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Experimental study on overall flexural deformation response control for smart high-rise structures

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Abstract

This paper discusses seismic response control of high-rise building utilizing magneto-rheological fluid damper (MR damper). Generally, during earthquake, high-rise buildings show not only shear deflection which occurs in inter-story must be taken into account, also the flexural deformation which is caused by column elongation must be considered. Some previous researches have proposed of protective system for such high-rise buildings based on a flexural deformation using some passive viscous dampers set in vertical direction of the building. Our challenges discuss the seismic response control for such high-rise buildings base on the flexural deformation using a variable damper. As a feasible study, we have conducted shaking table tests for a scaled bending-shear model with one mass system and scaled MR damper model set in vertical directions of the model. In this study, ON/OFF control algorithm that switched by damper response is adopted, and the reduction of response acceleration is discussed. A mechanical bending-shear model, which shows a behavior of bending vibration of a high-rise building is considered in this study. A cantilever (bending spring) is a principal member for the model. A suppress spring restricts rotational movement of the top of the model. A variable damper has been set into the vertical direction to control rotational motions of the system. The variable damper is switched ON or OFF during earthquake response. Damper becomes "stiff" when damper is switched ON. And the damper becomes "soft" when damper is switched OFF. We have conducted shaking table tests of our scaled bending-shear model inputted several observed ground motions. The variable damper force nine times larger than the force without magnetic field when 1.5 amps exciting currents is applied. As a result of tests, it is clear that ON/OFF control can reduce the maximum response well at the view point of acceleration response. In the case of passive ON, slightly larger response vibration continues under shorter period after maximum response. This control method is not cause of shortened natural period of the system and suppresses the increase of response acceleration. It shows that ON/OFF control has high efficacy to reduce mean average response acceleration and displacement during earthquake. It is expected that proposed control method would be a useful technique to control vibration of high-rise buildings where bending deformation is dominant.

Keywords: seismic response control, flexural deformation, MR damper

1. Introduction

During earthquake, high-rise buildings show not only shear deflection which occurs in inter-story must be taken into account, also the flexural deformation which is caused by column elongation must be considered. Thus, some previous researches have proposed of protective system for such high-rise buildings based on a flexural deformation using some passive viscous dampers set in vertical direction of the building.

Y.Shinozaki (2008) [1] developed response control system with intensive energy absorption devices. In this technique, vibration control system is divided into energy absorbing members and vertical support members. Steel dampers and oil dampers are incorporated as the seismic response control devices which can absorb most of all of the seismic response energy. Y.Omika (2004) [2] proposed the flexural deformation response control system. In this system, a horizontal force caused by earthquake or winds is resisted by the core wall which is located at the center of the plan. The horizontal behavior excites the rotational motion of top beam. A viscous damper is set in vertical direction of top beam. The force of viscous damper is expected to reduce rotational response of top beam.

On the other hand, several semi-active control systems, which controls structural characteristics according to vibration condition are proposed in base isolate systems and vibration control system. A Magneto-rheological fluid (MR) damper is used as one of the variable damper. MR damper can change its viscous characteristics by magnetizing. An exciting coil adopted in MR damper performs its viscous characteristics to change by exciting currents. Example of study on semi-active vibration control by MR damper installed in base-isolated layer has been reported (*e.g.* [3]). H.Kanno (2008) [4] has studied semi-active control by MR damper, and suggested a simple control method due to response displacement of inter-story level of structure. In this research, the simple control scheme for reduction of response acceleration and its influences of damper support member stiffness are already verified in those studies.

This paper discusses the semi-active seismic response control for such high-rise buildings base on the flexural deformation using a variable damper. As a feasible study, we have conducted shaking table tests for a scaled bending-shear model with one mass system and scaled MR damper model set in vertical directions of the model. In this study, ON/OFF control algorithm that switched by damper response is adopted, and the reduction of response acceleration is discussed.

2. Structural model and outline of the control method

2.1 Structural model with controllable damper

Bending shear model, which shows a behavior of bending vibration of a high-rise building is shown in Fig.1. A cantilever (bending spring) is a principal member for the model (in this figure, EI refers to bending stiffness). A limit spring (k_r) restricts rotational movement of the top of the model. Therefore the model behaves as a shear system, when the limit spring is enough stiff. A Controllable damper (in this study, MR damper is used as the controllable damper) is set into vertical direction connecting by pins as same as the limit spring connection. It should be note that MR damper is modeled in Bingham model, in which friction slider element (F_c) and dashpot (C_d) are connected in parallel. In this Figure, m means a mass of the system and I_m means a rotational inertia of the system.

A configuration of bending shear model that produced in this study is shown in Fig.2. The height of the model is 687mm, and flexible length of cantilever element is 600mm. A flat steel slab installed on top position is 300mm wide and 500mm long. The flat steel slab is regarded as a mass of 29.4kg.

Both of the limit spring and the MR damper are installed in a vertical direction connecting by bearings. The supporting member of MR damper has 10mm thickness which is enough stiff compared with the limit spring. The cantilever is made of phosphor bronze, which size is 120mm wide and 5mm thick. The limit spring is made of steel plate which size is 30mm wide and 2.3mm thick. From material tests, modulus of longitudinal elasticity of the phosphor is 5.8×10^4N/mm^2, stiffness of limit spring is 11.0N/mm.

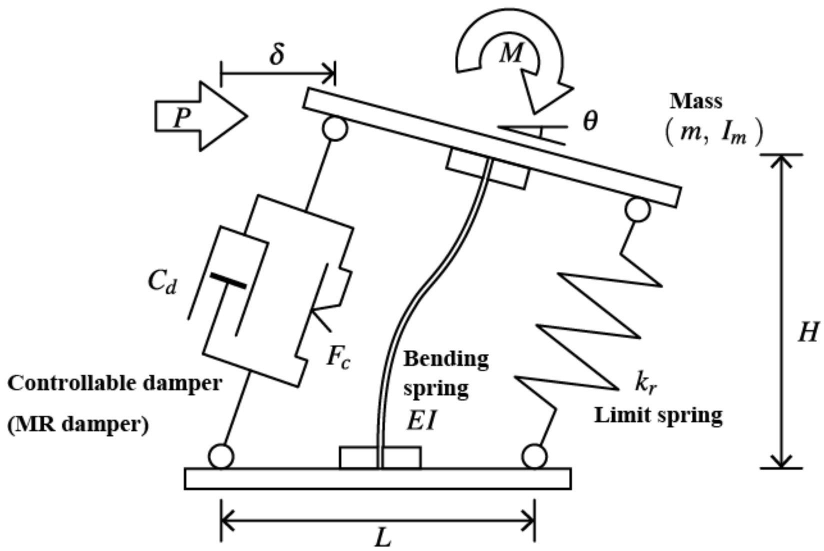


Fig. 1 – Structural bending shear model with controllable damper

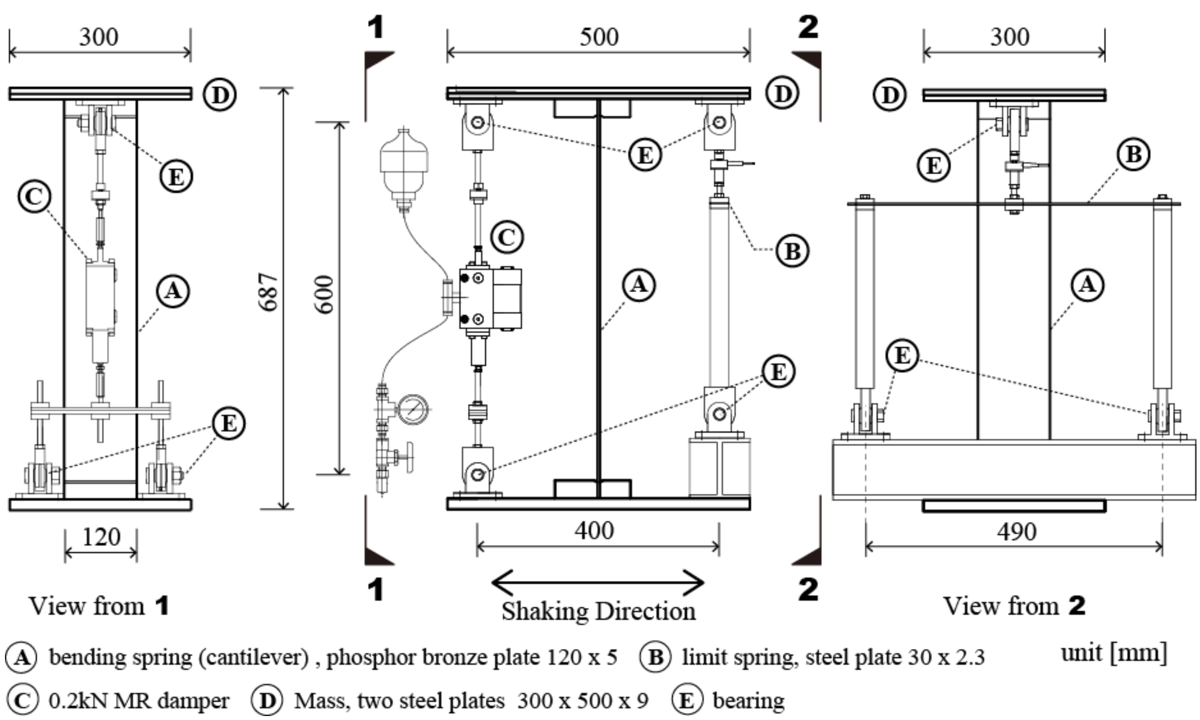


Fig. 2 – Configuration of tested one-mass bending shear model with MR damper

2.2 Properties of the MR damper

Sodeyama *et al*. (2004) [5] have proposed MR dampers, which have a bypass-flow type magnetizing mechanism. The MR dampers developed by them have a bypass portion in which the electromagnets are installed. The MR fluid passing through the narrow orifice in the bypass portion is applied the magnetic field by electromagnets.

In this paper, the bypass-type MR damper which has a capacity of 0.2kN was used. The schematic structure of the MR damper is shown in Fig.3. The piston stroke is 42mm. As a hydraulic oil, MRF-132DG developed by Load Corporation is used. The MR fluid was enclosed in the cylinder and the bypass portion.

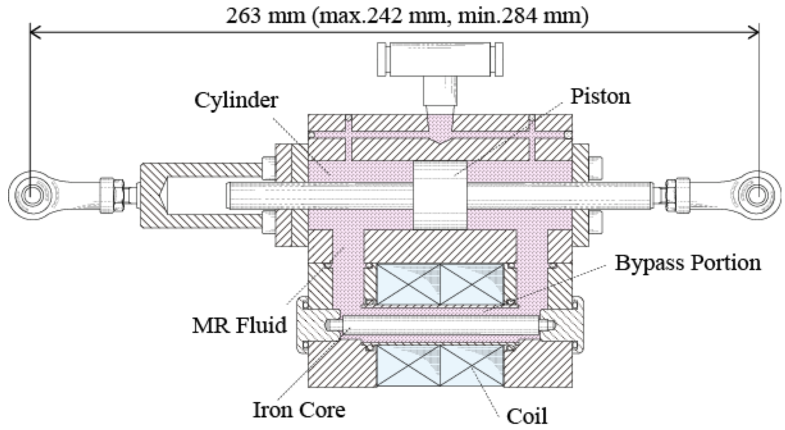
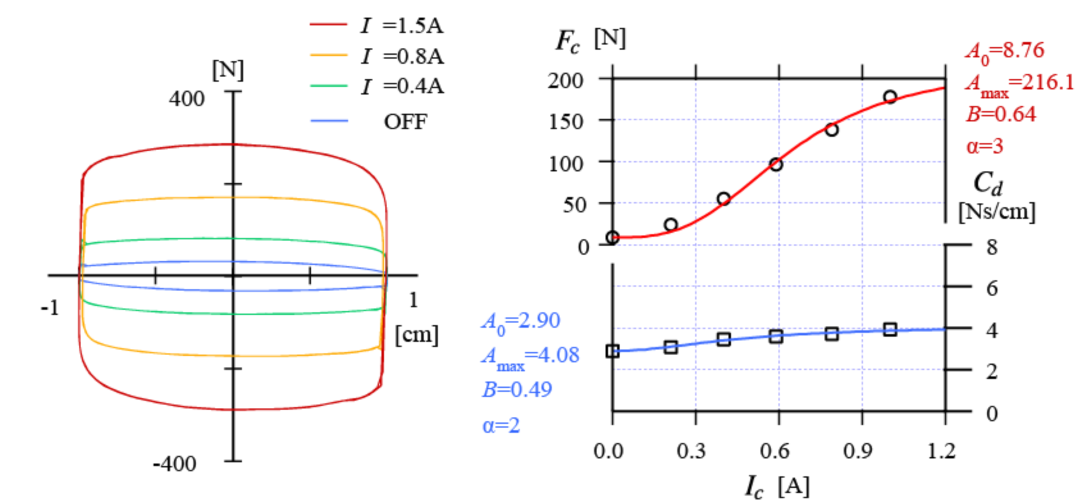


Fig. 3 – Schematic of 0.2kN MR damper

The cyclic loading tests were carried out to clarify the fundamental dynamic characteristics of the MR damper. Fig.4 shows displacement-force hysteresis loops and damper properties (F_c and C_d) as a function of exciting currents I_c. These are measured under the sinusoidal loading conditions as following: amplitude 10 mm; piston velocity 10 cm/s. Variable damper force becomes nine times larger than the force with free field (exciting current is OFF) when 1.5 amps constant exciting currents is applied. In this study, only F_c is taken into account under the semi-active control. The rigid red line in Fig.4 (b) indicates the predicted performance at the semi-active control. The predicted line is approximated by the Hill function as following

$$F_c = (A_{\max} - A_0)\times\frac{I_c^{\,a}}{I_c^{\,a} + B^a} + A_0 . \tag{1}$$



(a) Hysteresis loops inputted sinusoidal loading (b) Damper properties as a function of exciting current

Fig. 4 – Hysteresis loops and damper properties

2.3 Outline of the control method

The frictional force of the variable damper was controlled according to the ON/OFF control. In ON/OFF control, exciting currents is switched free field (OFF) or certain constant currents (ON) is adopted. The method of switching exciting currents is determined by damper velocity (v) and displacement (δ_d). MR damper switched ON when the sign of damper velocity and displacement are different. MR damper switched OFF when the sign of those are same. In the relationship between damper force and displacement as shown in Fig.5, exciting currents turned ON when the relationship is in second and forth quadrant, and turned OFF when the relationship is in first and third quadrant. This control method is not cause of shortened natural period of the system and suppresses the increase of response acceleration.

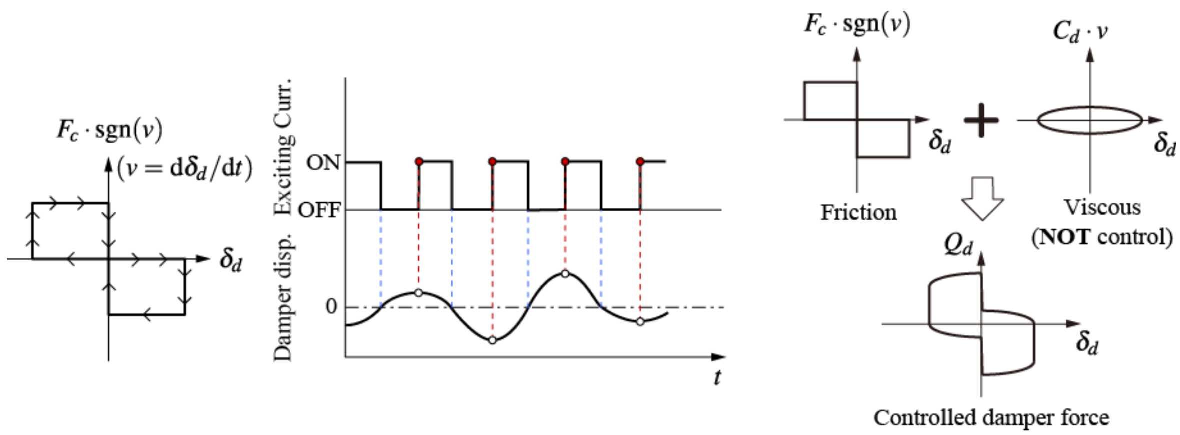


Fig. 5 – Diagram of ON/OFF control scheme

To examine the performance of the proposed control scheme under seismic excitations, numerical analysis based on equivalent linearization method were conducted. In this research, the case of inputted constant exciting current (called passive ON) is also examined to be compared with ON/OFF control. When the dashpot of the controllable damper is ignored such as shown in Fig.6, the equation of the motion is express as follows.

$$\begin{Bmatrix} P \\ M \end{Bmatrix} = \begin{bmatrix} s & -u \\ u & r \end{bmatrix} \begin{Bmatrix} \delta \\ \theta \end{Bmatrix} \tag{2}$$

P is a lateral force, M is a rotational moment, δ is a lateral displacement and θ is a rotational angle of top of the mass. Values of s, u, r is a stiffness matrix are given by

$$s = \frac{12EI}{H^3} \quad u = \frac{6EI}{H^2} \quad r(\theta) = K_R(\theta) + \frac{4EI}{H} \tag{3}$$

K_R as a function of θ is a rotational stiffness of the apparent according to the friction force F_c of the damper defined as

$$K_R(\theta) = \frac{k_r L^2}{4} + \frac{F_c L}{2\theta}. \tag{4}$$

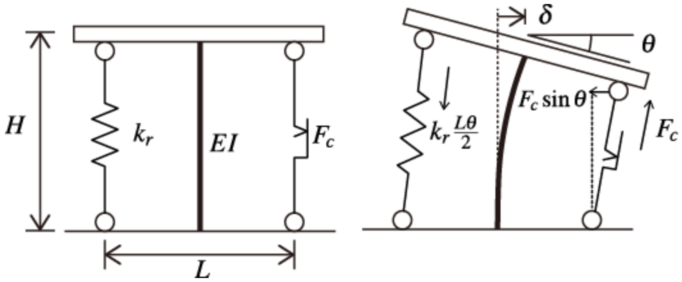


Fig. 6 – Simplified bending shear model with friction element in use of the equivalent linearization method

By placing M=0, θ and P can be obtained as following

$$\theta = \frac{u\delta}{r'} - \frac{F_c L}{2r'} \tag{5}$$

$$P = \left(s - \frac{u^2}{r'}\right)\delta + \frac{F_c L}{2r'} u \tag{6}$$

where $r' = \frac{k_r L^2}{4} + \frac{4EI}{H}$.

Considering stationary response of the system, if the friction force is assumed to act only sine component of the rotation angle as shown in Fig.7, equivalent damping factor h_{eq} and equivalent natural period T_{eq} can obtained as follows.

$$h_{eq} = \frac{1}{4\pi} \times \frac{\Delta W}{W_e} + h_0 = \frac{1}{\pi} \times \frac{2F_c \sin\theta}{P + F_c \sin\theta} + h_0 \tag{7}$$

$$\frac{T_{eq}}{T_0} = \sqrt{\frac{P}{P + F_c \sin\theta}} \tag{8}$$

Where h_0 is a damping factor of whole of system and T_0 is natural period when F_r=0.

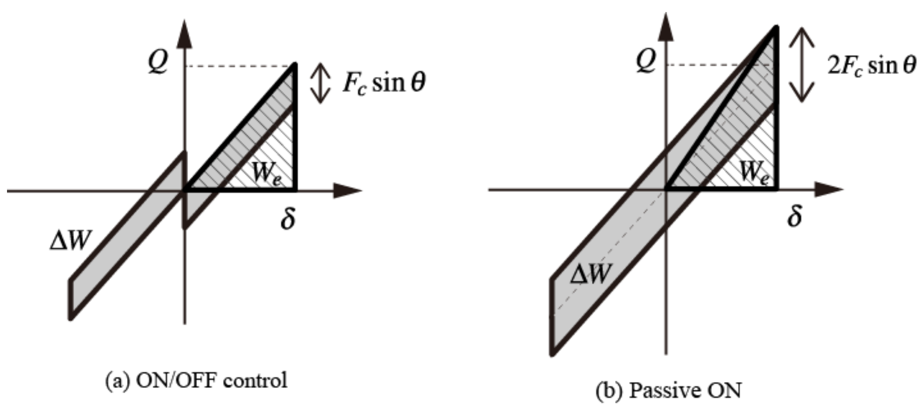


Fig. 7 – Force-displacement relationship under stationary response

To calculate the response reduction factor due to the friction element (damper force), assuming the earthquake response spectrum, such as Fig.8, velocity response spectrum is assumed to be a constant. When the frictional force (F_c) is controlled, the maximum response reduction ratio R_d and R_a are defined as the ratio of the maximum response in case of F_c = 0 (called as passive OFF).

$$R_d = D_h \frac{T_{eq}}{T_0} \qquad R_a = R_d \left(\frac{T_0}{T_{eq}} \right)^2 \tag{9}$$

Where D_h indicates a damping effect factor, which is introduced by Kasai *et al.*(2003)[6]. Under constant velocity response spectrum region, D_h is given by

$$D_h = \sqrt{\frac{1+10h_0}{1+10h_{eq}}} \ . \tag{10}$$

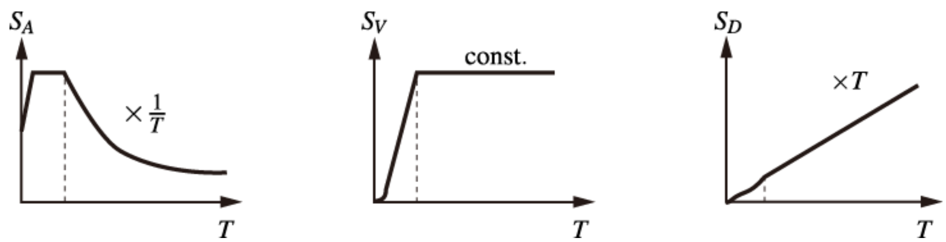


Fig. 8 – Typical seismic response spectrum for equivalent linearization method

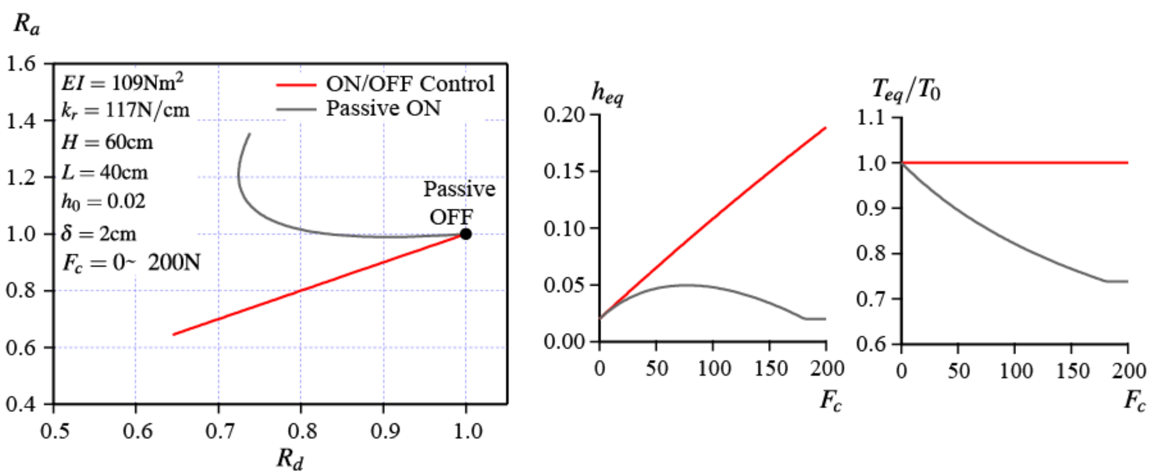


Fig. 9 – Evaluations of seismic response reductions using equivalent linearization method

Fig.9 shows predicted maximum response displacement and acceleration curves under the ON/OFF control compared with the passive ON. Proposed ON/OFF control scheme appears to be more effective in response reducing than passive ON. Under ON/OFF control, maximum response has a tendency to reduce response by increasing F_c. However, in the case of passive ON, these tendency shows to be bottoming out from a certain value of F_c. It's caused by the shortening rotational periods by F_c as shown in the figure. Under ON/OFF control, the change of natural period is rarely appeared and equivalent damping factor h_{eq} becomes large by increasing damper force F_c.

3. Shaking table tests

Shaking table tests have been carried out to examine a reduction effectiveness of seismic response using by the ON/OFF control method. A diagram of control system is shown in Fig.10. The computer installed AD/DA board which is used for control scheme. A feedback signal of main structure is only damper displacement. Switching ON/OFF control is determined by sign of damper velocity get from time derivative of damper displacement. The control signal, which is used a voltage considering the electrical resistance of MR damper, is 7 times larger through the amplifier. Damper displacement is measured at sampling frequency of 1 kHz, and the control is performed at 100Hz. As shown in Fig. 11, five observed strong ground motions and a simulated earthquake were used for input ground motions. These observed ground motions are records of El Centro (1940 Imperial Valley eq.), Hachinohe harbor (1968 Tokachi-Oki eq.), Japan Meteorological Agency (JMA) at Kobe (1995 Hyogoken-Nanbu eq.) and K-NET (a nation-wide strong-motion seismograph network managed by NIED, Japan) observation site in Sendai city and Tokyo (Shinjuku) at 2011 Tohoku-Chiho Taiheiyo-Oki eq. As a simulated earthquake, artificial design wave proposed by BCJ (The Building Center of Japan) is used. The direction of the shaking is uniaxial direction, in which the square root of the sum of the squares of the records of the north-south direction and the east-west direction is the maximum. These six ground motion were normalized so the response level is almost same when the exciting current to the MR damper turned OFF (passive OFF). Table 1 shows properties of six input ground motions.

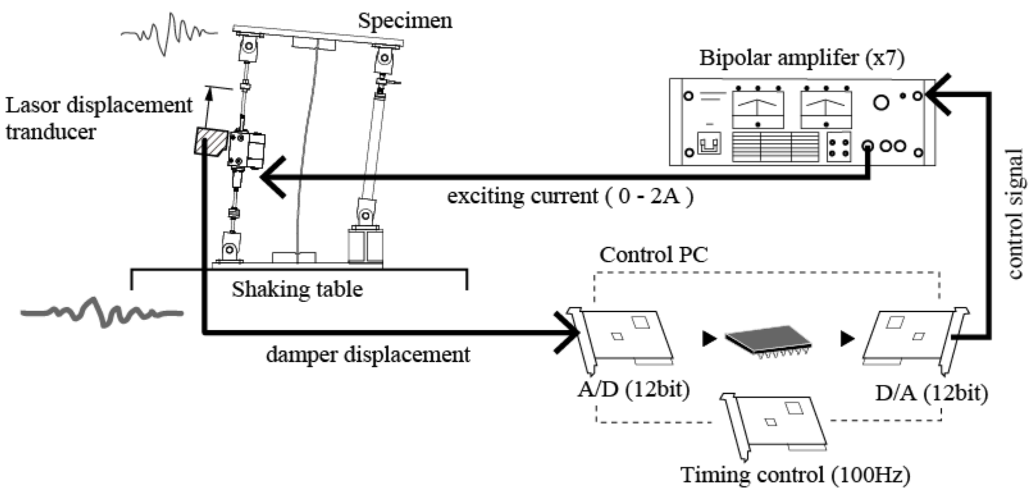


Fig. 10 – Diagram of the control system

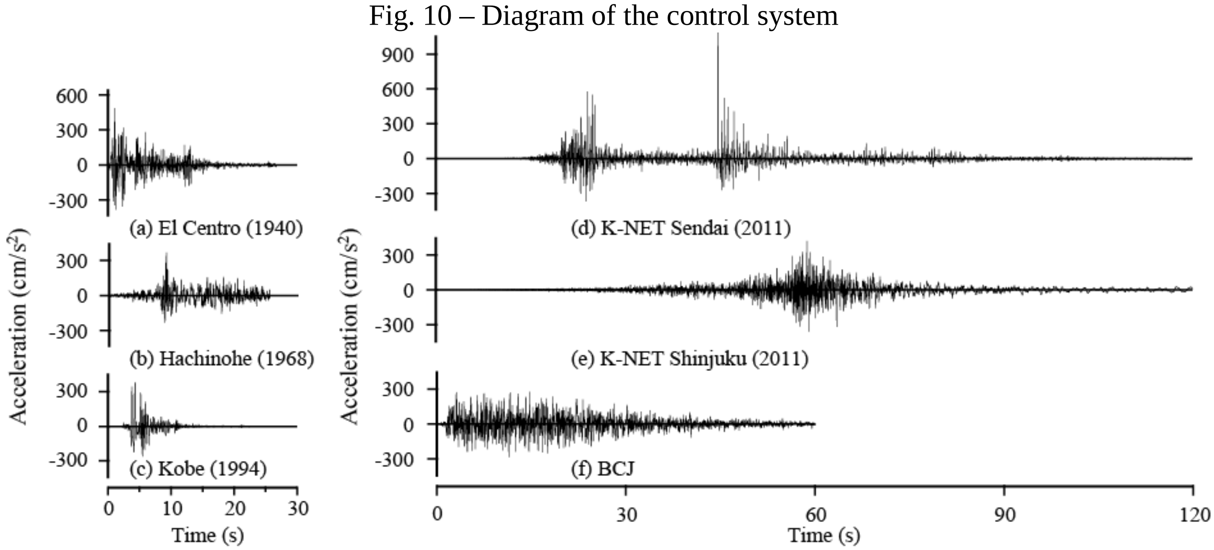


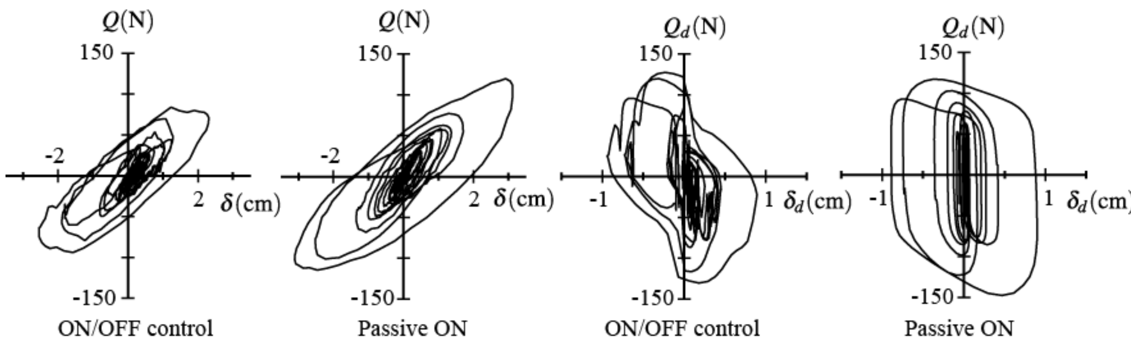
Fig. 11 – Six inputted ground motions

Table 1 – Properties of inputted ground motions

Name	Earthquake	Date	Amp.	A_{max} (cm/s^2)	V_{max} (cm/s)
El Centro	Imperial Valley Eq.	1940.5.18	x 1.40	476.3	27.9
Hachinohe	Tokachi-Oki Eq.	1968.5.16	x 1.60	371.5	28.3
JMA Kobe	Hyogo-Ken Nanbu Eq.	1994.1.17	x 0.45	382.3	23.4

K-NET Sendai	2011 Tohoku-Chiho Taiheiyo-Oki Eq.	2011.3.11	x 0.60	970.4	19.1	
K-NET Shinjuku			x 2.20	425.9	20.2	
BCJ	Artificial design wave by BCJ		x 0.80	280.8	21.2	Level 2

The relationships between displacement δ and inertia force Q and the relationships between damper displacement δ_d and damper force Q_d are shown in Fig.12. Inertia force of system is calculated from horizontal acceleration multiplied by mass. Hysteresis loop of ON/OFF control (relationships between δ_d and Q_d) shows that proposed control can draw intended hysteresis. According to the relationship between inertia force and displacement, ON/OFF control performs that the peak of inertia force is smaller than the case of passive ON. It suggests that high efficacy reducing response acceleration corresponds to proposed control method.



(a) Inertia force vs horizontal displacement (b) damper force vs damper displacement

Fig. 12 – Hysteresis loops compared between ON/OFF control and passive ON (under the condition of Kobe (1994), inputted 0.5 amp exciting current)

Fig. 13 shows maximum response displacement and acceleration comparing ON/OFF control and passive ON. In this figure, color lines shows response spectrum (S_A-S_D contour) under damping factor of from 2% to 25%.

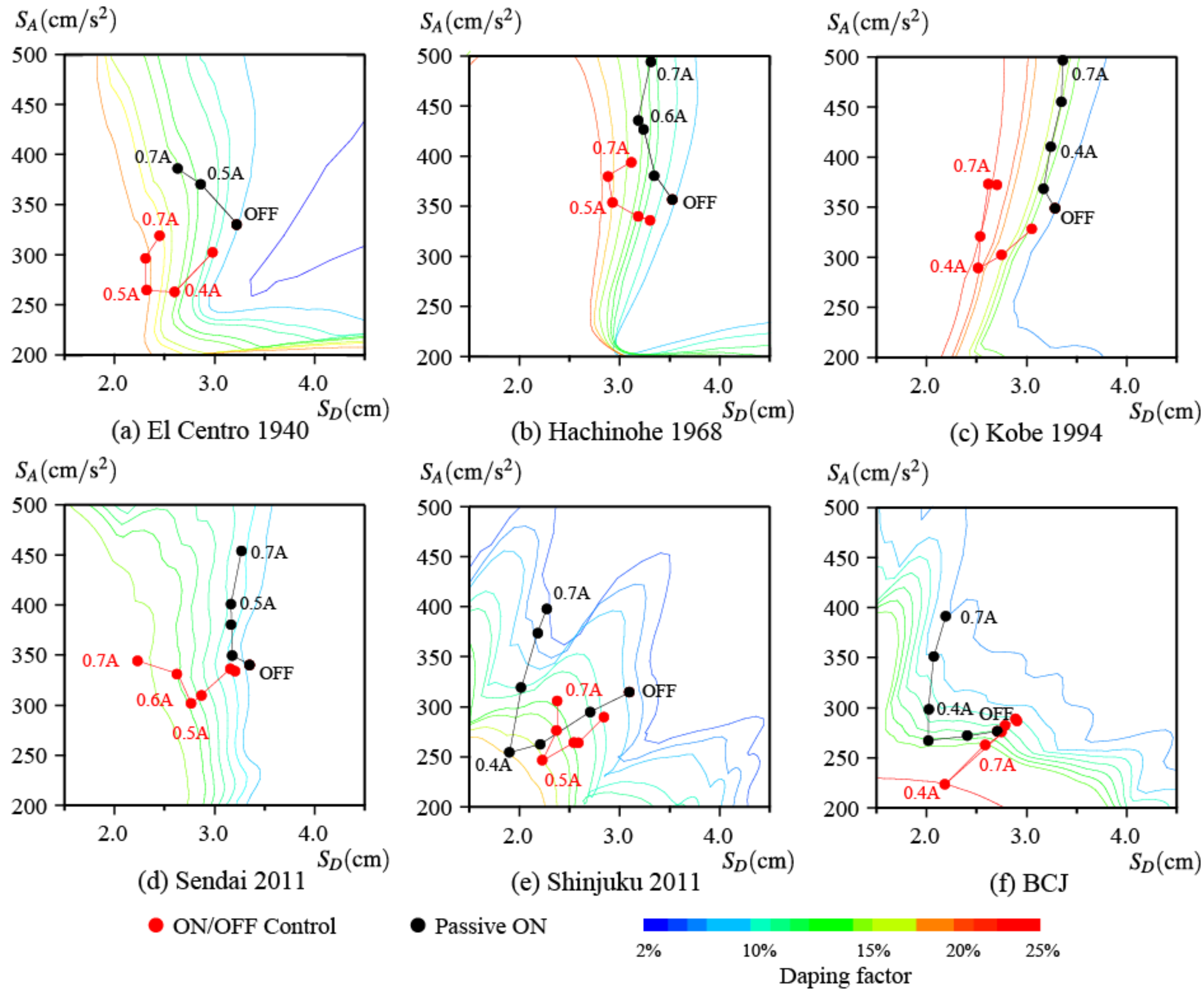


Fig. 13 – Experimental results of maximum response values plotted on the contour of the S_A-S_D

In the case of ON / OFF control, in most of the input ground motion condition, both the maximum response acceleration and the maximum response displacement are reduced with increasing the damping force F_c. In the case of passive ON, with an increase in the damping force F_c, the maximum response displacement are small, however maximum response acceleration show the tendency to increase. In the case of passive ON, with an increase in the damping force Fc, the maximum response displacement is reduced however the maximum response acceleration shows the tendency to increase. When a large exciting current than a certain value is inputted to MR damper, even under the ON/OFF control, increasing tendency of maximum response is observed. This tendency is remarkable in the case of inputted JMA Kobe (1994), although variations of the tendency can be seen depending on the conditions of inputted ground motion. Overall, it can be confirmed that the ON/OFF control can obtain the response reduction effect superior than the passive ON.

Fig.14 shows equivalent period and equivalent damping factor calculated by maximum response values. An equivalent period is calculated by the secant stiffness which connects maximum response value as shown in Fig. 13. An equivalent viscous damping factor is estimated by the intersection of the maximum response point and the response spectrum as shown in Fig.13. The equivalent period, shown in left-hand of Fig. 14, is shortened with an increase in an exciting current (*i.e.* damper force) under the control of passive ON. Comparison with the fact that ON/OFF control is not to shorten the equivalent period of the system. In the right-hand of Fig. 15, the equivalent damping factor increases as damping factor increases under the ON/OFF control, however the damping factor decreases as the damper force crosses a certain value in the case of passive ON. These experimental results correspond to the numerical results using the equivalent linearization method as described above.

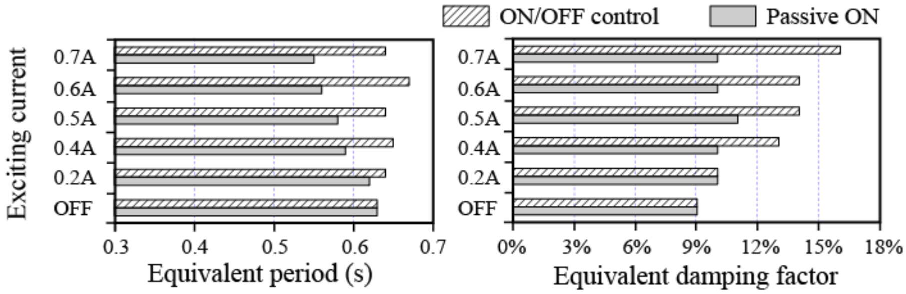


Fig. 14 – Equivalent period and damping factor of the system (Kobe 1994)

4. Conclusion

The bending shear scaled model to simulate the vibration properties of high-rise building was constructed and discussed a simple control method of switch ON/OFF of the damping force in a MR damper subjected to overall flexural deformation response. The response reduction of this scheme was confirmed through the shaking table tests performed on a one-mass bending-shear structure model. The control performance could be predicted by equivalent linearization method discussed here. When the damper is set into rotational direction, natural period of the system is shortened with increasing damping force. This has caused degradation of response control performance of the system. The ON/OFF control is not to shorten the equivalent period of the system. Furthermore, the equivalent damping factor increases as damping factor increases under the proposed control. It suggests that high efficacy reducing seismic response corresponds to proposed control method. It is expected that proposed control method would be a useful technique to control vibration of high-rise buildings where overall flexural deformation is dominant.

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