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SEISMIC DESIGN OF LOW TO MID-RISE BUILDING WITH A SOFT FIRST STOREY SUBJECT TO SEMI-ACTIVE VISCOUS DAMPING CONTROL

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SUMMARY

In this paper, a seismic control system of low to mid-rise buildings with a soft first story is studied. A capacity adjustable viscous damper is installed into the first story in order to enhance overall safety of the building against various types of disturbances. The coefficient of the damper is so decided as to maximize the hysteresis energy of the first story under the condition that the shear force remains within a specified maximum force. At first, the fundamental properties of the proposed system are obtained through the seismic response analyses with a 5-DOF shear model. Next, the feasibility of the proposed system is shown through a series of experiments. In the experiments, for the sake of convenience, a dynamic hydraulic jack is used to simulate the role of a semi-active control system, and mortar test pieces are used to simulate reinforced concrete columns of the soft first story. Good agreement between experimental results and analytical ones was found.

INTRODUCTION

Recently, a lot of researchers have been studying various kinds of vibration control systems actively. After the occurrence of the Northridge Earthquake(1994) and the Hyogo-ken Nanbu Earthquake(1995), the attempt to apply these vibration control systems to the seismic hazard mitigation is one of the great interest in this field.

Vibration control systems are mainly divided into three types; i.e., passive, active, and semi-active types. Among these, semi-active control systems attract a great deal of attention because of its superior properties as follows:

1) Semi-active control system is basically stable in contrast to an active one.2) Its control effect is more flexible than a passive one.3) External energy requirements are orders of magnitude smaller than typical active control systems.

Until now, some kinds of semi-active control devices have been developed. One of the fundamental devices for semi-active control systems is the capacity adjustable viscous damper. Its viscosity is adjustable in accordance with the opening rate of the flow control valve inside the damper. A series of studies with this type of damper has been carried out and good characteristics of the dampers and efficient properties of control systems with the dampers were found [e.g. Kurata *et al.*,1998 and Niwa *et al.*,1998]. On the other hand, recently, magneto-rheological (MR) and electro-rheological (ER) fluid dampers tend to attract significant attention. Damping properties of these types of dampers are changed based on magnetic/eletcrical field applied to each fluid [e.g. Spencer Jr. *et al.*,1997, Gavin et al.,1998 and Yi *et al.*,1998].

Authors studied a concise control algorithm for semi-active control system with a capacity adjustable viscous damper. In this algorithm,•the damper is assumed to be installed into a particular story, and the story shear force is so controlled as to remain within a specified constant value in order to suppress extreme story shear force (i.e. acceleration response) induced by strong earthquakes. This control method was incorporated with a soft first story system in order to enhance overall structural safety subjected to various types of disturbances [Soda *et al.*, 1997 and Iwata *et al.*,1999]. In this coupled system, the structural members of the first story are so designed as to yield earlier than other stories in order to absorb almost all of the seismic energy during strong seismic loads. At this time, it is anticipated that the extreme deflection is concentrated on the first story. So, in addition to the appropriate design of the first story not to collapse during strong earthquakes, it is also required to reduce its

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extreme deflection by some method. The semi-active control system works complementarily to reduce the extreme displacement without much increase of acceleration response. On the other hand, during mild seismic loads, only the semi-active control device works to reduce the displacement caused by the flexibility of the first story.

In this paper, authors experimentally and analytically examined the performance of the proposed seismic design of low to mid-rise buildings with a soft first story subject to semi-active control. At first, the efficiency of the proposed system is shown through numerical analyses. In the analyses, a 5-DOF shear model was used in order to simulate a low to mid-rise building with a soft first story. Next, the feasibility of the proposed system was examined experimentally. In a series of experiments, mortar test pieces were used as the RC column of the soft first story, and a dynamic hydraulic jack was used to simulate the role of a capacity adjustable viscous damper.

SEMI-ACTIVE CONTROL ALGORITHM

In almost all of the active vibration control methods developed for building structures, displacement, velocity and acceleration are mainly selected as the controlled variables. In contrast to this, a story shear force is selected as a controlled variable in the proposed algorithm. The control force (or viscosity of the damper) is determined based on a hysteresis loop of the story into which the damper is installed. Equation (1) shows the control algorithm. The control force is fundamentally decided at the value by which the story shear force becomes a constant value F_{max}. This simple control algorithm corresponds to maximizing absorbed energy under the condition that the story shear force remains within a specified bound. On the occasion that the total story shear force does not reach F_{max} by the limitation of the damper's coefficient C_{max}, C_{max} is used as the damper's coefficient. In this paper, the minimum coefficient of the damper is assumed to be zero.

$$c = \begin{cases} c_{\min} & c_0 \le c_{\min} \\ c_0 & c_{\min} < c_0 < c_{\max} \\ c_{\max} & c_0 > c_{\max} \end{cases} \tag{1}$$

where

$$c_0 = \begin{cases} (F_{\max} - F_0)/\dot{x} & \dot{x} > 0 \\ -(F_{\max} + F_0)/\dot{x} & \dot{x} < 0 \end{cases}$$

c: Viscosity of the capacity adjustable damper

$\dot{x}$: Relative velocity of the story

F_0: Shear force in columns

F_{max}: Maximum story shear force in the control

ANALYTICAL STUDIES

To investigate the basic properties of the proposed system, numerical analyses were carried out in which a 5-DOF model (Figure 1) was used as the models of low to mid-rise buildings with a soft first story. Mechanical properties of the models are shown in Table 1. Strength of each story is obtained based on Ai distribution specified in the current seismic design code of Japan. Zoning factor Z, structural characteristics factor Ds, and vibration characteristics coefficient Rt are set to be Z=1.0,Ds=0.3 and Rt=1.0 respectively. Stiffness of each story is assumed to be proportional to the strength of each story. Load-deflection relationship of each story is assumed to be the Degrading-Tri-Linear model (Figure 2) to simulate a reinforced concrete (RC) structure. The stiffness of the first story is reduced to 1/3 of the original value in order to simulate a soft story. This value is chosen to give effective results based on preliminary analyses. Inherent damping of this model is assumed to be zero.

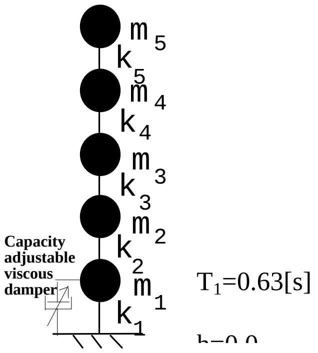


Figure 1: 5-DOF Model

Table 1: Mechanical Properties of the 5-DOF Model

story	Mass [t]	Initial stiffness [KN/m]	Clacking load [KN]	Yield load [KN]
5	20.41	17797.0	36.29	108.9
4	20.41	28886.0	58.90	176.7
3	20.41	37559.0	76.58	229.8
2	20.41	44225.0	90.18	270.5
1	20.41	16043.0	33.33	100.0

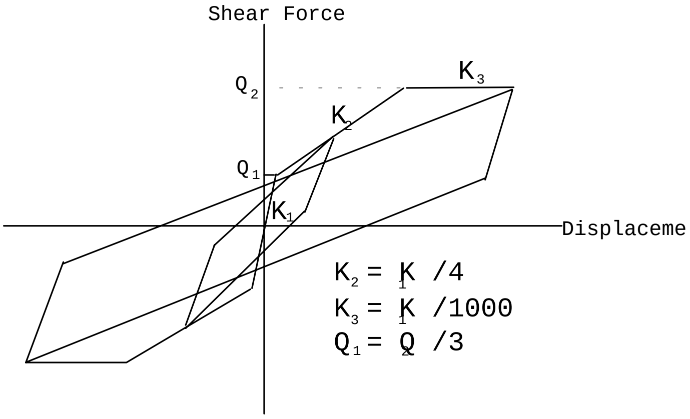


Figure 2: Load-Deflection Relation of the Degrading Tri-Linear Model

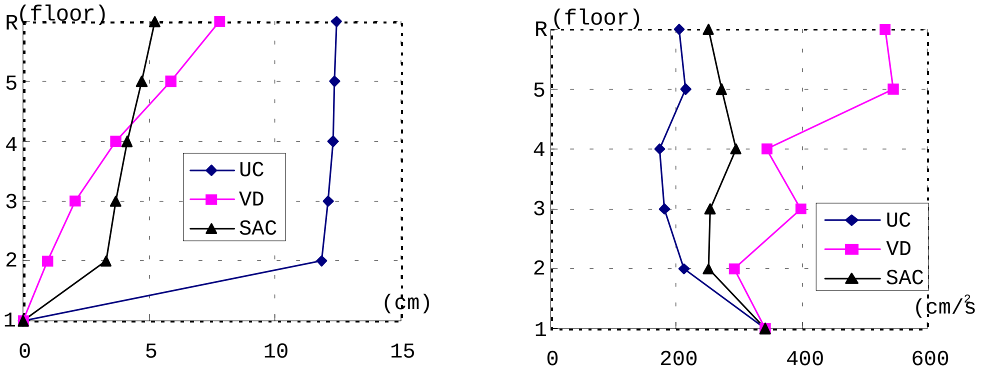
Input ground acceleration used in a series of analyses here is the NS component of the one recorded at EL Centro during the Imperial Valley Earthquake (1940). The maximum acceleration of the input ground acceleration is set to two different values. One is 341cm/s^2 to simulate a strong earthquake ground motion (EL_341) and the other 10cm/s^2 to simulate a small one (EL_10).

Three types of control on the first story is attempted (without control (UC), with semi-active control (SC), and with a passive viscous damper (VD)). The maximum coefficient of both semi-active and passive dampers is chosen to be C_{max}=3000[KN s/m], which corresponds to the addition of a critical damping ratio of 17% to the first mode of the structure. The maximum story shear force aimed in the control is set at 100[KN], which is equivalent to the yield load of the first story.

Figure 3 shows the maximum response exposed to EL_341. The comparison of hysteresis loops is shown in Figure 4. In (UC), extreme deflection concentrates on the first story, which may cause story collapse. In (VD), large displacement of the first story is not shown and the distribution of deflection is almost uniform along the stories. Although, acceleration response is increased to the significant level which may induce the falling down of facilities and contents in the structure. In (SC), on the other hand, it is found that the displacement of the first story is reduced to almost the uncontrolled one appropriately without much increase of acceleration response.

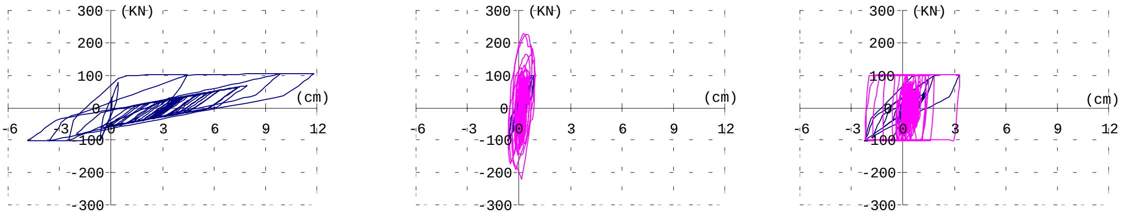
Figure 5 shows the maximum response exposed to EL_10. The comparison of hysteresis loops is shown in Figure 6. In these results, response of (SC) is perfectly equal to that of (VD) because the maximum value C_{max} is constantly chosen as the coefficient of capacity adjustable damper during the earthquake. That is, the total shear force of the first story does not reach the determined force F_{max}.

From these results, it is founded that the proposed system works as the passive viscous damper in small disturbances, and the damping coefficient is changed in order to reduce acceleration response appropriately during only strong ones.



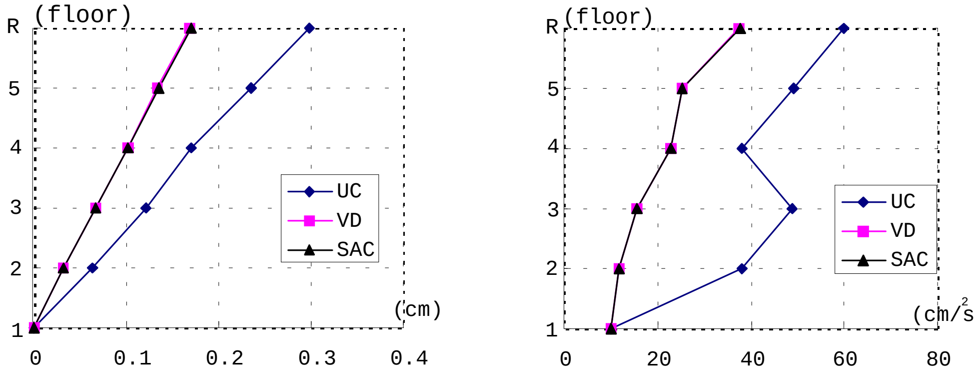
(a) Displacement (b) Acceleration

Figure 3: Maximum Response of the Model Exposed to EL_341
(UC: Un-Controlled, VD: Viscous Damping, SAC: Semi-Active Control)



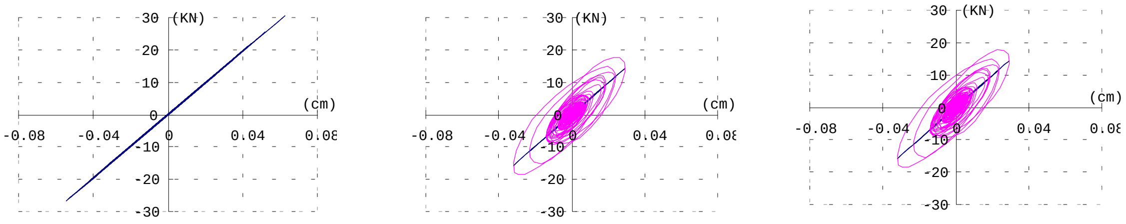
(a) UC (b)VD (c)SAC

Figure 4: Comparison of Hysteresis Loops of the First Story of the Model Exposed to EL_341



(a) Displacement (b) Acceleration

Figure 5: Maximum Response of the Model Exposed to EL_10
(UC: Un-Controlled, VD: Viscous Damping, SAC: Semi-Active Control)



(a) UC (b) VD (c) SAC

Figure 6: Comparison of Hysteresis Loops of the First Story of the Model Exposed to EL_10

EXPERIMENTAL STUDIES

Outline of Experiments

In this section, the feasibility of the proposed system is experimentally verified. Mortar test pieces are used as substitution of reinforced concrete (RC) columns and a dynamic hydraulic jack is used to simulate the roles of a capacity adjustable viscous damper.

Loading System

An experimental loading system is shown in Figure 7. As shown in this figure, the mortar test piece is put between 200KN and 30KN dynamic hydraulic jacks, and loading is done by the 200KN one. The 30KN dynamic hydraulic jack is used to simulate the capacity adjustable viscous damper based on the proposed semi-active control algorithm. In addition, the control to simulate the passive viscous damper is done to compare with the proposed method.

Specimen

Figure 8 shows details of the mortar test piece. To simulate the RC column, axial force corresponding to 1/6 of the compressive strength is applied to both ends of the test piece by means of a rubber bushing and an unbonded prestressing bar before each loading.

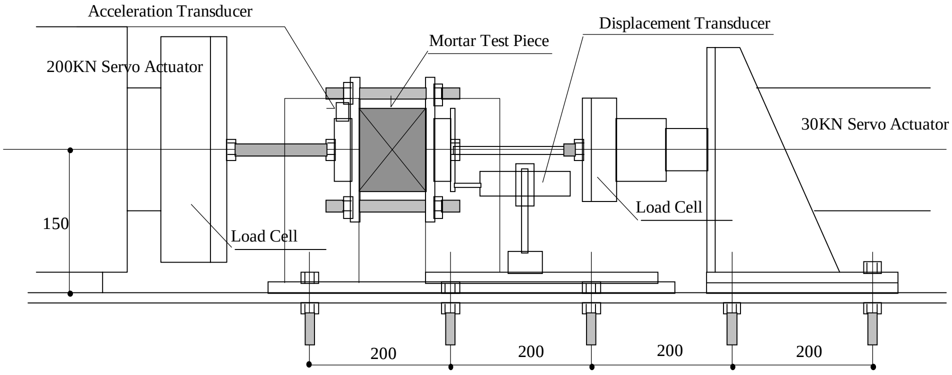


Figure 7: Loading system

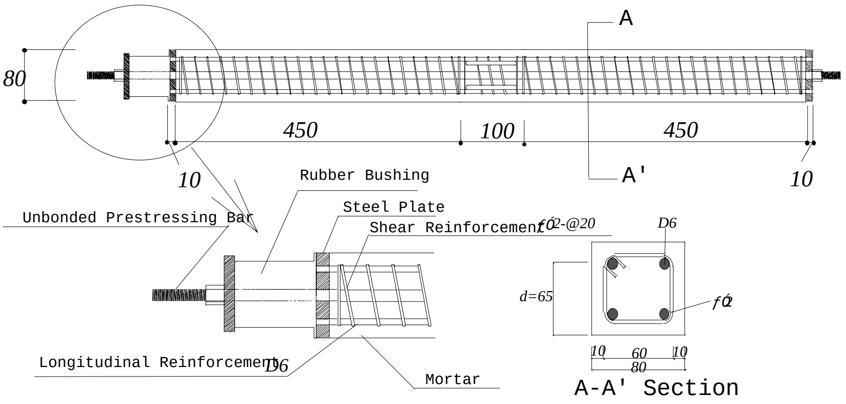


Figure 8: Details of the Reinforced Mortar Test Piece

Type of Loading

Two types of loading are carried out with a 200KN dynamic hydraulic jack. One is by displacement control and the other by load control. In both loadings, harmonic and random loading were done.

Random waves were obtained based on the seismic response analysis with the 5-DOF analytical model (Figure 1) subject to the NS component ground motion recorded at El Centro during the Imperial Valley Earthquake in 1940 (El Centro NS(1940)). Maximum values of both random and harmonic waves are changed appropriately.

Results of Experiments

Displacement Control

At the beginning, loadings by displacement control were carried out with the 200KN actuator. The maximum displacement of the harmonic wave is set to four times the yield point displacement of the test piece. The frequency is 0.86[Hz].

The random wave is shown in Figure 9. Total shear force F_{max} in the semi-active control is set to 16KN which is equivalent to the bending yield load of the test piece.

Figure 10 shows the comparison of hysteresis loops obtained in the experiments. In the viscous damping control, the total shear force tends to increase in accordance with the increase of displacement in both harmonic and random excitements, and the maximum loads exceed 20[KN]. In semi-active control, on the other hand, it is found that the story shear force is so controlled as to remain within a specified bound appropriately. The story shear force tends to converge at about 20[KN]. Here, the maximum shear load actually obtained is about 20[KN], and it differs from F_{max}(=16[KN]). This is due to the initial offset load.

Hysteresis loops obtained from analyses are shown in Figure 11. Good agreement between experimental results and analytical ones is confirmed.

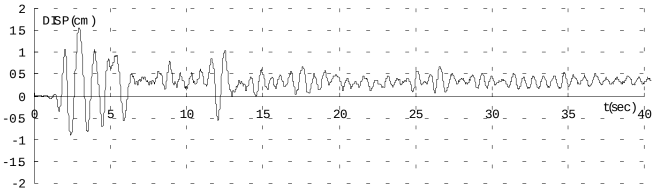
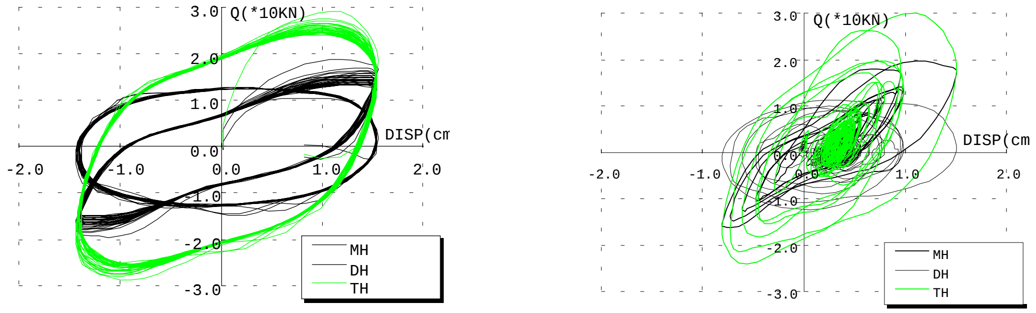
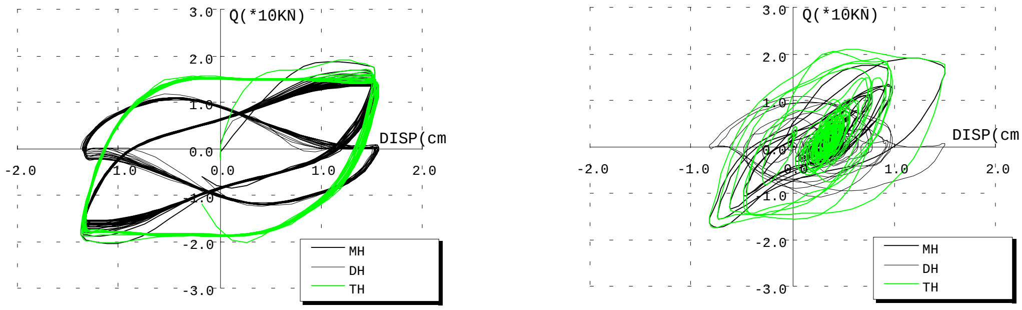


Figure 9: Time History of Input Random Displacement



(i) by Harmonic Loading **(ii) by Random Loading**

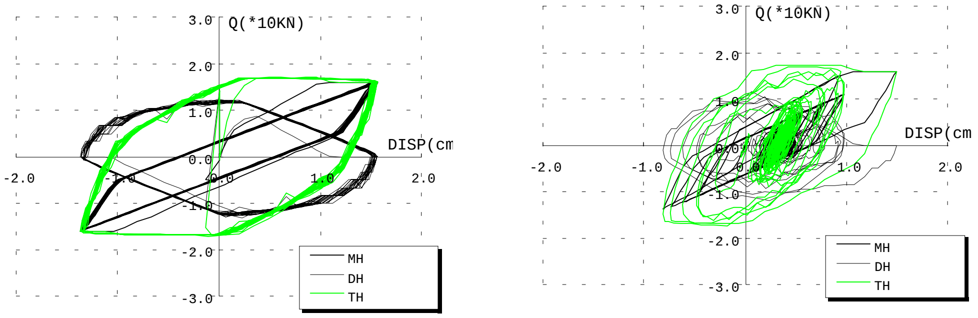
(a) with Viscous Damping Control



(i) by Harmonic Loading **(ii) by Random Loading**

(b) with Semi-Active Control

Figure 10: Hysteresis Loops by Experiments
(MH: Member's Hysteresis, DH: Damping Hysteresis, TH: Total Hysteresis)



(i) by Harmonic Loading **(ii) by Random Loading**

Figure 11: Hysteresis loops by Analyses (with Semi-Active Control)
(MH: Member's Hysteresis, DH: Damping Hysteresis, TH: Total Hysteresis)

Load Control

In the same way as displacement control, a series of excitements by load control was carried out with the 200KN actuator.

Maximum load of the harmonic wave is set at 12.8[KN], which corresponds to 4/5 of the yield load of the test piece, and the frequency is set at 0.8[Hz]. In the harmonic loading, F_{max} is set at 8.0[KN].

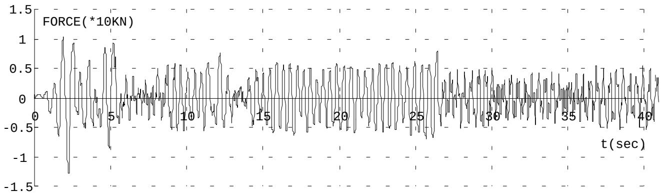
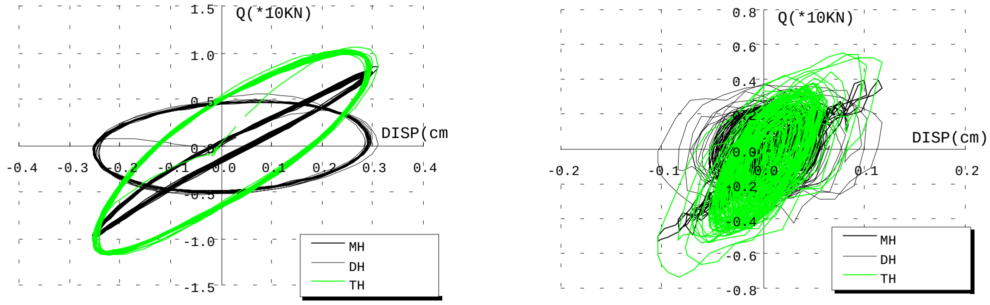
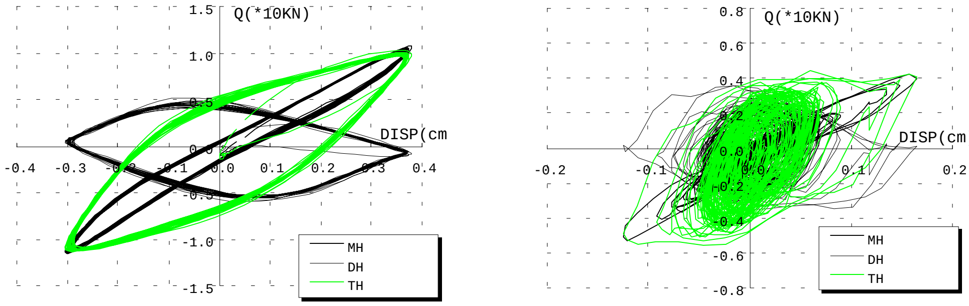


Figure 12: Time History of Input Random Load



(i) by Harmonic Loading **(ii) by Random Loading**

(a) with Viscous Damping Control



(i) by Harmonic Loading **(ii) by Random Loading**

(b) with Semi-Active Control

Figure 13: Hysteresis Loops by Experiments
(MH: Member's Hysteresis, DH: Damping Hysteresis, TH: Total Hysteresis)

The random wave obtained from the seismic response analysis with El Centro NS(1940) is shown in Figure 12. In the random loading, F_{max} is set at 5.0[KN].

Figure 13 shows hysteresis loops obtained from experiments. It is found that the maximum displacement in the semi-active control is greater than that in the viscous damping control, which depends on the fact that the hysteresis energy in the semi-active control is smaller than that in the viscous damping control. On the other hand, it is also found that the total shear force in the semi-active control tends to remain within a constant value. The properties of the proposed system to suppress extreme shear force (i.e. acceleration response) without much increase of the displacement response are verified.

CONCLUSIONS

In this paper, the effectiveness of the proposed seismic design for low to mid-rise buildings with a soft first story was studied. In order to enhance the overall safety of the building against various kinds of disturbances, a capacity adjustable viscous damper is installed into the first story. The semi-active control algorithm used in the proposed system aims at maximizing the hysteresis energy absorption under the condition that a story shear force remains within a specified value in order to suppress the acceleration response in the upper stories. The study was performed both analytically and experimentally. Important findings are summarized as follows.

1. The proposed semi-active control system suppresses the extreme displacement of the soft first story without much increase of acceleration response during even strong ground motions. This suggests that the proposed system is effective not only in improving the seismic safety of the structure but also in protecting the contents in the buildings.
2. During small ground motions, the semi-active control system works as the passive viscous damper and improves the habitability of the buildings as well.
3. Through a series of experiments, the feasibility and the applicability of the proposed system is confirmed because good agreement between experimental results and analytical ones was confirmed.
4. The proposed system has a great potential to grade up the performance of low to mid-rise buildings exposed to various types of seismic loads.

REFERENCES

1 Gavin, H. P. and Hanson, R. D. (1998), “Seismic Protection using ER Damping”, *Proc. of the 2nd World Conference on Structural Control,* pp.1183-1190

2 Hama, T. , Iwata, N. and Soda, S. (1997),”Seismic design of buildings with semi-active capacity adjustable viscous damper controlling shear force”, *Summaries of Technical Papers of Annual Meeting of AIJ,* B-II,pp.755-756

3 Iwata, N. , Hama, T. and Soda, S. (1999),”Seismic Control of the Soft-First-Story Building by Shifting Method in Sliding Mode Control”, *Journal of Structural and Construction Engineering,* AIJ, No. 516, pp.83-90

4 Kurata, N. , Kobori, T. , Takahashi, M. and Niwa, N. (1998), “Semi-Active Damper System in Large Earthquakes”, *Proc. of the 2nd World Conference on Structural Control,* pp.359-366

5 Niwa, N. , Kobori, T. , Takahashi, M. , Matsunaga, Y. , Kurata, N. and Mizuno, T.(1998), “Application of Semi-Active Damper System to an Actual Building”, *Proc. of the 2nd World Conference on Structural Control,* pp.815-824

6 Spencer Jr. , B. F., Dyke, S. J., Sain, M. K. and Carlson, J. D. (1997), “Phenomenological Model for Magnetorheological Dampers”, *Journal of Engineering,* ASCE, 123(3), pp.230-238

7 Yi, F., Dyke, S. J., Frech, S., and Carlson, J. D. (1998), “Investigation of Magnetorheological Dampers for Earthquake Hazard Mitigation”, *Proc. of the 2nd World Conference on Structural Control,* pp.349-357