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DISPLACEMENT CONTROL DESIGN CONCEPT FOR LONG-PERIOD STRUCTURES

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Abstract

The earthquake-resistant design code provision at the beginning in Japan required that structures resist seismic force produced by response acceleration. The design concept subsequently, in accordance with the increase of heights of structures to be constructed, evolved to take response displacement as well as response acceleration into account to utilize ductility of structures in reduction of required strength on the basis of energy balance concept. It is attracting much attention that excessive displacements in long-period structures such as high-rise or seismic isolated buildings, the number of which are designed and constructed is increasing nowadays, might occur due to long-period components of extreme ground motions. The excessive displacement may not necessarily cause structural damage, whereas the excessive displacement itself is harmful. It is considered to be effective to incorporate some damping devices that control vibrations in direct response to the response displacement. The authors define this concept as “displacement control design” and have developed some control strategies and devices to realize it. This paper outlines the basic concept of displacement control design and the mechanisms and application of the newly developed dampers.

The basic concept is utilizing a damper that generates resistant force in response to displacement without velocity dependency. Theoretical representation of such damping element is complex stiffness. Although the present damping element can be realized by using magneto-rheological (MR) fluid damper, the damper is unreliable in seismic events because of power source failure. The problem of non-causality of complex stiffness makes realization of such damping device more difficult. To solve these problems, we developed tuned viscous mass dampers for seismic control, rotational viscous mass dampers, performance variable oil dampers, and friction dampers with coupling mechanism for seismic isolation. By using these devices, we can build systems that can reduce response displacements without deterioration of floor response accelerations in response to each criterion for the corresponding earthquake input level. These devices can be, so to speak, categorized as smart passive damper and are effective in response control of structures against expected extreme seismic events.

Keywords: displacement control; long-period structure; high-rise building; seismic isolation; smart passive damper

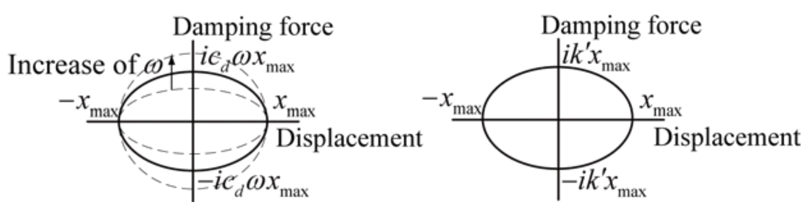
1. Introduction

The long duration vibrations with excessive displacements in high-rise and seismic isolated buildings observed in the recent massive seismic event, the 2011 Great East Japan Earthquake, pronounced the need for some design strategies to control excessive displacements in long-period structures subjected to long-duration/long-period ground motions. There is, however, a dilemma that just adding damping devices to suppress displacements might compromise the response reduction effects; response shear forces and floor response accelerations might increase[1]. To address the dilemma, many research works have been conducted at the aim of reduction of displacements without increasing response shear forces and accelerations, which can be done by changing control forces in accordance with the response displacements[2-11].

Following discusses the benefit of rate-independent linear damping, whose control force is proportional to displacement and not velocity, in long-period structures subjected to short period ground motions and introduces innovative damping devices developed by the authors to mimic the behavior of rate-independent linear damping.

2. Concept of displacement control design

Viscous damping, commonly used as a damping element, produces a resistance force proportional to the response velocity. A rate-independent damping element dependent only on displacements, on the contrary, is represented by complex-valued stiffness[12]. Here, we consider two single-degree-of-freedom systems incorporated with rate-dependent and linear rate-independent dampers, respectively. Fig. 1 shows the relationships between the damping forces and displacements of the two differently damped models.



(a) Rate-dependent model (b) Rate-independent model

Fig. 1 – Relationships between damping forces and displacements

We compared the response time history and hysteretic response by conducting frequency domain analysis in order to examine the differences in response characteristics. As an analytical example, a seismically isolated building having a period of 4 s is employed. The superstructure is regarded as a rigid body, thus the analytical model reduces to a single-degree-of-freedom system. As for the input ground motion, the JMA Kobe record of the 1995 Kobe Earthquake, which is scaled such that its peak ground velocity (PGV) is 0.5 m/s, is used. The viscous damping ratio and complex damping ratio for the rate-dependent damper and rate-independent damper, respectively, are 0.2 each.

Fig. 2 depicts the time histories yielded by the two models. The thick lines in the hysteresis loops represent the one-cycle hysteresis in which the maximum displacements are included. The rate-independent damper obtained the largest damping force in a loop (shown by the thick line) in which the maximum displacement is marked, because it generates damping force in response to the displacement. On the contrary, the rate-dependent damper obtained the maximum damping force regardless of the maximum response displacement because it generates damping force in response to velocity and not displacement. Thus, the maximum damping force generated by the rate-dependent damper does not serve for maximum displacement control. Ground motions containing short period components as dominant frequencies, such as the JMA Kobe 1995 NS record, particularly tend to exhibit phenomena mentioned above. Indeed, the JMA Kobe 1995 NS record showed that the rate-independent model reduced the maximum response damping force and input energy to about half of those obtained by the rate-dependent model.

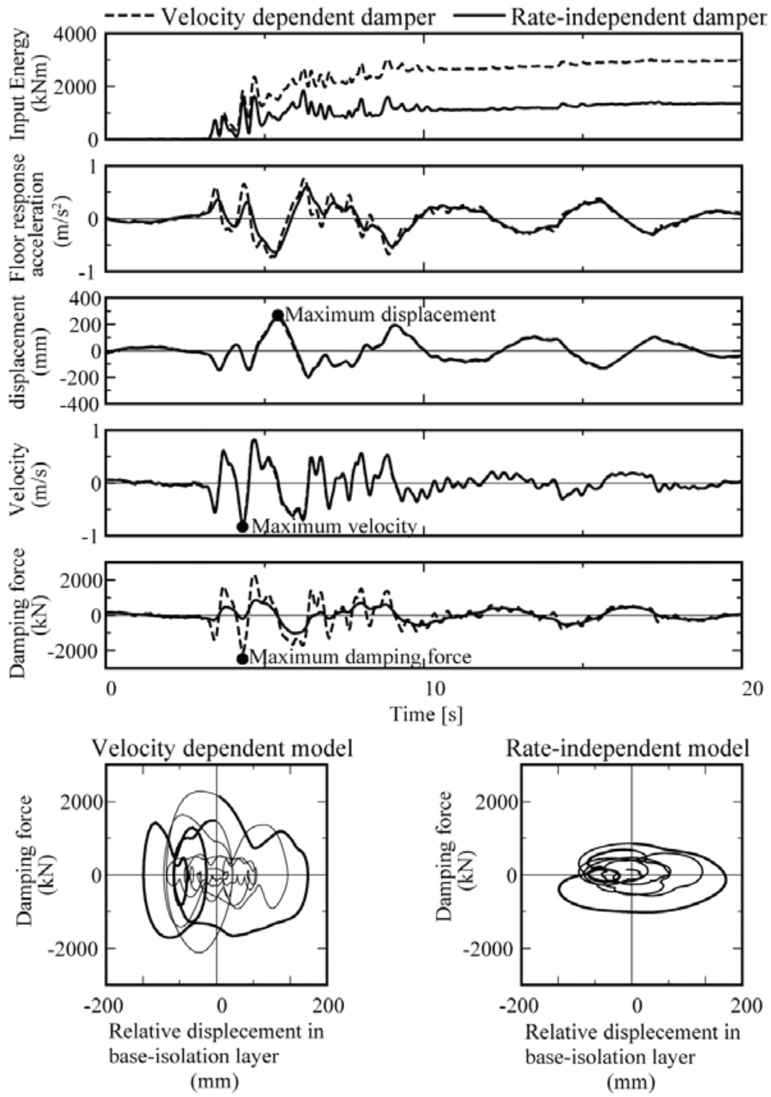


Fig. 2 – Comparison of rate-dependent model and rate-independent model

(JMA KOBE 1995 NS record)

3. Application to seismic control

Supporting a rotary mass damper consisting of a viscous damping element and apparent mass produced by a ball-screw mechanism in a parallel configuration results in a tuned-mass damper-like energy dissipation device, which is an effective seismic control system[13-22]. The authors named this system the tuned viscous mass damper (TVMD) system. The rotational mass damper is equipped with a rotational friction mechanism to restrict damping forces to avoid excessively large reaction forces, which is referred to as the force-restricted viscous mass damper (FRVMD)(Fig. 3)[23,24].

As shown in Fig. 4, the secondary mass multiplied by the absolute response acceleration generates the control force in a conventional TMD, which is known to be effective against wind-induced vibrations[25]. The secondary mass of the TMD, however, is usually insufficient for the control of earthquake-induced vibrations[26]. In contrast, the TVMD can provide a secondary mass several thousand times larger than the physical mass that is activated by inter-story relative accelerations. Thus, a sufficient apparent mass can be obtained for the control of vibrations induced by severe earthquakes.

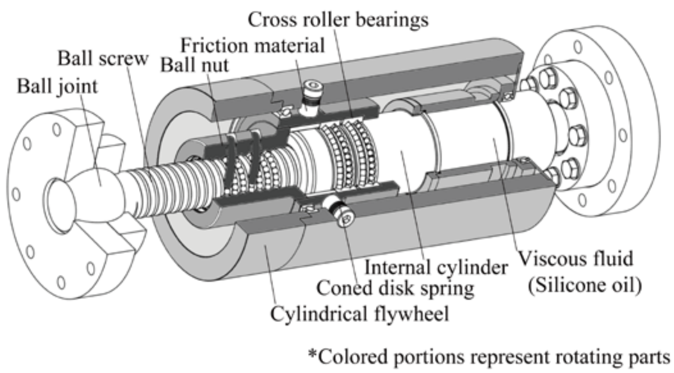


Fig. 3 – Schematic representation of force-restricted viscous mass damper

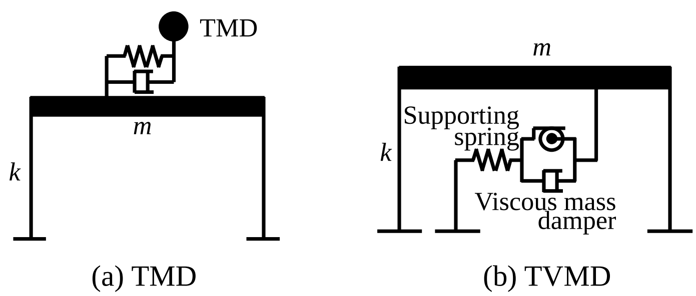


Fig. 4 –Conventional TMD and TVMD

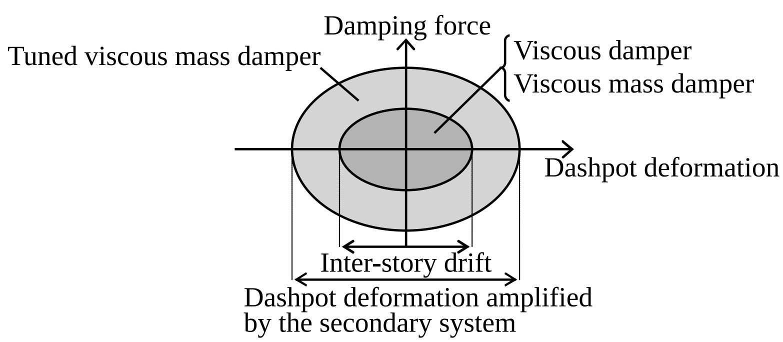


Fig. 5 –Energy dissipated in damping elements

Fig. 5 illustrates the energy dissipated per cycle by the viscous damper, viscous mass damper, and TVMD when they all have the same damping element. As depicted in Fig. 5, the secondary vibration system in the TVMD tuned to the primary system enlarges the deformation of the damping element, resulting in more efficient energy dissipation in the damping element having the same damping coefficient as the viscous damper and viscous mass damper.

Fig. 6 compares the performance of FRVMDs and oil dampers incorporated into a fifty-story high-rise building subjected to the TAFT 1952 EW record that is scaled such that its PGV is 0.5 m/s. Five FRVMDs or oil dampers are located on each floor for each case.

Each oil damper has a maximum load capacity of 1,000 kN and a relief load of 800 kN. Thus, five dampers on each story result in an equivalent damping ratio of 0.6% for the first modal critical damping. Combining the equivalent damping and the inherent damping ratio of 2% gives a damping ratio of 2.6%.

Incorporating multiple types of FRVMDs tuned to specified modes into a building enables a TVMD seismic control system to perform multi-modal control[16,23]. Thus, FRVMDs tuned to the first mode are incorporated into the first to the 35th floor and those tuned to the second mode are incorporated into the 36th to the 50th floor in the TVMD controlled case, where the secondary mass amplification factor in an FRVMD is 6,940.

Comparison between the cases of control using the oil damper and the TVMD shows that inter-story drifts yielded by both cases are almost identical, whereas the maximum damper forces yielded by the FRVMDs are approximately half of those yielded by the oil dampers as shown in Fig. 6.

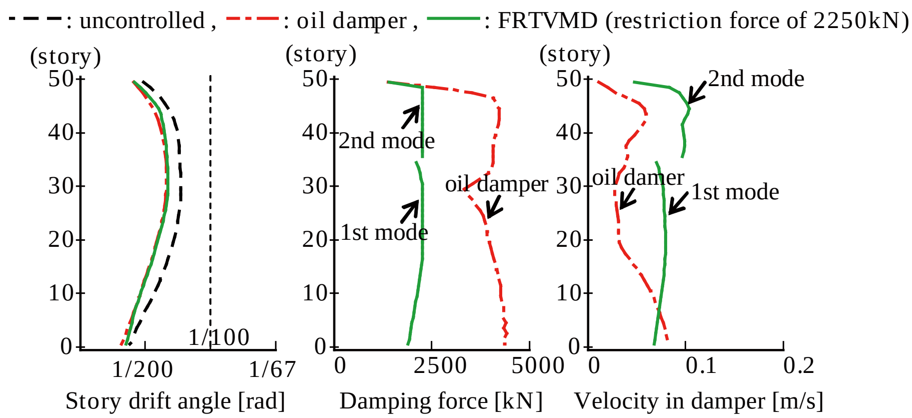


Fig. 6 – Maximum responses yielded by the TAFT 1952 EW record (PGV = 0.5 m/s)

4. Application to seismic isolation

4.1 FRVMD with rotational mass amplifier[27-30]

Unlike a TVMD system, a supporting spring is designed to have a large stiffness so that it is detuned to the primary system when an FRVMD is applied to a seismically isolated building; instead, a large secondary apparent mass is applied to the FRVMD to compensate for the deterioration in the displacement amplification in the damping element by the detuning effect. The supporting spring acts as a buffer spring to suppress the accelerations induced by the force restriction mechanism.

A large effective mass ratio can be obtained because the secondary apparent mass exhibits a large effect with respect to the displacements in the base isolation layer. It is expected that the large mass ratio results in the elongation of the fundamental period and reduction in the seismic input. To restrict the excessively large reaction force induced by the large apparent mass, the maximum friction force in the force restriction mechanism is designed to be smaller than that of a TVMD. As shown in Fig. 7, an FRVMD for base isolation has a longer ball screw shaft and housing to hold it compared to that used in a TVMD seismic control system.

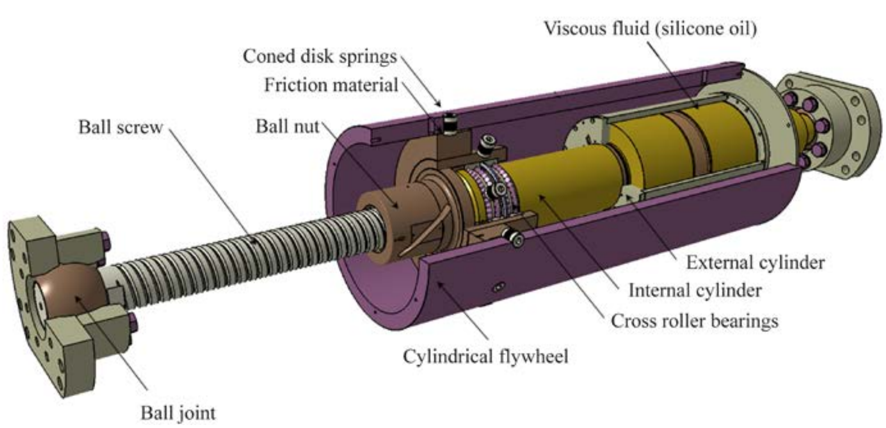


Fig. 7 – FRVMD for seismic isolation

Here, as an analytical example, we assume that a seismically isolated five-story building having fundamental periods of 0.67 s and 4 s when fixed to the ground and supported by rubber bearings, respectively, is subjected to the EW component of an artificial ground motion named SANNOMARU wave containing numerous long-period components whose peak ground acceleration (PGA) is 1.86 m/s^2. As the isolators, laminated natural rubber bearings, lead-plug bearings, and cross-linear bearings are used. The performance of an oil damper equipped with a relief valve is compared to that of an FRVMD whose maximum damping forces are designed to be the same as those of the oil damper. Fig. 8 compares the maximum responses obtained by oil dampers and FRVMDs with those of the undamped case. The FRVMDs achieve a much better response displacement reduction effect than oil dampers with almost the same maximum accelerations.

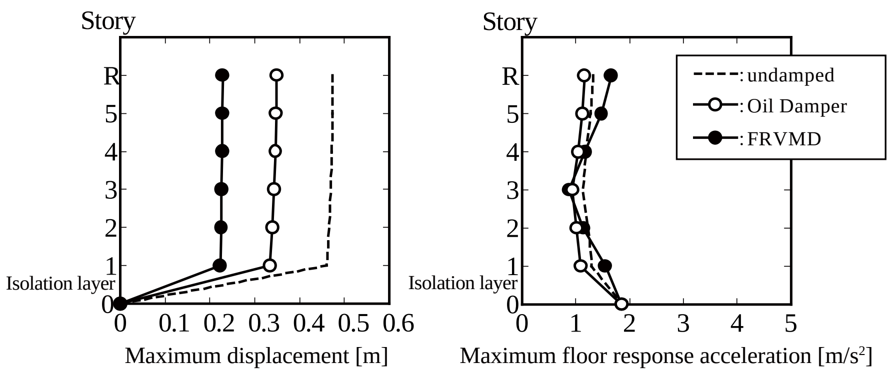
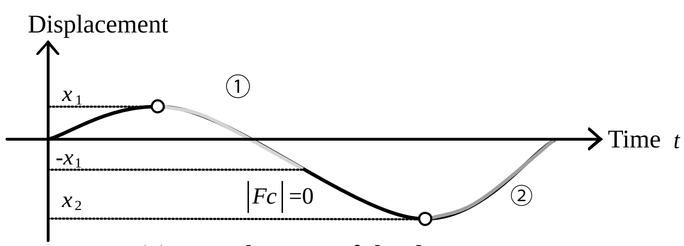


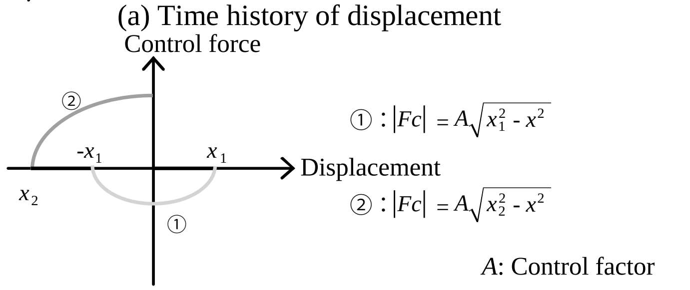
Fig. 8 – Maximum responses (SANNOMARU EW)

4.2 Magnetorheological Fluid Damper[31-34]

The apparent viscosity of a magnetorheological (MR) fluid can be varied when it is subjected to a magnetic field generated by an electric current. Thus, an MR fluid damper is one of the suitable semi-active devices for realizing the displacement control design concept because arbitrary and relatively large resistance forces can be obtained by controlling the electric current applied to the magnet coil in the damper. This device can simulate the damping forces represented by complex-valued stiffness that comply with the basic concept of the displacement control design. As is well known, the complex-valued stiffness creates the issue of non-causality, which results in the requirement for future inputs of ground motion[35]. Obviously, the ideal concept of rate-independent devices must be subjected to some modification for real-time control using past inputs of ground motions.



(a) Time history of displacement



(b) Hysteresis loop of the variable oval control algorithm

Fig. 9 – Outline of variable oval control

Here, we propose a causal control algorithm, referred to as variable oval control, for an MR damper and examine its effectiveness by comparing its performance with that of an oil damper.

The variable oval control algorithm substitutes the displacement–control force relationship of the ideal complex-valued stiffness, as shown in Fig. 1(b), with a segment-wise equivalent oval-shaped hysteresis, as shown in Fig. 9. Here, the control forces are generated only in accordance with the response-relative displacement in the seismic isolation layer. The size of an oval-shaped segment of the hysteresis loop that starts from a zero displacement and ends at the next zero displacement is varied in response to the maximum displacement experienced in the previous segment. Thus, the two segments ① and ② in the displacement time history, as shown in Fig. 9(a), depict the hysteresis loops ① and ② shown in Fig 9(b), respectively. This realizes the complex-valued stiffness model in a real-time operation.

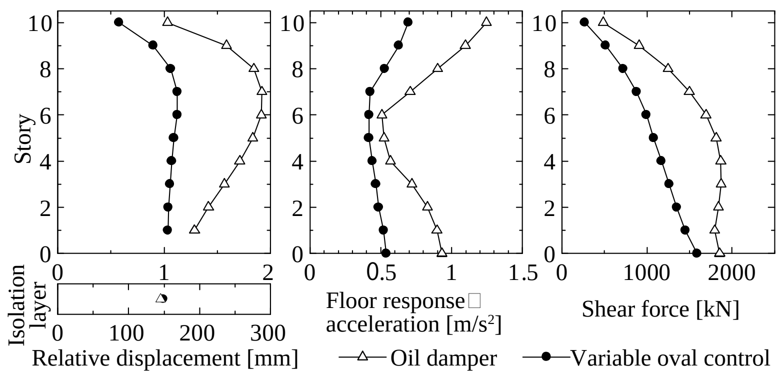


Fig. 10 – Comparisons of maximum responses

Fig. 10 compares the performances of an MR damper using the variable oval control algorithm with that of a linear viscous damper incorporated into a base-isolated ten-story reinforced concrete structure subjected to the JMA KOBE 1995 NS (scaled such that its PGV = 0.5 m/s) record. Both models have an equivalent damping ratio of 20%. Whereas the maximum relative displacements of the base-isolation layer are almost identical for the two models, the variable oval control algorithm obtained smaller maximum inter-story drifts, maximum floor response accelerations, and maximum shear forces in all the stories as compared with those obtained by the linear viscous damping model.

4.3 Variable-performance Oil Damper[36-40]

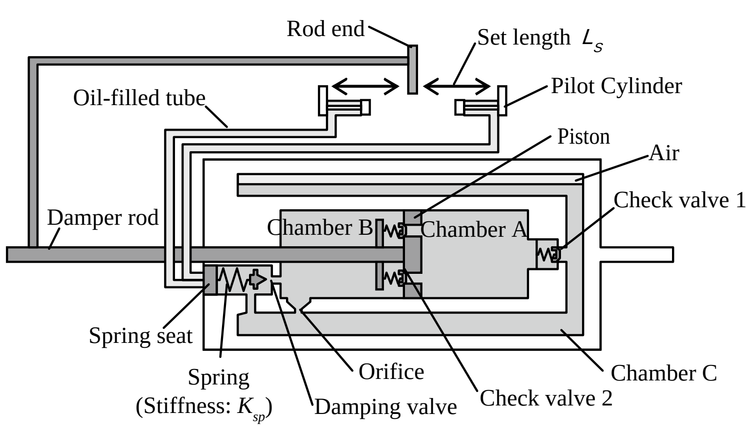


Fig. 11 – Mechanism of the variable-performance oil damper (VOD)

We herewith propose a passive damping device, called a variable-performance oil damper (VOD), whose damping performance varies in response to displacement; this damper requires no external power sources and computers to change its damping performance. Fig. 11 shows a schematic representation of a uniflow-type VOD. The damping force increases automatically when one of the oil-filled pilot cylinders that are attached out of the damper housing is activated by a large displacement. Figs. 12(a) and 12(b) depict the damping force–velocity relationship and the damping force–displacement relationship before and after activation, respectively, under the performance change process. Like an oil damper, the damper generates a damping force proportional to velocity while the relative displacement in the seismic isolation layer is smaller than the prescribed set length L_s. Once the displacement exceeds the set length L_s, the activated pilot cylinder closes the damping valve, resulting in an increased damping coefficient. The damping valve opens and closes in response to the response velocity and damping force, which yields the bilinear characteristics of the damping force–velocity relationship.

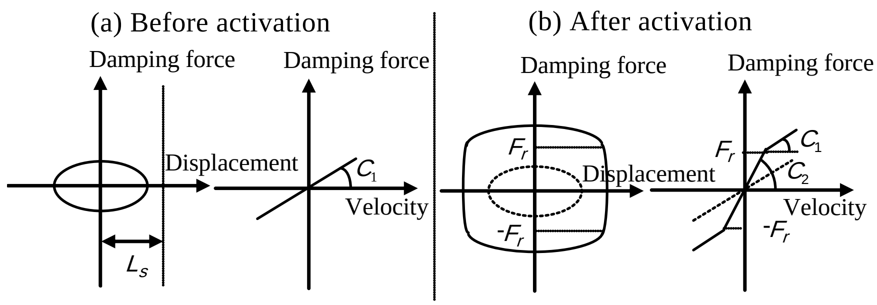


Fig. 12 – Property of the VOD

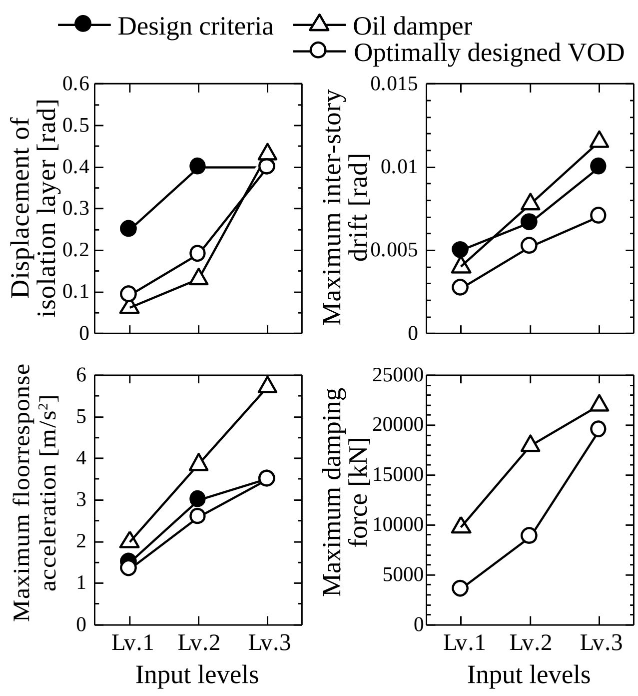


Fig. 13 – Comparisons of maximum responses

As an application example, we consider a 14-story base-isolated reinforced concrete structure containing VODs; the superstructure is reduced to a 5-degrees-of-freedom model. Furthermore, lead dampers are incorporated into the base-isolation system along with the VODs to resist the horizontal forces induced by strong winds. The yield strength coefficient of the lead dampers is 0.02. The VODs are optimally designed subject to the criteria regarding floor response accelerations and displacements determined for three seismic input levels: moderate (Level 1), severe (Level 2), and extremely severe (Level 3). Four historical ground motion records and an artificial ground motion are employed. For moderate, severe, and extremely severe seismic events, PGVs of the historical ground motion records are scaled to 0.25 m/s, 0.5 m/s, and 0.75 m/s, respectively. Moreover, an original record of a strong ground motion recorded in the 1995 Kobe Earthquake is also employed as an extremely severe (Level 3) ground motion. For a control case, we consider the same base-isolated structure containing oil dampers equipped with a relief valve whose equivalent damping ratio is 20%, instead of containing VODs. As illustrated in Fig. 13, this oil damper violates the design criteria shown by solid circles in the figure, whereas the optimally designed VODs comply with the design criteria with the smaller damping force.

4.4 Friction Damper with Coupling Mechanism[11,41-43]

Fig. 14 shows schematic diagrams of the friction damper with a coupling mechanism (FDC). The friction force is generated when displacement in the seismic isolation layer exceeds the prescribed set length L_s, resulting in the coupling in the damper. Arbitrary friction force can be generated by adjusting the tightening force in the friction mechanism. The coupling mechanism consists of a male plug and female connector socket that connect external and internal rods to transmit the resisting force without disconnection after the coupling. The coil springs deform to generate an elastic restoring force until it reaches the maximum friction force F_d and then the internal rod starts to slide, keeping the resistant force F_d. This mechanism gives the FDC perfect elastoplastic bilinear restoring force characteristics, resulting in suppression of short-period vibrations by absorbing the shock induced by coupling.

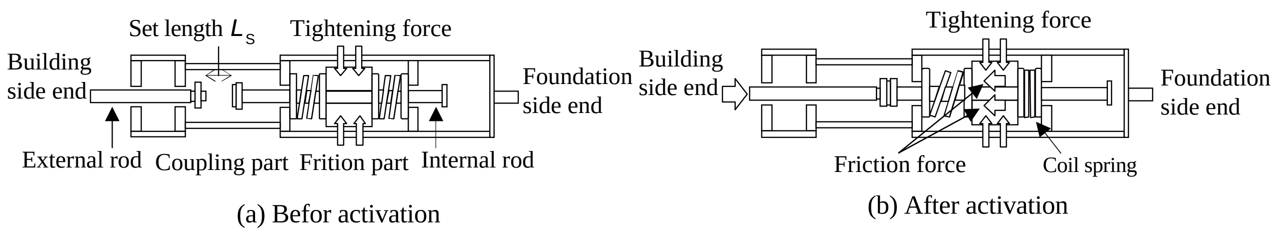


Fig. 14 – Schematic representation of damper mechanism

Fig. 15 illustrates the restoring force model for a friction damper with a two-stage coupling mechanism, wherein two coupling mechanisms having two different set lengths are combined. As shown in the figure, the restoring force model is divided into three cases in response to coupling status.

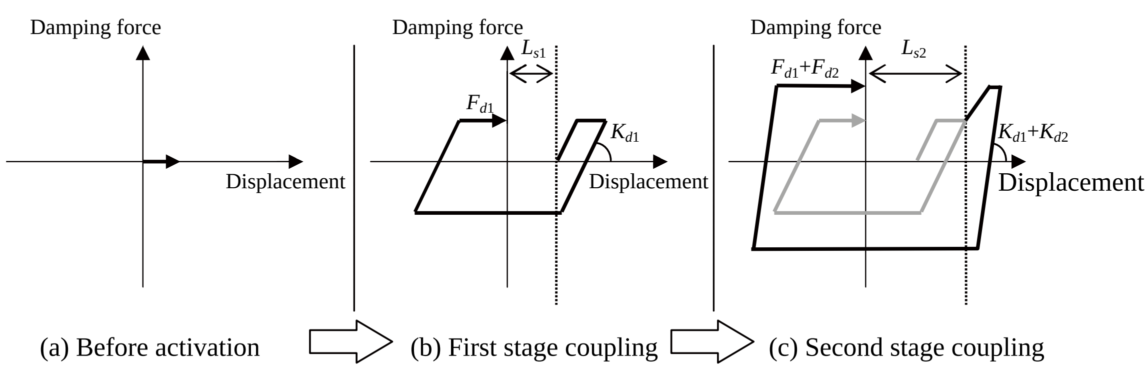


Fig. 15 – Restoring force model for friction damper with two-stage coupling mechanism

Here, we consider a two-story seismically isolated detached house supported by sliding bearings subjected to the TAKATORI 1995 EW record. Two cases—a case containing a single-stage coupling damper (FDC1) and the other case containing a two-stage coupling damper (FDC1+FDC2)—are compared. Here, the seismic isolation clearance is 0.35 m and the damper initial stiffness K_d and maximum friction force F_d as well as the friction factor of the sliding bearings are optimally designed, subject to the criteria of the response accelerations and displacements against an artificial ground motion and four historical ground motion records whose PGVs are the same as those used in Section 4.3. The optimal design gave a friction factor of 0.02 for the sliding bearings. Fig. 16 shows that the single-stage coupling damper suffers a large displacement exceeding the seismic isolation clearance, whereas the two-stage coupling damper suppresses the displacement to less than the clearance. Both cases yielded larger floor response accelerations than those of the undamped case where moat wall impact is ignored. Nevertheless, it is assumed that they are much smaller than those of the undamped case if the moat wall impact is taken into account.

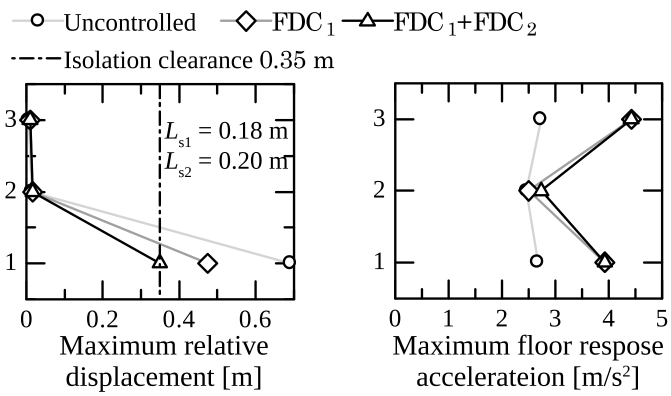


Fig. 16 – Maximum responses (TAKATORI 1995 EW)

Concluding remarks

In this paper, “displacement control” design strategies that use rate-independent damping devices that generate damping forces in direct response to displacements are shown to be effective for long-period structures such as high-rise and seismically isolated buildings. A rate-independent linear damping element can be represented by complex-valued stiffness, whose noncausality makes real-time operation difficult. To mimic the behavior of rate-independent linear damping, the authors developed tuned viscous mass dampers for seismic control of high-rise buildings, as well as rotational viscous mass dampers, variable-performance oil dampers, and friction dampers with a coupling mechanism for seismic isolation to resolve this problem. Applications of these devices enable reduction of displacements in long-period building structures without increase of shear forces and floor response accelerations. These devices can be considered smart passive dampers and will be effective against future extreme seismic events.

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