. It was found that the shear force of wood frame with the damper device at 0.5% of drift is 3.52kN which is 79% of the one with nailed plywood, however, the shear force of wood frame with the damper device at 1% of drift is 5.48kN which is almost the same level as the one with nailed plywood.

From the shaking table test of wood frame with single damper device in addition to single nailed plywood or double wood braces, it was found that addition of the damper device reduced maximum response drift by approximately 50%, while no remarkable increase of maximum shear force was detected.

The result of earthquake response analysis showed that the optimum number of damper devices exists for every wooden house. For example, replacing 30% or 40% of nailed plywood by the damper device decreases response drift by 21%, while the other replacing rate introduced larger response drifts.

The new developed damper device has stable force-displacement relationship even under repeated cyclic loads. However shear stiffness of wood frame with the damper device is relatively low compared to the one with nailed plywood or wood brace, replacing some plywood or wood brace by the optimum number of the damper device is able to reduce earthquake response of wooden houses effectively.

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