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Application of Magnetorheological Fluid to Semi-Active Control of Building Structures by BRI and Partners

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Keywords: Magnetorheological (MR) Fluid, Variable damper, Semi-active control, Large-scale shaking table test, Implementation to an actual building

Abstract. This study was aimed at developing an application technology of magnetorhological (MR) fluid with improving the stability of MR fluid. Variable damper using MR fluid (MR damper) has been expected to control the response of building structures in recent years, because of its large force capacity and variable force characteristics. The MR damper changes the controlling force by adjusting the magnetic field with electric current, and can control the damping forces simply. The semi-active control using MR damper stabilizes the response of the building in earthquake better than the conventional passive control. Authors developed some MR dampers and conducted shaking table tests for the research to improve the performance of building structures against earthquake. A 40kN MR damper with 500mm (+/-250mm) stroke was constructed. Authors conducted a shaking table test of the three-story large-scale structure that has an isolated base using MR damper, and the effectiveness of MR damper was verified. Finally, a 400kN MR damper was constructed and installed in an actual base-isolated residential building in order to improve the performance of the building.

Introduction

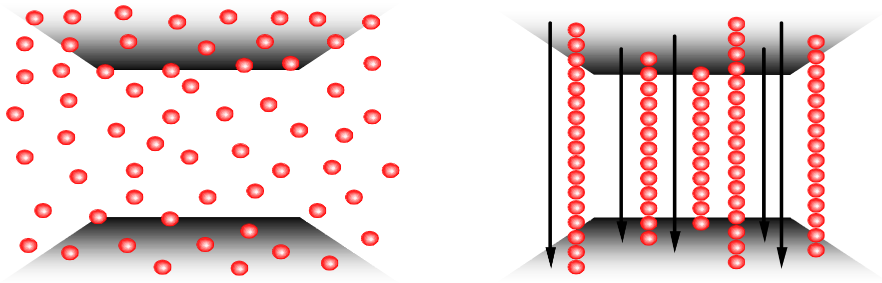
The Building Research Institute (BRI) of Japan and the U.S. National Science Foundation (NSF) initiated the U.S.-Japan Cooperative Research Program on Auto-adaptive Media (Smart Structural Systems) in 1998 [1], under the aegis of the U.S.-Japan Panel on Wind and Seismic Effects of the U.S.-Japan Cooperative Program in Natural Resources. At the Joint Technical Coordinating Committee (JTCC) meeting, research items and plans were discussed in detail for three research thrusts: (1) structural systems, (2) sensing and monitoring technology, and (3) effecter technology.

BRI conducted a series of large-scale tests to verify some smart systems developed in this project [2]. The effectiveness of "Semi-active control by MR dampers", "Damage detection system" and "Rocking energy dissipation system" was confirmed.

This paper outlines the development of MR fluid and MR damper, the large-scale test results of response control of base-isolated building by MR damper and the implementation of an MR damper to an actual residential building. Some researchers worked on semi-active control by MR damper [3, 4]. But such a large-scale test has not been conducted.

Development of Magnetorheological Fluid

Magnetorheological (MR) fluid [5] is a dispersion of fine magnetizable particles in a liquid medium. Their rheological properties can be changed dramatically by applying a magnetic field (Fig.1). This phenomenon was explained that fine magnetizable particles formed anisotropic structures as chains in a liquid medium with applying a magnetic field. The particles were distributed randomly, if it stops applying a magnetic field.



(a) Particles without magnetic field (b) Particles in the magnetic filed

Fig. 1. Magnetic particles in magnetorheological fluid

Authors have been studied the application of controllable dampers for reducing earthquake response of buildings and/or wind induced sway. In general, MR fluid has a problem of the settlement of the particles. In order to improve the stability, authors developed MR fluid *"#230"* with enhanced stability [6]. MR fluid *"#230"* is a hydrocarbon type of MR fluid. Properties of MR fluid *"#230"* are shown in Table 1.

Table 1. Properties of MR fluid *"#230"*

Properties	MR fluid *"#230"*
Base fluid	Hydrocarbon oil
Density	$3.3*10^3$ kg/m^3

The stability of MR fluid is evaluated from sedimentation volume. This is a simple method of measuring sedimentation volume for every time. Stability is defined by Eq. (1).

$$\text{Stability}\ (\%) = V(t)\ /\ V(0) * 100 \qquad (1)$$

$V(t)$: sedimentation volume (cm^3) after t min.

$V(0)$: original sedimentation volume (cm^3)

Fig. 2 shows the result of the stability. The sedimentation is hardly observed for 1 month. The level of stability is about 96% for 1 month. So, MR fluid *"#230"* has the good stability. The MR fluid *"#230"* was developed by the third author.

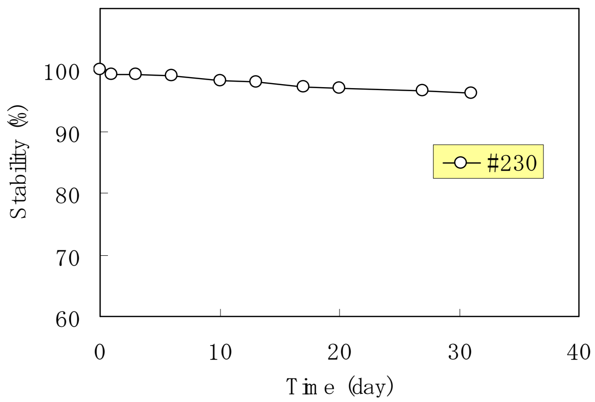


Fig. 2. Stability of MR fluid

Development of MR damper

The second author of this paper developed a MR damper used in the experimental test of base isolation system. The design of the bypass-flow-type MR damper is shown in Fig. 3 and Table 2. It is composed of three parts: bypass-flow and pressure chambers and a reservoir. In bypass-type hydraulic damper such as this, the cylinder is divided into two pressure chambers by a piston with rubber O-rings. The bypass flow portion is a passage for MR fluids connecting two pressure chambers. The bypass flow portion has an orifice for effectively magnetizing the fluid. The uniform magnetic field is applied perpendicularly to the MR fluid flow at the annular orifice. The thermal expansion due to the temperature rise of the MR fluid is absorbed by the reservoir.

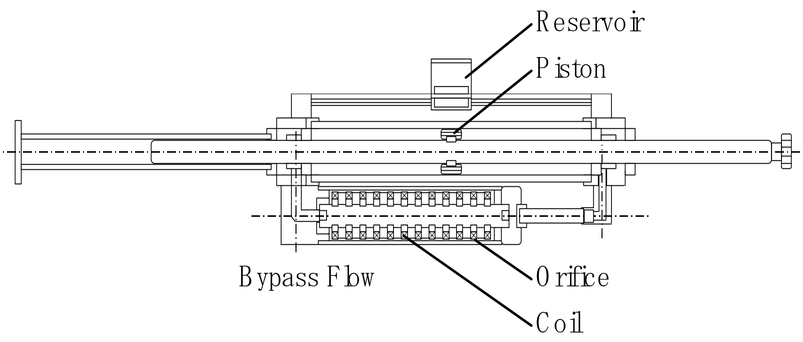


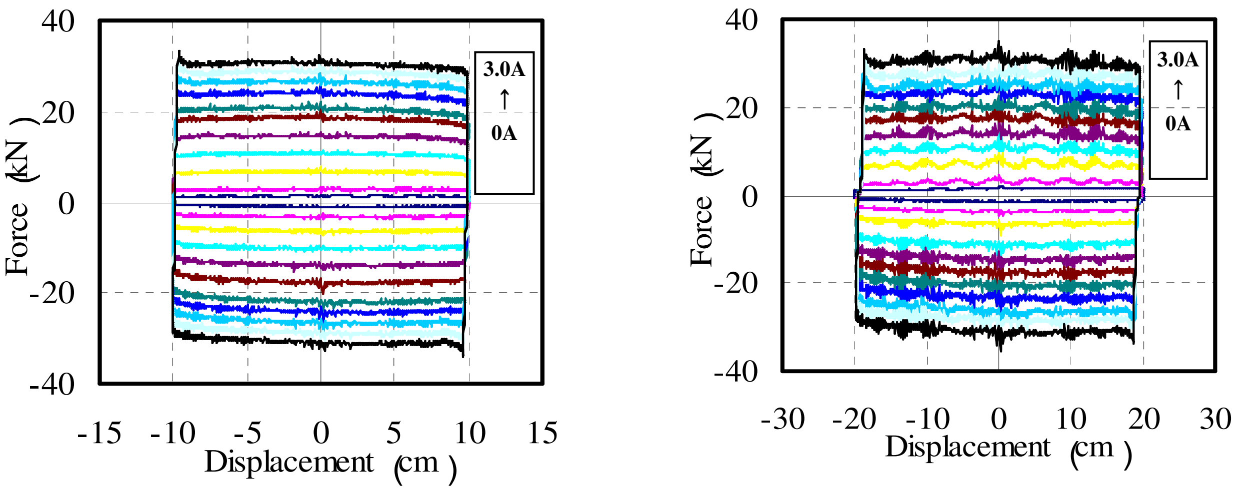
Fig. 3. Structure of MR damper

Table 2. Design specification

Max.Force		40kN
Stroke		± 295mm
Cylinder Bore		φ 90mm
Orifice	Section	Outer diameter φ 48mm
		Gap 3.0mm
	Length	420mm
Electromagnet	Inductance	37.4mH× 3
	Resistance	12Ω × 3
	Max.Current	3A
MR fluid		Bando:# 230

Mechanical characteristic of MR damper by cyclic loading

Cyclic loading tests were conducted to clarify the performance of the MR damper. Fig. 4 shows the force-displacement relationship. The electric current to the electromagnet was set at the constant value at 0A～3A in the 0.3A interval. The hysteretic loop shows like a rigid-plastic characteristics caused by friction force of MR fluid with magnetic field. The force increases almost proportionally to the increase in the electric current. Fig. 5 shows the force-velocity relationship. The velocity is the maximum velocity of piston in case of sinusoidal loading in this figure. This figure also shows that the force increases almost proportionally to the increase in the electric current and the force does not depend on the piston velocity so much.



(a) 0.1Hz, 10cm, 6.28cm/sec

(b) 0.1Hz, 20cm, 12.56cm/sec

Fig. 4. Force-displacement relationship of MR damper

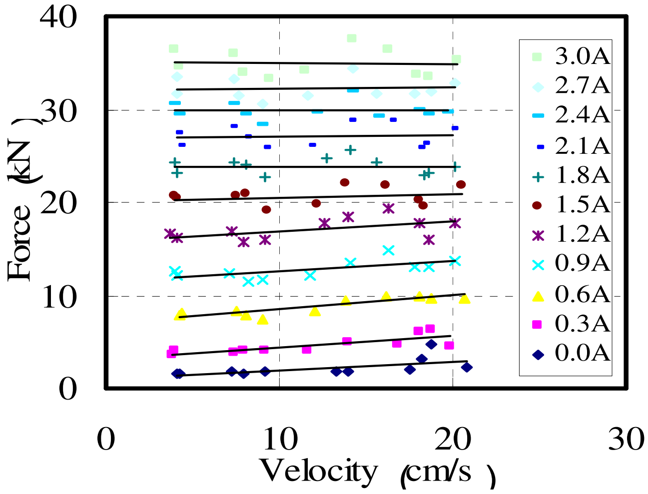


Fig. 5. Force-velocity relationship of MR damper

Shaking table test

The base isolation system is constituted of six roller bearings with four laminated rubber bearings (Photo 1) [2]. The laminated rubber bearing gives the restoring force, and the roller bearing supports the vertical load. The input waves for the shaking table test were sweep sinusoidal wave, white noise wave, and five earthquake waves of El Centro 1940 NS, Hachinohe 1968 NS, JMA Kobe 1995 NS and Taft 1952 EW standardized at a maximum velocity of 50cm/s. Fig. 6 shows the performance of the shaking table.

Photo 1. Test frame

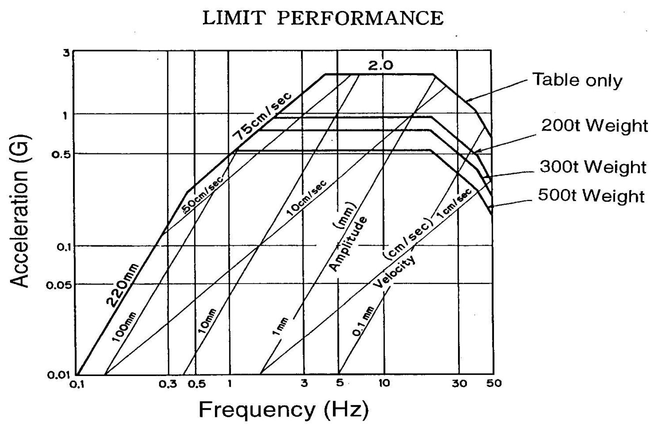


Fig. 6. Performance of the shaking table

Control system

The measurement and control system in the shaking table test is shown in Fig. 7. Accelerometers, transducers for measuring displacement and strain gauges were installed at each part of the test frame, and the data were recorded. There were 256 recording channels, and the data sampling was 2kHz. The data were recorded by an EWS for the measurement, which served as D/A converter of input waveform to the shaking table. The control signal incorporated the signal from the sensor in the amplifier, and it took in a voltage signal output from the amplifier to the A/D converter of the control PC. The control signal of electric current supplied to the MR damper was output from the D/A converter of the control PC to the high-speed DC power supplies.

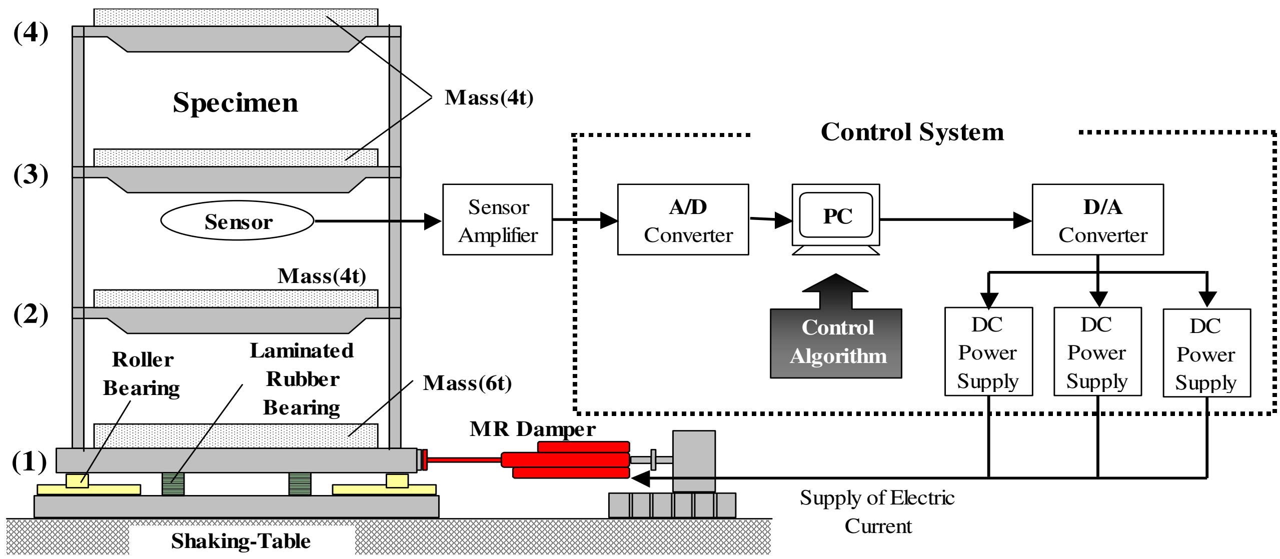


Fig. 7. Control system

Test results

The control algorithm is simple Sky Hook theory [7]. The control force is generated when the product of the absolute velocity and the relative velocity of the 1st floor is positive. The control force is generated by an electric current of 0.3A (when piston velocity is less than 15 cm/sec), 0.6A (when piston velocity is more than 15 and less than 30 cm/sec) and 0.9A (when piston velocity is more than 30 cm/sec).

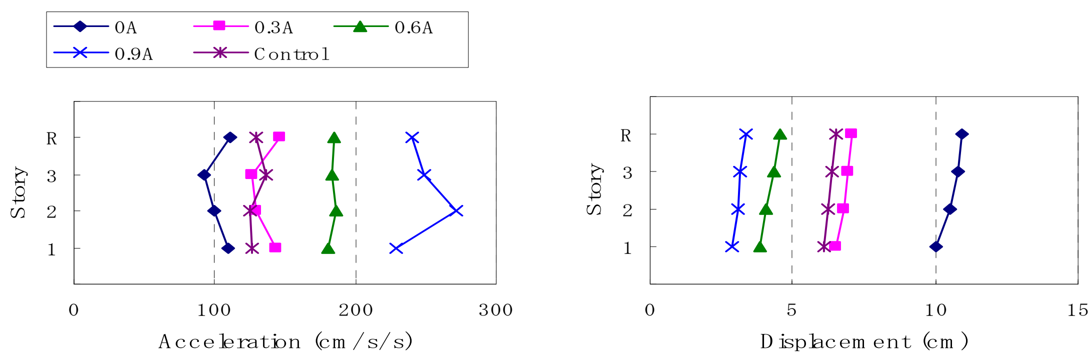


Fig. 8. Average values of response of each story of positive side and negative side (El Centro 1940 NS, 25cm/sec)

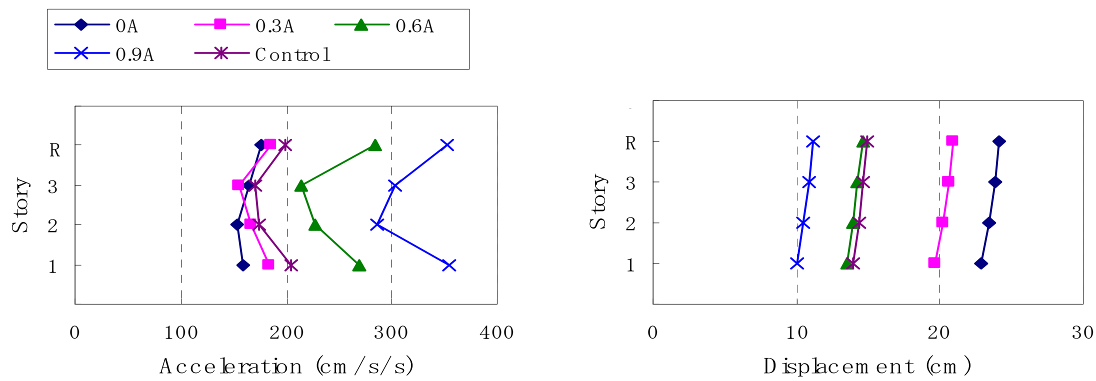
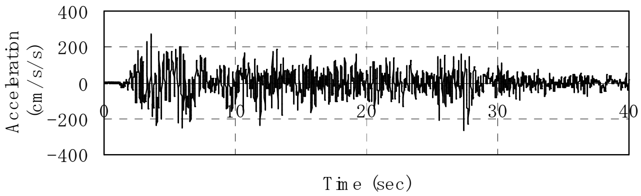


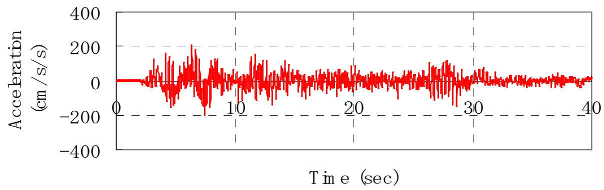
Fig. 9. Average values of response of each story of positive side and negative side (El Centro 1940 NS, 50cm/sec)

In Japan, the performance of a building structure against an earthquake is verified in two stages of maximum ground motion velocity: 25 cm/sec (for keeping operation) and 50 cm/sec (for structural safety). The test results in the case of 25 cm/sec and 50 cm/sec of El Centro 1940 NS are shown in Figs. 8 and 9. When the electric current is increased, the damping force of MR damper is increased. Although the larger damping force reduces the response displacement more effectively, it increases the absolute acceleration. The controlled accelerations are reduced the same as one of 0.3A, and the controlled displacements are reduced the same as 0.6 A or 0.3A in both cases. This shows that semi-active control by an MR damper can reduce the response displacements while reducing the response acceleration.

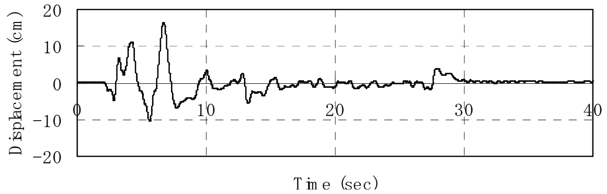
Fig.10 shows the test results in time history comparing the case of 0.6A constant electric current applied with the case controlled. Although the response displacements are almost same in two cases, the absolute acceleration is reduced by sky-hook control.



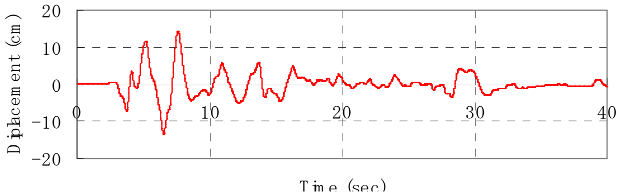
(a) Absolute acceleration of 1st floor (0.6A)



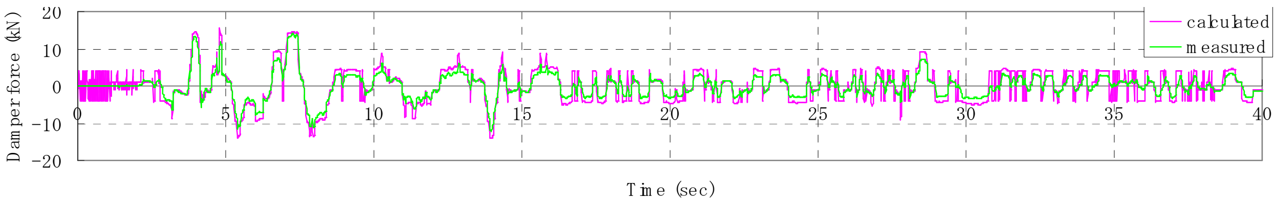
(b) Absolute acceleration of 1st floor (controlled)



(c) Response displacement of 1st floor (0.6A)



(d) Response displacement of 1st floor (controlled)



(e) Calculated and measured force of MR damper (controlled)

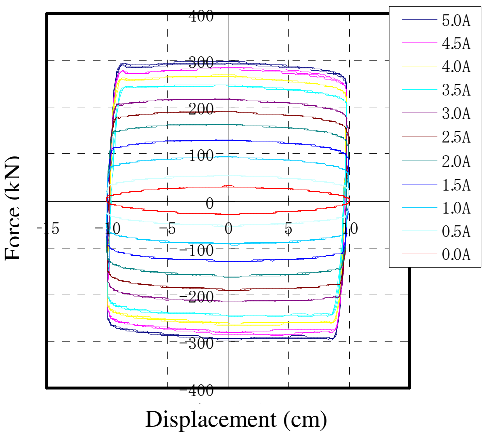
Fig. 10. Time history data of shaking table test in case of El Centro 1940 NS

Implementation of MR damper to an actual building

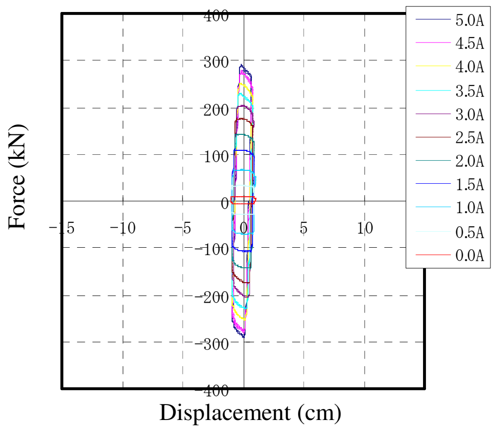
The MR damper for the base-isolation system has a stroke of 950mm to accept a large displacement of the structure at the excitation by the actual earthquake motion. In the design of the MR damper for the base-isolation system, the dependency of the damping force on the piston velocity must be concerned. The design specification for the maximum piston velocity of the damper is almost 100cm/s. Therefore, even a minute increase in damping force can have a large influence on the controllable force range in the high velocity region. To solve this problem, the cross sectional area of the flow passage in the bypass portion and the number of coils installed along the fluid passage were investigated carefully.

Dynamic loading tests have been carried out using the vibration-testing machine to verify the damping characteristics of the developed MR damper. Various displacements were applied to the MR damper (sinusoidal waves, sweep sinusoidal waves, and random waves) and the generated damping forces were measured by a load-cell (±500kN) on the opposite side of the actuator. A displacement transducer (±50cm) measured the piston displacement. The input electric current applied to the electromagnet is selected as the one of the test parameters and is maintained to a constant value during the dynamic loading tests. The dynamic loading tests were performed under input electric currents at 0A～5A in the 0.5A interval.

The damping force and the force-displacement relationship were evaluated. Fig.11 shows the measured force-displacement relationships for the sinusoidal loading. Fig. 12 shows the damper's force-piston velocity relationships. It was confirmed that the yield force of the MR damper increases with the rise of the electric current, and it was verified that the maximum damping force was controllable by adjusting the magnetic field.



(a) 100mm, 0.35Hz, 22cm/sec



(b) 10mm, 0.35Hz, 2.2cm/sec

Fig. 11. Force - Displacement relationships by sinusoidal loadings.

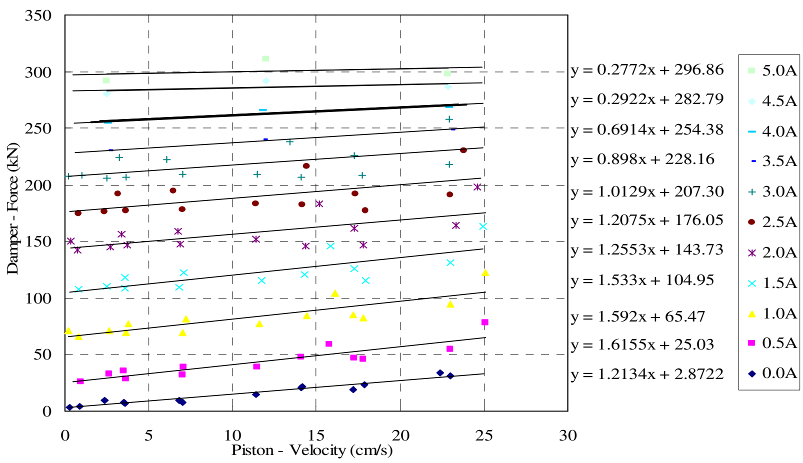


Fig. 12. Damper's force - Piston velocity relationships

Photo 2. Residential building

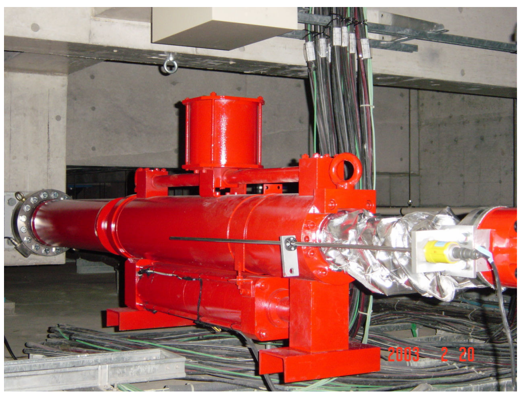


Photo 3. 400kN MR damper

Controlled Residential Building

The 400kN MR damper was installed to an actual residential building in the earthquake prone region in Japan on February 20 in 2003. Photo 2 shows the building and Photo 3 shows the MR damper.

Summary

The MR fluid showed the good results in the point of view stability. An MR damper developed for this large-scale test showed the good results, too. The force-displacement relationship is like rigid-plastic characteristics caused by friction force and shows that the MR damper responds quickly to the inversion of the movement of the piston. The test results of sky-hook control shows that semi-active control by an MR damper can reduce the response displacements while reducing the response acceleration. The effectiveness of the semi-active control for the passive control was clarified.

The MR damper installed to an actual base-isolated building had good properties. Authors continue to observe the response of the building.

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