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EFFECT OF CHARACTERISTICS OF VARIOUS INTER-STORY DAMPERS ON RESPONSE CONTROL FOR VIBRATION OF BUILDING STRUCTURES

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ABSTRACT

Various types of dampers such as friction damper, viscous damper or hysteretic damper are used for response control of building structures. Those dampers can be applied to the joints which connect non-structural elements to main structural elements in order to make good use of non-structural elements. Each of them has different dynamic characteristics of non-linear behavior and different effects on structural response reduction. Differences among them are examined here by numerical simulations, varying intensity and variety of earthquake ground motion. Reduction factor of story deformation response is used to evaluate the effect of dampers. It is observed that reduction factor varies depending on intensity and type of earthquake, type of dampers, and the story of building structures.

KEYWORDS

inter-story damper system; structural response control; non-structural element

1. INTRODUCTION

In recent years, remarkable progress has been made in the field of structural response control. In particular, structural response control for insuring comfortable residence against wind or lower level earthquake load has been already put to practical use, and lots of examples have been made. They are called TMD,TLD,AMD,HMD and most of them basically have mass dampers installed on the top of the buildings. On the other hand, the different type of structural response control has also developed.They are walls with viscous damper or bracings with variable stiffness disposed on each story of the buildings. These kinds of structural response control with devices not concentrated are in practical use in only a few cases. They are ,however, able to be used for controlling high frequency modes of vibration and have, in principle, the advantage of having potentiality for response controlling a great earthquake load.
These kinds of dampers can be introduced to the joints which connect non-structural elements such as curtain walls, partition walls, and stairs etc., to structural elements to make good use of non-structural elements and to aim at reasonable and economic design in a view point of performance of function, safety, and residential comfort of the building. Nevertheless, they are now in test use. The general researches on the effect of inter-story damper on response control for vibration have not been actively made yet.
In this paper, numerical analysis is made in order to investigate the effects on response control of structural buildings of dynamic characteristics of non-linear behavior of inter-story passive dampers.
In the analysis, variables are a variety of dampers, that of earthquake, intensity of earthquake and damper force. The effects of the dampers on response reduction is examined in comparison with the case without the dampers.

2. CONDITION OF ANALYSIS

2.1 Analytical Model

A 10-story steel building is assumed as an analytical model, which has the story weight, and the dynamic characteristics of non-linear behavior shown in Table1. The dynamic characteristics of non-linear behavior is supposed to be bi-linear type. In Table 1, k_1 is the initial stiffness and k_2 is the second stiffness. Q_y, δ_y are respectively the shear force and the deformation of elastic limit. The elastic limit is defined as the time when the plastic hinge occurs in a member belonged to the story in the first place.

Table 1.

Story	Weight (t)	Stiffness k_1 (t/cm)	k_2/k_1	Q_y (t)	δ_y (cm)
10	600	590	0.414	1540	2.61
9	600	615	0.453	1660	2.70
8	600	630	0.530	1730	2.75
7	600	640	0.570	1850	2.89
6	610	680	0.547	1930	2.84
5	610	700	0.537	2020	2.89
4	610	760	0.516	2020	2.66
3	810	870	0.413	2100	2.41
2	810	870	0.410	2230	2.56
1	1010	1070	0.198	2390	2.23

2.2 Variety of Devices and Assumption of Damping Force

In this analysis, friction damper, viscous damper, and hysteretic damper are applied, and all of them are arranged on each story. Each of them has the same characteristics throughout the stories. The dynamic characteristics of non-linear behavior of each damper is defined as follows.

(1)Hysteretic Damper : High Damping Rubber Bearing with Low elasticity
It is regarded to function auxiliarily, which has no influence on a basic vibration characteristics of the structures. For that purpose, it is supposed to have the equivalent shear stiffness of 100t/cm, which is 10% of the initial stiffness of structure, with its shear strain being 50%. Meanwhile if the rubber bearing with the thickness of 1cm is used for introducing to the curtain walls, the shear deformation is to be 2cm which is nearly equal to the elastic limit deformation of the building with the shear strain of rubber bearing running up to 200%. In other words, the shear deformation is to be 5mm with the shear strain being 50%, and the damping force is given 50t at that time.
The material characteristics of high damping rubber bearing with low elasticity is defined by the following formulae presented by the rubber maker.

$$
\begin{aligned}
G_0 &= 18.6 - 56.9\gamma + 95.0\gamma^2 - 58.4\gamma^3 && (0.1 \le \gamma < 0.5)\\
&= 10.7 - 10.5\gamma + 4.99\gamma^2 - 0.775\gamma^3 && (0.5 \le \gamma < 1.6)\\
&= 4.33 + 0.144\gamma - 0.752\gamma^2 + 0.211\gamma^3 && (1.6 \le \gamma < 3.0)
\end{aligned}
$$

$$G_1 = \left(1 + \frac{\alpha \cdot H_{eq} \cdot \pi/2}{\alpha - H_{eq} \cdot \pi/2}\right) \cdot G_0$$

$$G_2 = (1-\alpha) \cdot G_0$$

$$
\begin{aligned}
H_{eq} &= 0.189 - 0.141\gamma + 0.162\gamma^2 - 0.066\gamma^3 && (0.1 \le \gamma < 1.0)\\
&= 0.157 - 0.013\gamma && (1.0 \le \gamma < 3.0)
\end{aligned}
$$

$$
\begin{aligned}
\alpha &= 0.350 - 0.220\gamma + 0.175\gamma^2 - 0.052\gamma^3 && (0.1 \le \gamma < 1.1)\\
&= 0.277 - 0.024\gamma && (1.1 \le \gamma < 3.0)
\end{aligned}
$$

$$\tau_d = G_0 \cdot \gamma \cdot \alpha \cdot \frac{G_1}{G_1 - G_2}$$

$$F = F(\gamma, \dot{\gamma}, G_1, G_2, A) \quad (t)$$

G_0: secant shear modulus
G_1: initial elastic modulus
G_2: second elastic modulus
A : area of rubber bearing
α : introducing function of intercept on Y-axis
τ_d : yield stress
γ : shear strain

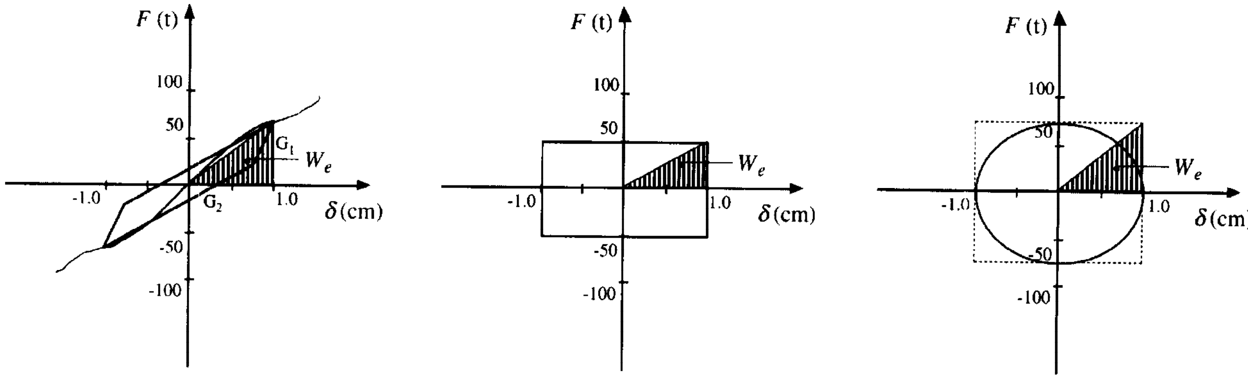
(2)Friction Damper
The rigid-plastic hysteresis type is introduced, and its damping force F is given ±50ton.

(3)Viscous Damper
The relative story velocity corresponding to the deformation of 5mm is calculated to be almost 3cm/sec based on the first degree frequency of the building with the damping force of 50t. The damping force of viscous damper is defined by the following formula in which the temperature T is assumed to be 15°C because the basic response behavior is examined here.

$$F = \text{sgn}(v) \cdot 042 \times e^{-0.043T} \times (|v|/d)^{0.59} \times A \qquad (kg)$$

v : velocity (cm/s)
d : depth of viscous material (cm)
A : area of resisting board (cm^2)

The dynamic characteristics of non-linear behavior of three kinds of dampers mentioned above is shown by Fig. 1. The hysteretic energy of one cycle of its loop in the case of its deformation being 0.5cm,1.0cm, and 2.0cm is shown by Table 2, and the equivalent damping constant (heq) is on Table 3. In calculating the equivalent damping constant(heq) of the viscous damper, the hysteresis loop is assumed to form an ellipse and circumscribed rectangular is supposed for convenience sake.



(a) Hysteretic Damper (b) Friction Damper (c) Viscous Damper

Fig. 1. Dynamic Characteristics of Non-Linear Behavior

$$h_{eq} = \frac{\Delta W}{4\pi W_e}$$

h_{eq} : equivalent damping constant
ΔW : dissipated energy per one cycle
W_e : equivalent potential energy

Table 2. Dissipated Energy per One Cycle (t cm)

	δ = 0.5	δ = 1.0	δ = 2.0
Hysteretic Damper	23.7	60.5	164.5
Friction Damper	100.0	200.0	400.0
Viscous Damper	78.5	236.6	711.9

δ : Story Displacement (cm)

Table 3. Equivalent Damping Constant (h_{eq})

	δ = 0.5	δ = 1.0	δ = 2.0
Hysteretic Damper	0.151	0.144	0.131
Friction Damper	0.637	0.637	0.637
Viscous Damper	0.500	0.500	0.500

δ : Story Displacement (cm)

2.3 Intensity and Variety of Earthquake

Four types of earthquake such as EL CENTRO(1940)NS, TAFT(1952)EW, HACHINOHE(1968)NS, TH 030(1978)NS are used here, and the intensity of ground motion is regulated by the value of velocity, which are 10cm/s,20cm/s, and 40cm/s. 10cm/s is also intended to be used for the low-level earthquake which occurs frequently. Runge-Kutta 4th method is applied. Duration time of analysis is 20 seconds. Time interval of analysis is 0.01sec.

2.4 Damping Constant of Structure

It is assumed that inner viscous damping type proportional to natural frequency is applied with damping constant for 1st mode vibration without response control being 2%.

Table 4. Natural Period (sec)

1st	2nd	3rd	4th	5th
1.17	0.43	0.27	0.19	0.16

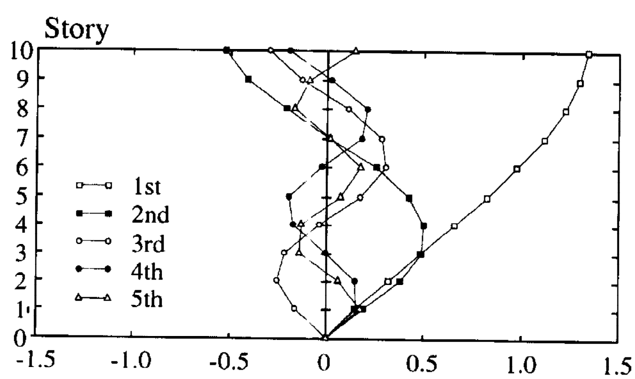


Fig. 2. Participation Function

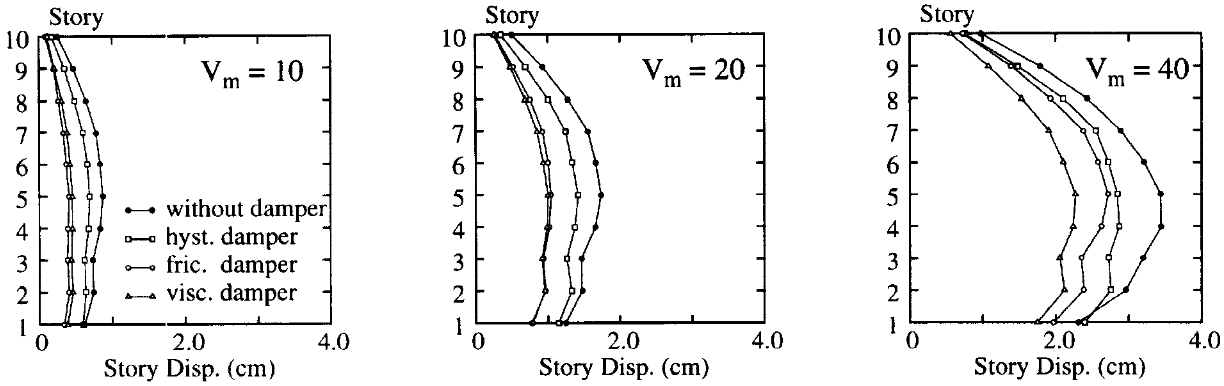


Fig. 3. Story Displacement (input motion : EL CENTRO)

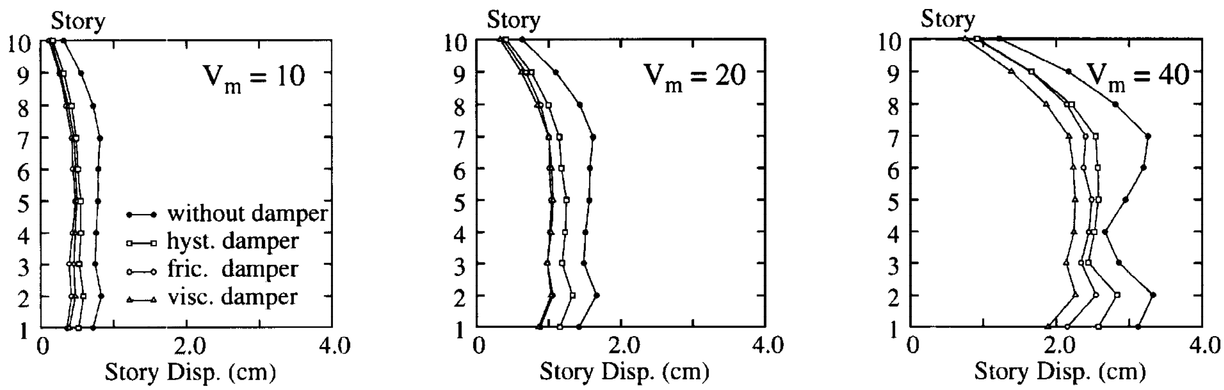


Fig. 4. Story Displacement (input motion : TAFT)

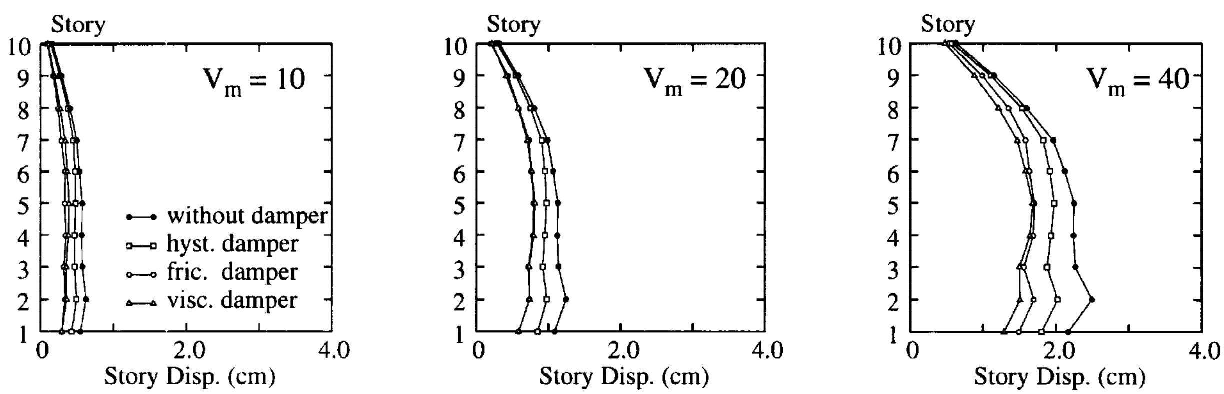


Fig. 5. Story Displacement (input motion : HACHINOHE)

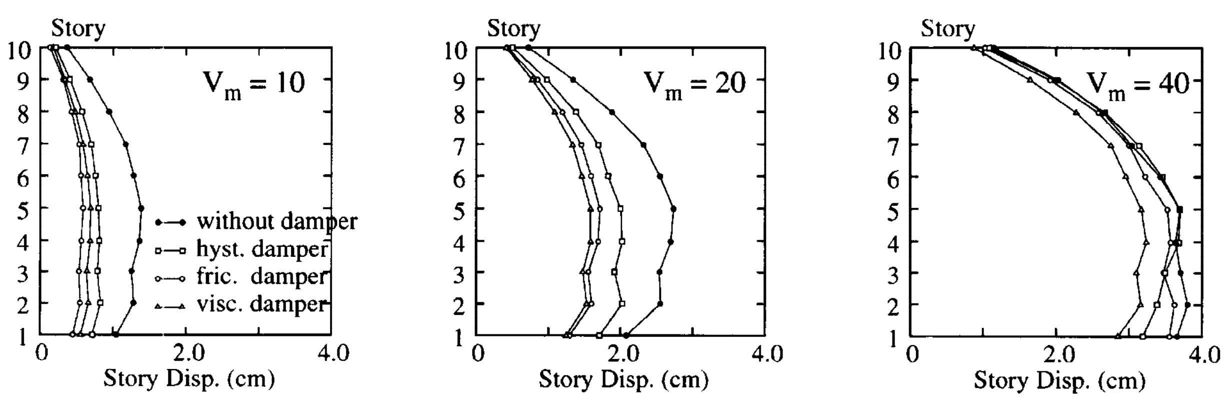


Fig. 6. Story Displacement (input motion : TH 030)

2.5 Natural period and Participation Function

Natural period of the structure without response control is shown by Table 4, and its participation function is shown by Fig. 2.

2.6 Values of Response

The examination is made on maximum response value of relative story displacement, story shear force, top displacement, actual damping force of devices, and total energy dissipated by devices.

3. RESULT OF ANALYSIS AND EXAMINATION

3.1 Relative Story Displacement

Maximum values of relative story displacement (δ_d) of each story caused by the earthquake waves are shown by Fig. 3, 4, 5, 6. The maximum values are as follows, δ_d=0.5cm, for Vm=10, δ_d=0.7~2.0cm, for Vm=20, δ_d=2.0~3.5cm, for Vm=40. In any case, the value of δ_d is the largest when the hysteretic damper is applied, and it is even larger than without devices regarding the 1st story for Vm=40. As the intensity of earthquake is higher, it is observed that the viscous damper takes more effect on response reduction than any other damper.

3.2 Distribution over Stories of Value of D.R.F. Averaged by Earthquake Waves

D.R.F. is the ratio of relative story displacement with the damper to that without the damper.
D.R.F distribution of relative story displacement averaged by types of earthquake waves are shown in Fig. 7. And the normalized values of them by the value of the first story are shown in Fig. 8.
(1) In case of Vm=10,20, the hysteretic damper reduces less the displacement of the first story than the other stories. On the other hand, the other dampers have less reduction effect on the intermediate story displacement than that of the first story. Those tendency is observed more remarkably in case of Vm being less.
(2) In case of Vm=40, the hysteretic damper has almost the same reduction effect on all stories. D.R.F. is 0.83~0.89.

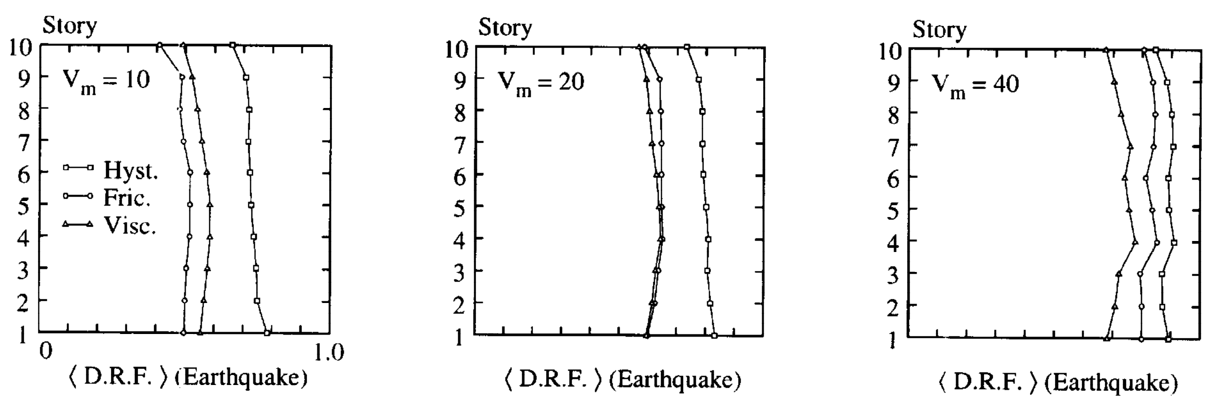


Fig. 7. Average Reduction Factor of Story Displacement

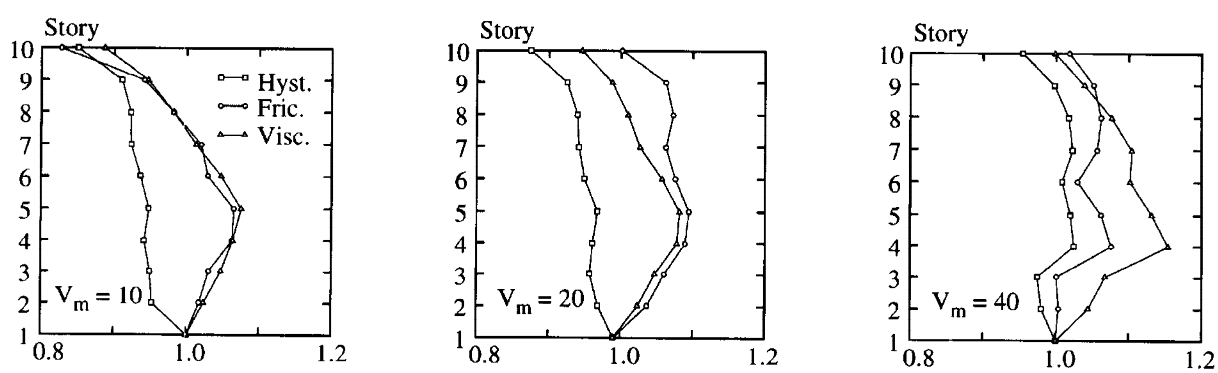


Fig. 8. Normalized Average Reduction Factor of Story Displacement

(3) Regardless of the value of Vm, D.R.F.varies most depending the story when the viscous damper is applied, while it varies least, the hysteretic damper being applied.

3.3 Value of D.R.F.Averaged by Stories------<D.R.F>(story)

Fig.9 graphs the interrelation between <D.R.F>(story) and Vm in case of all earthquake waves and their average. The observation is as follows.

(1) The hysteretic damper has less reduction effect than any other damper in any case of Vm and earthquake waves. And the difference of reduction effect between the hysteretic damper and the other dampers is more remarkably observed as Vm is less. It is because the equivalent damping factor of the hysteretic damper is much less in comparison with the other dampers, and Vm getting more, the reduction effect of dampers is relatively less, which is caused by plasticity of the structure itself.
(2) In case of Vm=10, the reduction effect of the friction damper is the most, D.R.F. being 0.42~0.56. In case

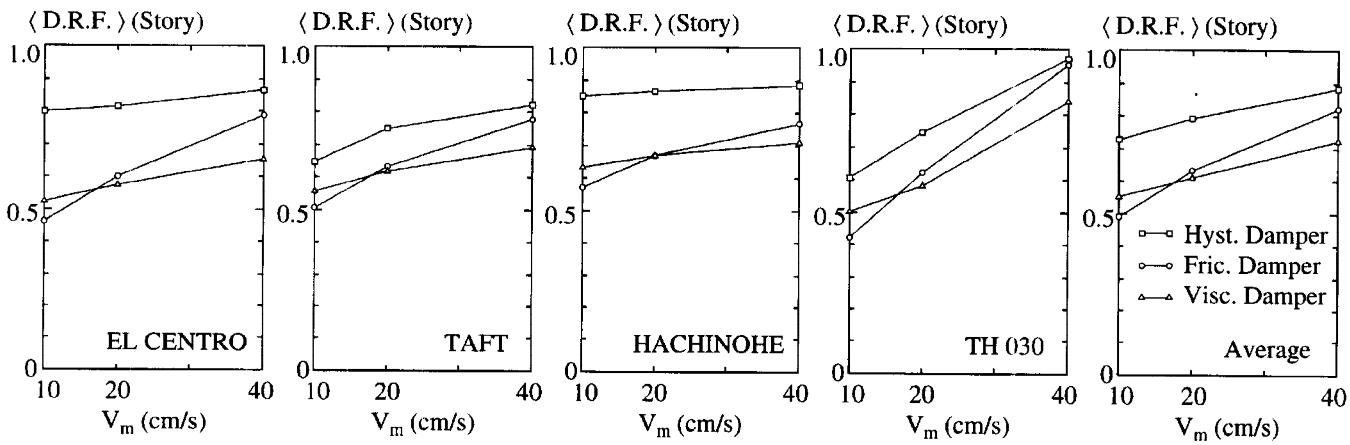


Fig. 9. Story Displacement Reduction Factor Averaged by Story

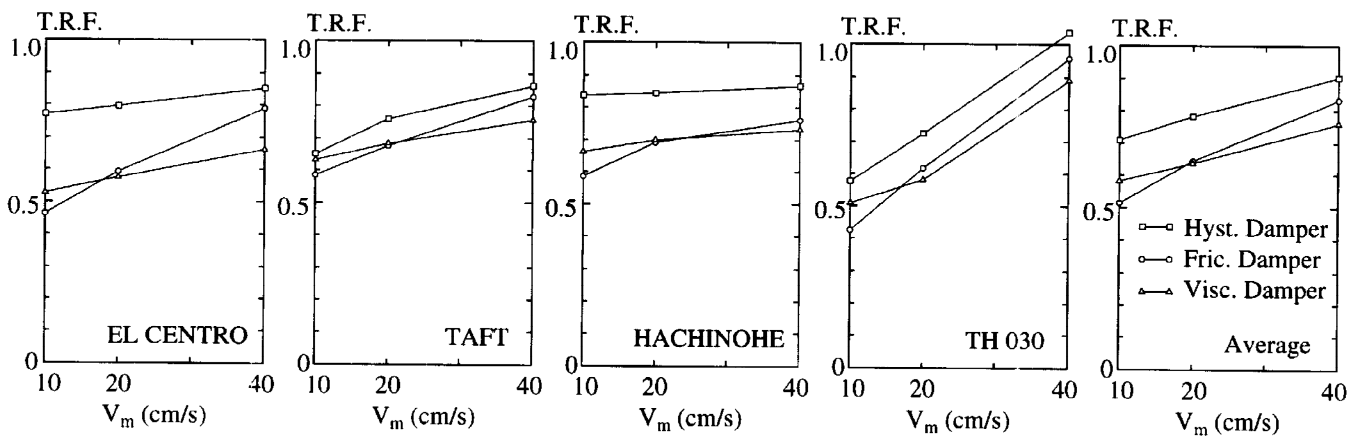


Fig. 10. Top Displacement Reduction Factor

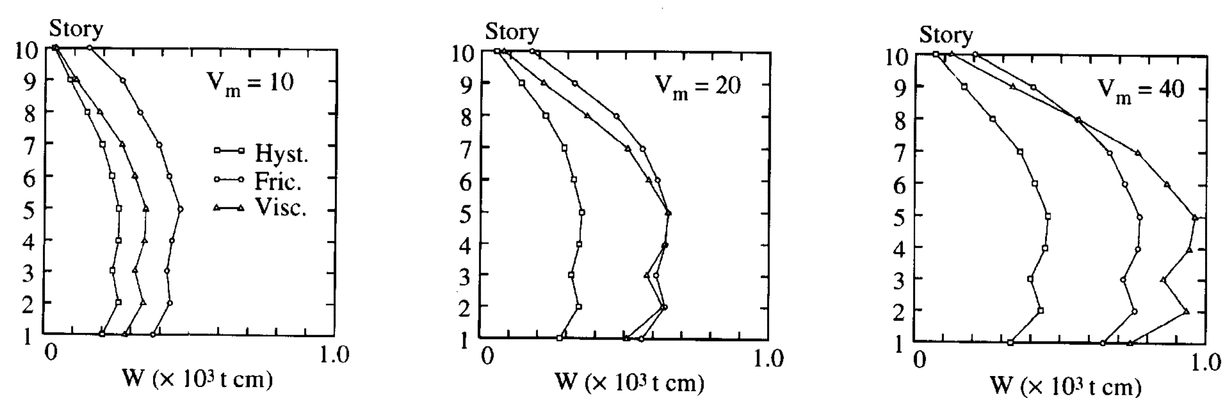


Fig. 11. Energy Dissipated by devices (input motion ELCENTRO)

of Vm=20, the viscous damper has more reduction effect than the friction damper. It is caused by the fact that the damping force of the friction damper being constantly 50t, that of the viscous damper increases as the amplitude of response becomes more. When Vm is more than 20, it generally appears that the reduction effect of the viscous damper is the most, that of the friction damper is the secondly most, and that of the hysteretic damper is the less. D.R.F of the viscous damper in case of Vm=10,Vm=20,and Vm=40 is respectively 0.56,0.61,and 0.73 regarding to the average by earthquake waves.
(3) All types of dampers have less reduction effect as Vm increases.
(4) Reduction effect varies almost the same regardless of the value of Vm.

3.4 Reduction Factor of top displacement------T.R.F.

T.R.F. is defined as the ratio of the top displacement with dampers to that without dampers.
T.R.F. changes similarly like D.R.F. as the parameters such as the types of earthquakes, and the value of Vm vary. (Fig. 10)

3.5 Maximum damping force of devices

Table 5. Maximum Damping Force of Devices (t)

	$V_m = 10$	$V_m = 20$	$V_m = 40$
Hysteretic Damper	51.6 (0.157)	75.7 (0.104)	131.1 (0.083)
Friction Damper	50.0 (0.260)	50.0 (0.099)	50.0 (0.042)
Viscous Damper	48.0 (0.185)	75.8 (0.132)	115.0 (0.096)

The value inside parentheses shows the ratio to story shear force

The averaged maximum damping force of devices of each story by the types of earthquakes and the averaged ratio of maximum damping force to story shear force of the structure by the types of earthquakes are shown in Table 5. In case of Vm=10, the maximum inter-story displacement is about 0.5cm and damping force is about 50t which is assumed in 2.2 with all types of devices. In case of Vm=20, the ratio of device damping force to story shear force is about 0.1 with all types of devices. The hysteretic damper has more damping force than any other damper.

3.6 Energy Dissipated by Devices

For typical example, the energy dissipated by device of each story in case of EL CENTRO NS being introduced is shown in Fig. 11. In any case of Vm, the hysteretic damper dissipates less energy and its variation with stories is less than any other damper. In case of Vm=10 and 20, the friction damper dissipates the most energy, while the viscous damper does the most in case of Vm=40. As the value of Vm gets more, the variation of energy with stories and the types of devices becomes more distinguished.

3.7 Total amount of energy dissipated by devices -----Wtotal

Fig. 12 shows the relation between Wtotal and Vm in case of four types of earthquakes and between the averaged Wtotal and Vm.
(1) The curve indicating the relation between Wtotal and Vm is like the 2nd degree curve.
(2) The difference of Wtotal among the types of dampers is more remarkable as the value of Vm is larger.
(3) Regardless of the intensity and type of earthquake introduced, Wtotal dissipated by the hysteretic damper is the least ,and the difference between the viscous damper and friction damper is comparatively small as far as Wtotal is concerned.

4. CONCLUSION

Regarding the reduction effect of each damper, the following behavior is observed as the conclusion of this analysis.

(1) Hysteretic damper
Its reduction effect is the least and reduction factor of story displacement is 0.73~0.89. Above all in the field of the intensity of input motion being lower and the amplitude of displacement being small, the reduction effect is much less than other dampers.
Dissipated energy is also the least. The variation of reduction effect depending on the story is less than the other dampers.
(2) Friction damper
In case of Vm=40, reduction effect is less than the viscous damper, however, reduction factor of story displacement is 0.49~0.82, and reduction effect for the same dissipated energy is the most in case of Vm=10.

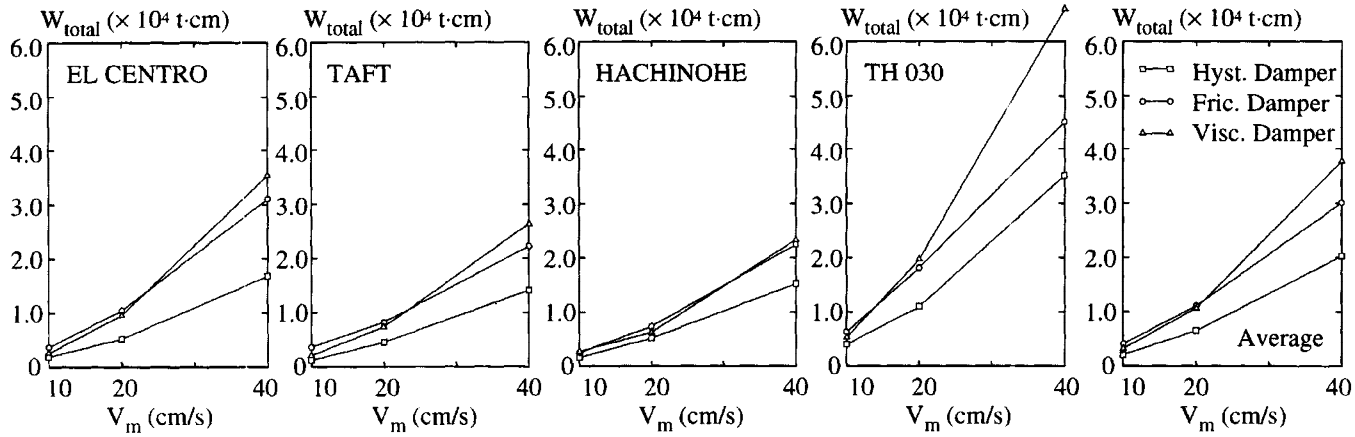


Fig. 12. Total Energy Dissipated by Devices

(3) Viscous damper
In any case of the intensity and type of earthquake, it has generally remarkable reduction effect on story displacement, story shear force, and top displacement. Reduction factor of story displacement is 0.56~0.73.
The variation of reduction effect depending on the story is the most among all dampers. The appropriate disposition of devices regarding the story should be investigated. As the damping force by the viscous damper depends on the temperature of atmosphere, the variation of damping force should be carefully taken into consideration when it is applied to the position like an outside wall which is directly influenced by the change of the open air temperature.
In this analysis, it is assumed that the characteristics of the devices are the same on all stories.
The change of reduction factor depending on it and the appropriate disposition of devices is expected to be examined.

5. ACKNOWLEDGMENT

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