FULL-SCALE SHAKING TABLE TEST OF PASSIVE RESPONSE CONTROL IN EXISTING OLD BUILDINGS

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SUMMARY

In order to confirm the effects of energy absorbing elements added to the RC frame, shaking table tests are conducted. The prototype of the RC frame was designed based on seismic regulations for buildings that had used before 1971. The amount of shear reinforcement in the columns is very poor comparing the reinforcement by the current code. Five specimens are tested. Three RC frame specimens with energy absorbing element and one RC frame specimen without energy absorbing element were for shaking table test. Another one RC frame specimen without energy absorbing element was for static test. Diene type visco elastic, low yield point steel, and rubber modified asphalt dampers, are used as energy absorbing elements. The shear failure occurred for RC frame without damper by 290cm/sec^2 shaking table test. But other three specimens are durable to the same excitation. The shear force of the frame is shared to RC frame and energy absorbing elements. And the maximum story drift is reduced through absorbing the energy in dampers. Consequently, a shear failure of the column has been avoided. Simulation analysis is conducted by assuming these dampers to be Maxwell, bi-linear, and Voigt models. It is confirmed that the results of the analysis coincide well to test results.

INTRODUCTION

While the building design code in Japan was amended in 1971 and 1981 according to information collected from strong earthquake attacks. It was the dreadful damage resulting from the 1995 Kobe earthquake that revealed the necessity for seismic-capacity evaluations of all buildings designed under outdated codes. There has been a surge of general interest in increasing the seismic safety of existing buildings that do not meet the requirements of the present code. Ways to increasing the safety include the following: 1) increasing the building's strength and/or ductility to resist against strong ground motion, 2) adding some energy-absorbing elements to reduce the dynamic response, a procedure called "dynamic response control". The purpose of this paper is to prove the practicability and effectiveness of the dynamic response control using a full-scale RC frame model through shaking table tests and static loading tests.

SCHEME OF SHAKING TABLE TEST

Test Parameter

To begin this study, the situation of a 5-story RC building, that was designed under a code established before 1971, was postdated. The shaking table tests were carried out for five specimens, out of which were one-story

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one-bay full scale models, each representing an intermediate story of RC building. Those ways of designing specimen are shown in Fig.1 schematically.
Kinds of test specimens are shown in Tab.1. Energy absorbing elements are installed between top and bottom beams as an intermediate column. The energy absorbing element consists of damper and upper and lower support, using the diene type, the low yield point steel type, and the rubber modified asphalt type dampers.

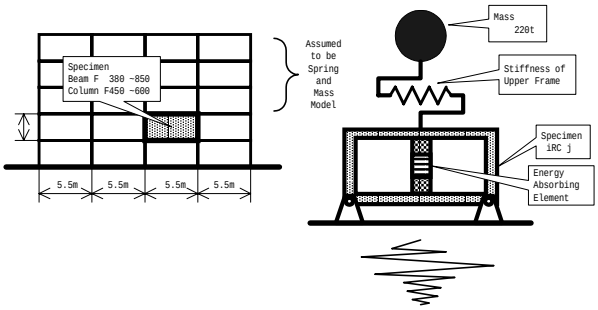


Figure 1 Modeling of specimens

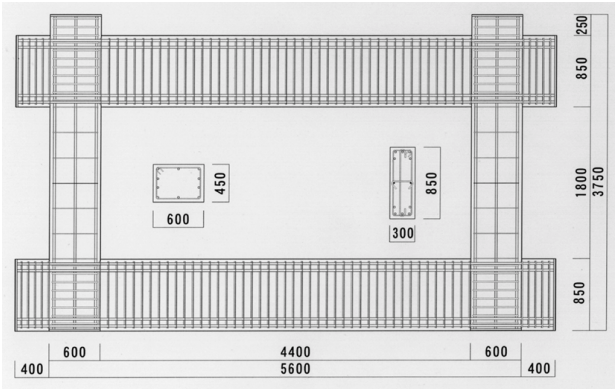
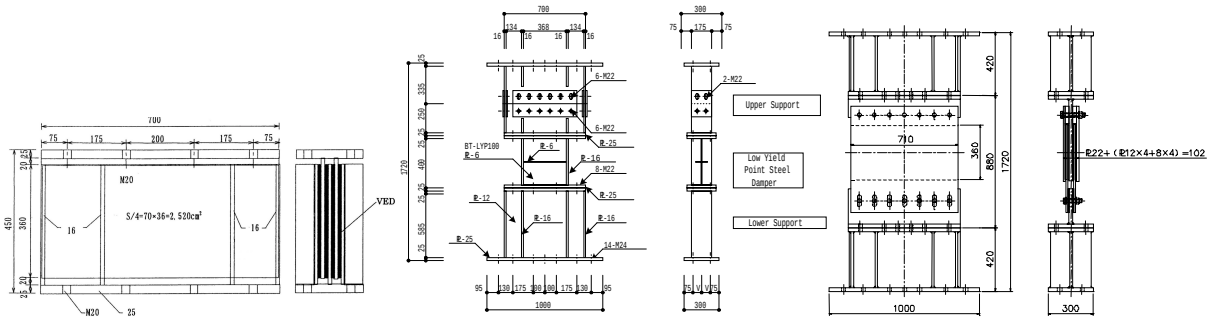


Figure 2 RC Frame

Test Frame

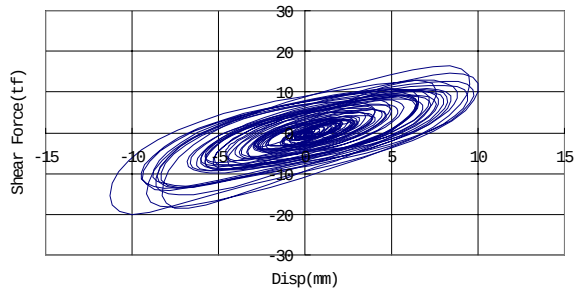
Test RC frame is a one-story one-bay full-scale model shown in Fig. 2. The amount of shear reinforcement in the columns is very poor comparing the requirement of current code. This frame is designed that the shear failure of the column should occur before the bending fracture of the column. As the results, the distance of column hoop is 30cm, and the shear coefficient of this model is 0.36.
The energy absorbing elements are shown in Fig.3. These consist of a damper in the center part and two supports at the top and bottom sides. Those supports are fixed by PC-bars to the beams at the frame. The characteristics of these dampers are shown in Fig.4, which are results of dynamic tests controlled by displacement time history obtained from shaking table test in this study.



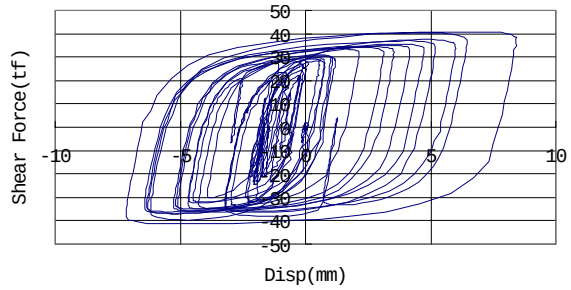
A) Diene Type B) Low Yield Point Steel Type C) Rubber Modified Asphalt Type
Figure 3 Energy Absorbing Element

The diene type damper absorbs energy by the shear deformation of visco elastic materials. Four seats of visco-elastic material are adhered to 3 steel plates coming down from upper side and 4 steel plates coming up from lower side of the frame and the total shear area of the damper is 10080cm^2. The hysteresis loop of the damper shown in Fig. 4(A) revolves in inclined elliptic orbit, and it can be expressed easily by complex stiffness using the 6-elements Maxwell model.
The low yield point steel damper absorbs energy by the elasto-plastic shear deformation of the steel plate whose yield stress is about 1tf/cm^2. The plate is used at the web as a shear panel. The ribs are attached at the web to prevent the plate from buckling and to have enough durability to repeated load. Because the steel damper has a little dependence on velocity, the damper test shown in Fig. 4(B) is performed at the half speed to the shaking table test. The maximum shear force (41tf) is obtained at the first main shock of the earthquake. The shear force decreases a little, but the hysteresis characteristics show large energy absorbing capacity. And the steel damper can be assumed to be bi-linear model with maximum shear force coefficient of 0.19.
The rubber modified asphalt type damper has almost same shape to the diene type damper. It absorbs energy by the shear deformation of the visco elastic material adhered to steel plates shown in Fig.3. The total shear area of the damper is 10080cm^2, which is same to diene type damper. But the thickness of the viscous material sheet is

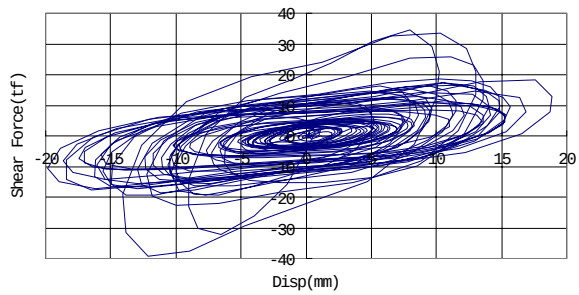
8mm. The hystereses loop shown in Fig.4 (C) has small equivalent stiffness and resembled to elasto-plastic damper. The characteristics of this damper can be modeled by the Voigt model.



A) Diene Type Damper



B) Low Yield Point Steel Damper



C) Rubber Modified Asphalt

Figure 4 Hysteretic Characterisitics of Dampers

Table 1 List of Specimen

NO	Damper
1	RC frame with diene type damper
2	RC frame with low yield point steel damper
3	RC frane with rubber modified asphalt
4	RC frame without damper
5	RC frane without damper (static test)

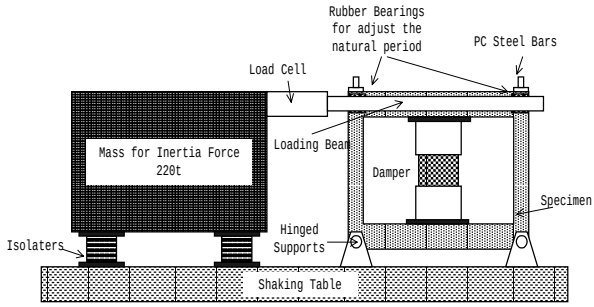


Figure 5 Experimental Facilities

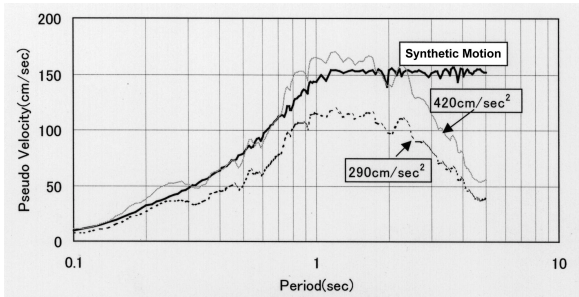


Figure 6 Spectrum of the Input Motion

Experimental facilities

The experimental facilities of the shaking table are illustrated schematically in Fig. 5. The RC specimen is on hinged support at the bottom of columns. To adjust the natural period of the specimen to that of the prototype building with five stories, four rubber bearings are installed between a load beam connected to the mass and an upper beam of the specimen. The resonant period of the specimen is 0.6sec. under small excitation. A loading mass, which is supported by rubber bearings, is connected to the specimen. During the shaking table test, the specimen was subjected to lateral inertia force of the mass. The weight of the mass is 220tf. The resonant period of this mass is about 2.0sec, which is enough long not to affect the RC frame period. The acting system was designed for the column and beam test by Akiyama H.

To install axial force to columns, PC steel bars are under post tensioned through weak springs, which will protect to release the axial deformation by temporary change of axial force or cracks of columns.

The table input motions

An artificial earthquake motion was adopted as an input motion through the shaking table. The artificial motion was corresponding to equivalent seismic force for second soil type (medium soil deposit) in Building Regulation in Japan. The amplitude of the motion is obtained when the equivalent seismic force dependent on periods is equal to a response acceleration spectrum with 5% damping, shown in Fig. 6. As a phase of the motion, the property of 1952 Taft EW component is utilized.
The artificial earthquake motion is considered until 10 sec in period and maximum values of acceleration, velocity and displacement are 402.2 cm/sec^2, 83.5cm/sec and 65.5cm respectively. On the other hand, maximum values of acceleration, velocity and displacement of the shaking table input motion are 478.3cm/sec^2, 40.4cm/sec and 14.5cm, respectively. With the limitation of stroke of the shaking table, an analog filter is used to reduce long period regions. After filtering period regions more than 2 sec., a signal is transferred to shaking table controller. And the target maximum acceleration is set by the controller.

EFFECTS OF ENERGY ABSORBING ELEMENTS

Summary of Test Results

The summary of the test result is shown in Tab. 2. For the specimens with damper, the target maximum input acceleration is 290 cm/sec^2, and the resulting maximum accelerations for the specimens with damper are 301cm/secc^2 to 307cm/sec^2, which are almost same to target value. And the maximum displacements of the frame are 13.8mm to 18.8mm. It results in some bending clack in the columns for each specimen, but the shear failure does not occur.
For the specimens without damper, tested on the shaking table, the shear failure of the column occurred, when the horizontal displacement reaches about 28.4mm and the maximum shear force reaches 121tf. The resulting maximum acceleration of the shaking table is 322cm/sec^2 and a little larger than that to other specimens, because the dynamic characteristics of the specimen was changed by the share failure, and the maximum acceleration is obtained after the shear failure. Static test was also conducted for the specimen without damper. The maximum shear force was 113tf and the maximum displacement was 22.9mm, when the shear failure of the column occurred. The results of those specimens without damper are almost same.

Table 2 Summary of the test results

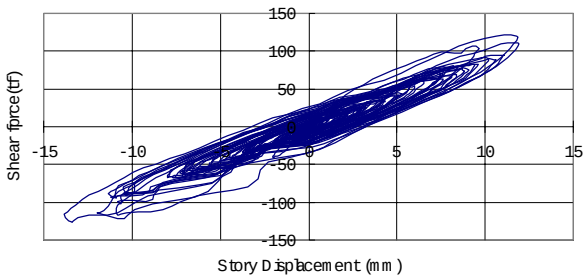
Case	Max Acceleration	time	Shear Force			Displacement		Energy		
			whole	damper	RC frame	story	damper	Input	energy absorbing element	damper
	(cm/sec^2)	(sec)	(tf)	(tf)	(tf)	(mm)	(mm)	(tfcm)	(tfcm)	(tfcm)
Dien Type Damper	301									
Maximum Shear Force		15.37	126	42	84	13.4	10.6	6940	5360	5300
Minimum Shear Force		5.73	-122	-45	-77	-11.1	-8.1	1900	1080	1010
Maximum Displacement		15.40	116	39	77	13.8	11.3	7000	5380	5330
Minimum Displacement		15.00	-109	-32	-79	-11.9	-9.8	6280	4820	4790
Low Yield Point Steel Damper	308									
Maximum Shear Force		5.43	118	79	79	13.1	8.1	1880	944	689
Minimum Shear Force		5.78	-121	-37	-84	-13.7	-7.1	2800	1540	1190
Maximum Displacement		5.45	114	37	77	13.4	8.8	1910	955	715
Minimum Displacement		5.81	-111	-33	-78	-14.2	-7.7	2860	1560	1210
Rubber Modified Asphart	307									
Maximum Shear Force		6.06	128	28	100	12.8	8.4	4150	1680	1570
Minimum Shear Force		5.71	-128	-27	-100	-13.4	-10.8	2980	1120	1030
Maximum Displacement		21.21	111	7	104	18.8	17.6	22000	9460	9810
Minimum Displacement		21.60	-106	-6	-99	-18.8	-19.5	22600	9760	10100
Without Damper (Dynamic Test)	322									
Maximum Shear Force		7.39	121	-	-	28.4	-	5670	-	-
Minimum Shear Force		7.82	-120	-	-	-26.7	-	6630	-	-
Without Damper (Static Test)	-									
Maximum Displacement		-	113	-	-	22.9	-	2610	-	-
Minimum Displacement		-	-100	-	-	-33.9	-	5810	-	-

Diene Type Damper

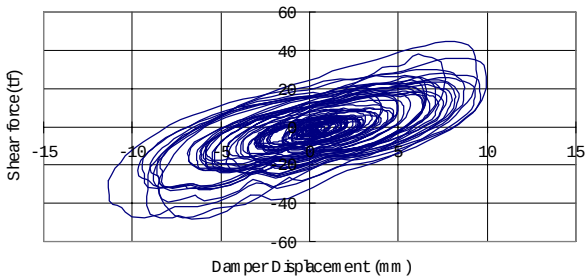
Small cracks can be seen at the RC columns and beams after the 290cm/sec^2 test, but all the steel reinforcement are not yielded and damages are very little. A slight slippage occurs because the fixed ends of the damper supports are a little loose. And same slippage was also seen at the hinged supports of the frame and the rubber bearings at the top columns.

Fig. 7 (A) shows the relationship between the shear force and the horizontal displacement of the specimen. The shear force of the damper shown in Fig. 7(B) is measured by the strain gages attached to the two supports at the top and bottom ends. It could be said that the value got by the strain gage is appropriate, because the hysteresis loop of the damper is almost same as the results of damper test shown in Fig. 4(A). The shear force of the RC frame is obtained by subtracting the damper shear force from the total shear force. The hysteresis loop of RC frame is shown in Fig.7(C). The result of static test is also shown. Because of the cracks caused by the preliminary test, the initial stiffness is a little smaller than the results of static test. But generally speaking, these results are almost similar to each other.

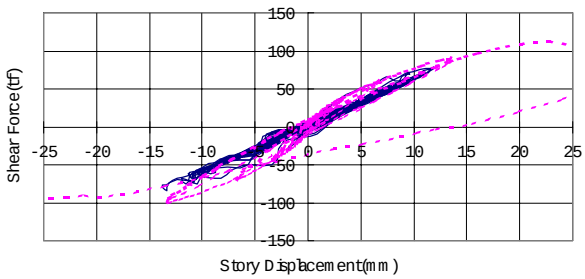
The maximum forces and displacements are shown in Tab.2. The shear force of the damper is from 38% to 39% of the total shear force when it reached to maximum.



A) RC Frame + Energy Absorbing Element

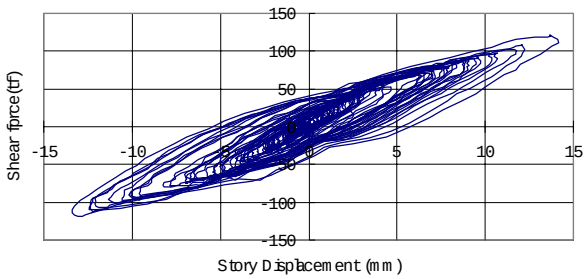


B) Damper

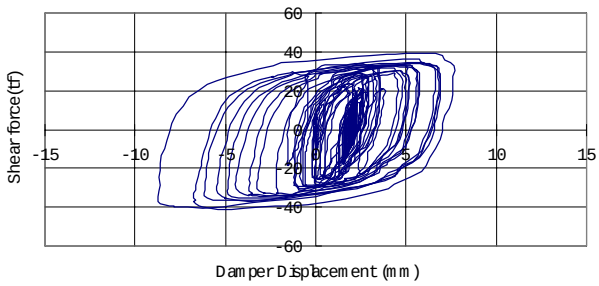


C) RC Frame

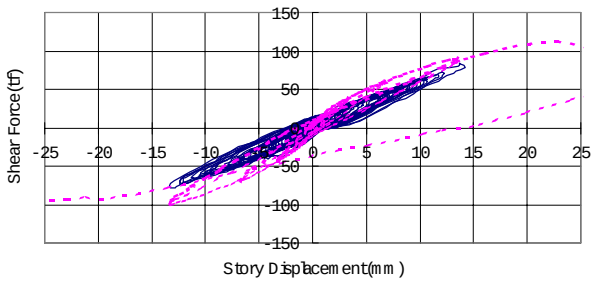
Figure 7 Hysteresis Loop (Diene Type Damper)



A) RC Frame + Energy Absorbing Element



B) Damper



C) RC Frame

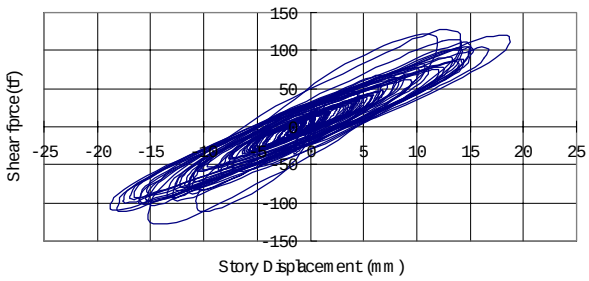
Figure 8 Hysteresis loop (Low Yield Point Steel)

Low Yield Point Steel Damper

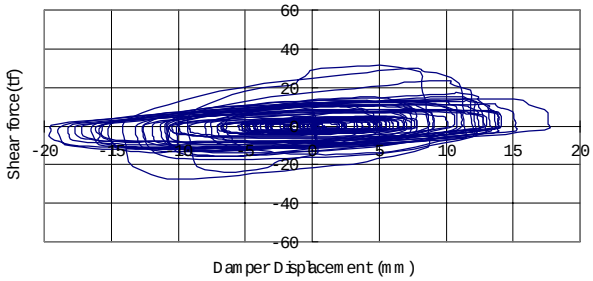
The preliminary test is performed before the planed 290cm/sec^2 test, small bending cracks developed. But these cracks do not grow, and the yield of the reinforcement does not appear by the earthquake motion of 290cm/sec^2. Fig. 8 shows the relationship between the shear force and the horizontal displacement of the specimen. The hysteresis loop of RC frame is shown in Fig. 8(C).
Adding the energy absorbing element shown in Fig. 8(B) to the RC frame which has little energy absorbing capacity shown in Fig.8(C), the whole frame shown in Fig. 8(A) becomes to be a frame which has large energy absorbing capacity and large shear force capacity.
The maximum forces and displacements are shown in Tab.2. The shear force of the damper is from 31% to 34% of the total shear force when it reached to maximum. The maximum displacement of the damper is about 60% of the frame, rest of them is shared by the deformation on the supports.

Rubber Modified Asphalt Damper

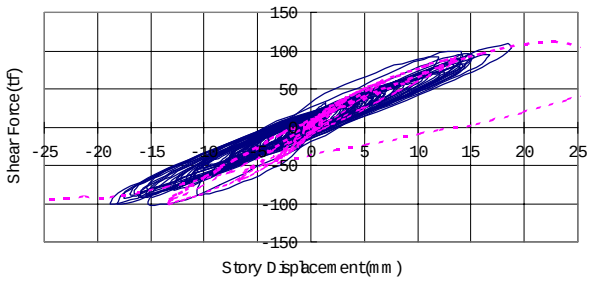
Fig. 9 shows the relationship between the shear force and the horizontal displacement of the specimen. The hysteresis loop of RC frame is shown in Fig. 9(C). The maximum forces and displacements are shown in Tab.2. The shear force of the damper is from 21% to 22% of the total shear force when it reached to maximum.



A) RC Frame + Energy Absorbing Element

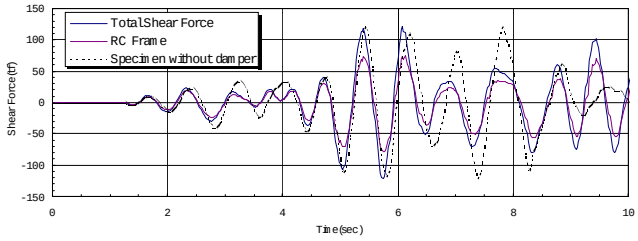


B) Damper

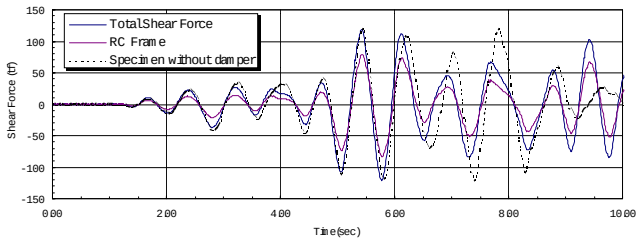


C) RC Frame

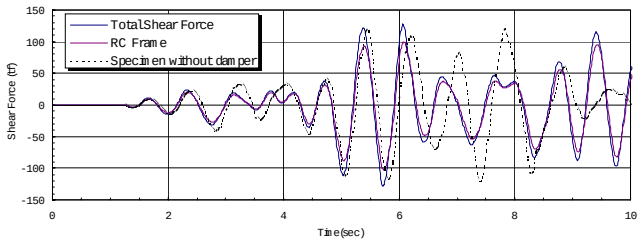
Figure 9 Hysteresis loop (Rubber Modified Asphalt type)



A) Diene Type Damper



B) Low Yield Point steel Damper



C) Rubber Modified Asphalt

Figure 10 The Effects of the Energy Absorbing Element

Effects of the Energy Absorbing Element

To verify the effect of the damper, these results are compared with the results of the specimen without damper tested by the same input motion and discussed. Fig. 10 shows the time history of the shear force. It also shows the results of bare RC frame removed the shear force of the damper. The maximum shear forces of the specimen are almost same. But the shear force of the bare RC frame is small, because the damper shares the shear force about 38% for diene type damper, about 35% for low yield point steel damper, and about 21% for rubber modified asphalt damper, respectively. In case of the frame without energy absorbing element, the shear collapse of columns occurs at 7.82sec. But in case of the RC frame with energy absorbing element, the shear force which is shared by columns becomes considerably small, and the shear collapse does not appear. With decreasing the shear force of columns, a decrease of story drift results in prevention to the shear collapse.

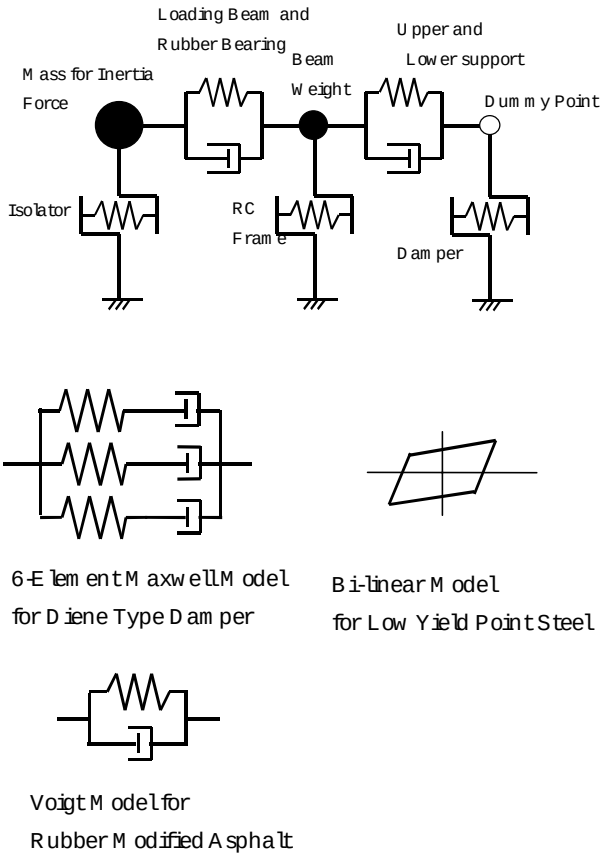
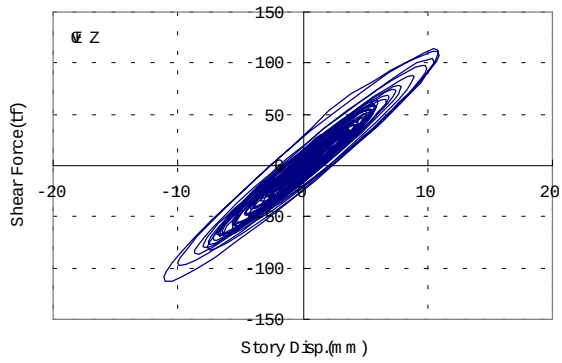
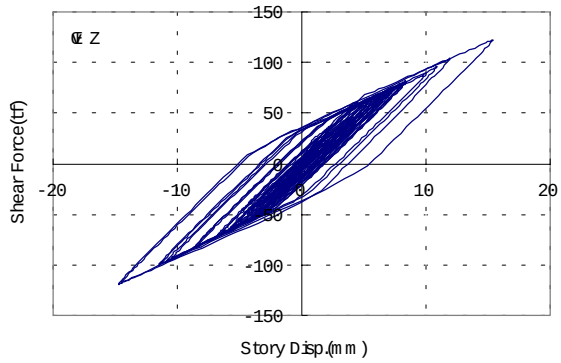


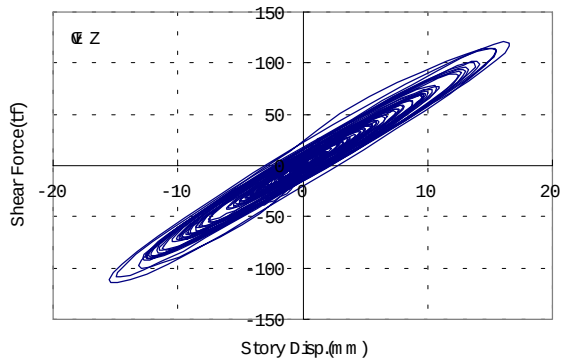
Figure 11 Simulation Model



A) Frame+Damper (Diene Type Damper)



B) **Frame+Damper (Low Yield Point steel)**



C) Frame +Damper (Rubber Modified Asphalt)
Figure 12 Hysteresis Loop (Results of Simulation)

SIMULATION ANALYSIS

Simulation analysis is conducted to investigate the modeling of energy absorbing elements. Analytical model is shown in Fig.11. The energy absorbing elements are attached to the bare frame and mass. Damper and supports are assumed to be springs connected in series. The diene damper, the low yield point steel damper, the rubber modified asphalt damper are assumed to be 6-element-Maxwell model, to be bi-linear model and to be Voigt model, respectively. The characteristics of the dampers are determined according to the results of the damper tests. In case of low yield point steel damper, the loose and rattling of the supports is assumed to be viscous damper.

The results of the analysis are shown in Fig.12. Those figures are corresponding to the experimental results shown in Fig.7 (A), Fig. 8(A) and Fig. 9(A). For the visco elastic damper such as the diene type and rubber modified asphalt damper, the equivalent stiffness of the results are a little large, because the increase of the temperature is not considered in the analysis. But the maximum responses and the hysteresis are almost similar to the experimental results. In case of the low yield point steel damper, the analytical result is almost same to the test result also. It is verified that analytical results using simple model will appropriately simulated

CONCLUSION

This study used full-scale shaking-table tests to prove the practicability and effectiveness of the dynamic response control method, which adds energy-absorbing elements to the building that was designed through building code of 1971.

The results of this study are as follows:

1) The shear force is shared to bare RC frame and energy absorbing element. And story drift of the frame is reduced by adding the energy-absorbing element.

2) As a result, shear failure of the column has been successfully avoided in specimens with dampers, even the shear failure occurred in the columns of the frame that had no damper.

3) The simulation analysis is conducted by assuming the damper to be Maxwell model, bi-linear model, and Voigt model. It is confirmed that the results of the analysis with simple model agree well with the test results.

ACKNOWLEDGEMENT

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