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DEVELOPMENT OF A HIGH PERFORMANCE OIL DAMPER FOR SEISMIC ISOLATED BUILDINGS SUBJECTED TO EXTREMELY LARGE EARTHQUAKE

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ABSTRACT

This paper presents a new passive oil damper developed for seismic isolated buildings subjected to extremely large earthquakes such as ones considered for Nuclear Power Plant facilities. Two major characteristics of the developed damper are a variable damping system and its high velocity capacity. The developed damper can switch its damping coefficient low and high passively at specified velocity. At very large earthquake response, damping force should be increased rapidly to stop a collision between a moat wall and a base isolated building. Yaguchi et al. (2014) have developed a stroke control system, which is similar to but much larger than the developed damper, and applied the stroke control system to the Tuned Mass Damper system for an actual high-rise building in Tokyo. First, we present the features and the target specifications of the developed damper, and show the effectiveness through the seismic response analyses. Next, we show the results of dynamic loading tests conducted on a full-scale prototype device and the results of simulation analyses. It was confirmed that the dynamic characteristics of the damper can be accurately simulated by the nonlinear Maxwell model.

INTRODUCTION

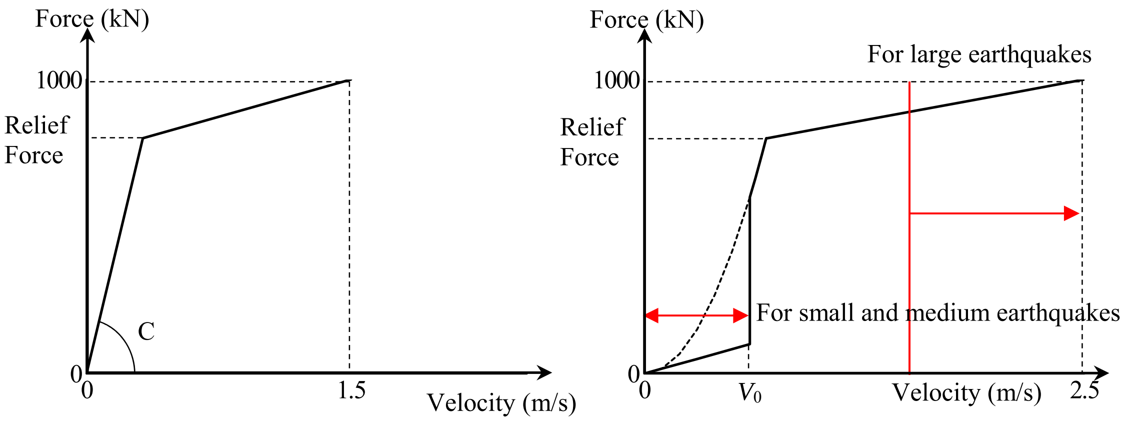
In 2006, Nuclear Safety Commission of Japan revised the regulatory guidance for seismic design of Japanese Nuclear Power Plants (NPP) and this revision made it possible to apply a seismic isolation system to the NPP's facilities. An extremely large ground motion was observed at the Kahiwazaki-Kariwa NPP by the Niigataken Chuetsu-oki Earthquake in 2007, but any serious damage that could affect the safety system was not caused. However, owing to the damage of non-structural members such as doors and ceilings, the emergency response center, which was housed in the conventional seismic building, could not fully demonstrate its performance. Based on the experience of the Niigataken Chuetsu-oki Earthquake, it was recognised that the emergency response center should be housed in a building called the Seismic-isolated Important Building, which adopts the base isolation system. The Seismic-isolated Important Building of the Fukushima Dai-Ichi NPP was completed in March 2010. Based on the evaluation analyses of the observation records of the 2011 off the Pacific coast of Tohoku Earthquake by Hijikata et al. (2012), it was confirmed that the Seismic-isolated Important Building functioned as expected and demonstrated a seismic isolation effect when dealing with disasters.

Since the 2011 off the Pacific coast of Tohoku Earthquake, however, Nuclear Regulation Authority of Japan, which reorganized by NSC, has required to ensure the safety of NPP's facilities against extremely large earthquakes which greatly exceeds the level of earthquakes in notification for general buildings. As a result, the deformation of the seismic isolation layer became large, and the collision with the moat wall has become a concern for extremely large earthquakes. It is a common measures to add or increase oil dampers to avoid collisions. Installing a large number of oil dampers, however, sacrifices the seismic isolation effect for medium or smaller earthquakes. In addition, in the case of using a conventional oil damper for base isolation system, it is necessary to keep not only the displacement but also the velocity within the allowable range of the oil damper, which is often a more severe limitation.

This paper presents a new passive oil damper developed for seismic isolated buildings subjected to extremely large earthquakes such as ones considered for NPP facilities. First, we present the features and the target specifications of the developed damper, and show the effectiveness through the seismic response analyses. Next, we show the results of dynamic loading tests conducted on a full-scale prototype device and the results of simulation analyses. It was confirmed that the dynamic characteristics of the damper can be accurately simulated by the nonlinear Maxwell model.

TARGET PERFORMANCE

The typical force-velocity relations of a normal oil damper that used for seismic isolation system in Japan is linear or bi-linear type as shown in Figure 1(a). Therefore, installing a large number of oil dampers to limit displacement of the seismic isolation layer sacrifices the seismic isolation effect for medium or smaller earthquakes. In order to achieve both the seismic isolation effect for medium or smaller earthquakes and the displacement suppression effect for extremely large earthquakes, it is conceivable to limit the velocity, which is kinematic energy, only for large earthquake to avoid a collision to a moat wall. Specifically, as shown in Figure 1(b), the damping force should increase sharply if the velocity of the damper reaches the predetermined velocity V_0, and recover immediately to the original damping coefficient when the velocity of the damper falls below V_0. This characteristic is the same as the characteristic given to the large-size TMD by Yaguchi et al. (2014), and it can be also expected to suppress the increase in the overall layer shear force, which is equivalent to the upper structure's acceleration. In addition, the maximum velocity of normal oil dampers used for seismic isolation system in Japan is 1.5 m/s at most, which causes an increase in the number of dampers installed. Therefore Maximum velocity of the developed damper is set to 2.5 m/s.



(a) Normal damper (b) Developed damper

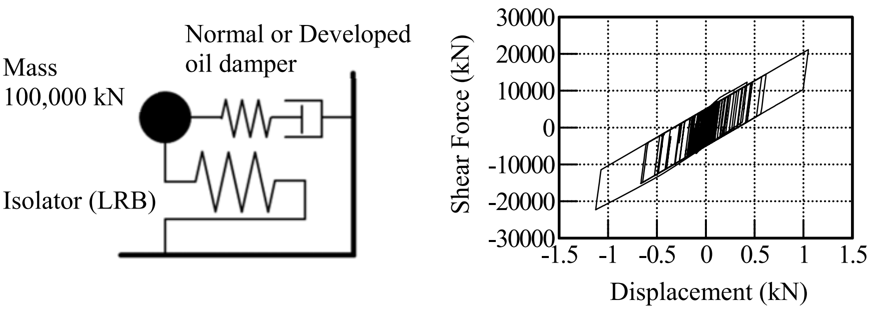
Figure 1. Force–velocity relationship of oil dampers.

SEISMIC RESPONSE ANALYSIS

To demonstrate advantages of the developed damper, seismic response analyses were conducted for a base isolated building with oil dampers modelled as Figure 2(a). The model is a single degree of freedom model with a base isolator spring and an oil damper dash pot. Lead Rubber Bearings are used as the isolator spring. The hysteresis of the isolator spring is also shown in Figure 2(b). The dashpot indicates normal or developed oil dampers. As the normal damper, a typical type is selected which has the largest capacity of velocity of

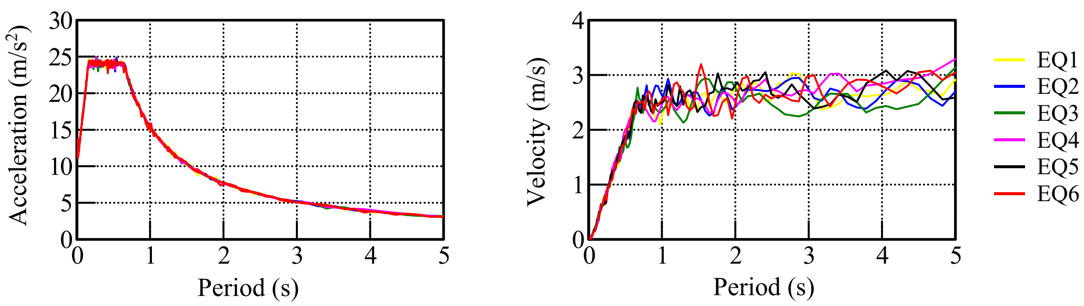
1.5 m/s in the market in Japan and its damping characteristic is shown in Figure 1(a). The initial damping coefficient C in the Figure 1(a) is 2500 kNsec/m. The damping characteristic of the develop oil damper is shown in Figure 1(b). Relief forces of both kind of dampers are same 800 kN. The developed damper has a relatively small damping coefficient at low to medium velocity region, which will result in maintaining good base isolation effect for medium or smaller levels of ground shakings even if quite a lot of dampers are used for extremely large earthquakes to prevent collisions between the base isolated building and the moat wall. The developed damper will sharply increase its damping coefficient at a specified velocity. In this analytical study, the specified velocity V_0 is set at 0.6 m/s to keep base isolation effect under the level of design earthquakes for ordinary buildings. Maximum velocity of the developed damper is set at 2.5 m/s to use the damper even under the extremely large earthquakes for NPPs.

First, we determined the number of dampers necessary for extremely large earthquakes, and examined the responses of the base isolated building under moderate level of earthquakes. The required number of dampers was determined so that not to exceed a liner limit of shear strain of the Lead Rubber Bearings, and that not to exceed the velocity limit of the damper. The allowable horizontal displacement at the isolated layer is 0.75 m because of the 250 % liner limit of shear strain and the 0.3 m thickness of the rubber isolator. The velocity limit is 1.5 m/s and 2.5 m/s for the normal damper and the developed damper, respectively. Six design earthquake motions, which is used for seismic design of ordinary base isolated buildings in Japan, were selected for input ground motions as the moderate earthquake level (L2). As the extremely large earthquake for the study, we tripled the acceleration of those design earthquake motions (L2 x 3.0). Response acceleration and velocity spectrum of the extremely large earthquake level (L2 x 3.0) are shown in Figure 3. The velocity spectrum of damping ratio h=5% is around 2.5 m/s, and it is larger than that of the earthquake design motions considered in the study on seismic isolation systems of nuclear power facilities by Shimizu et al. (2015).



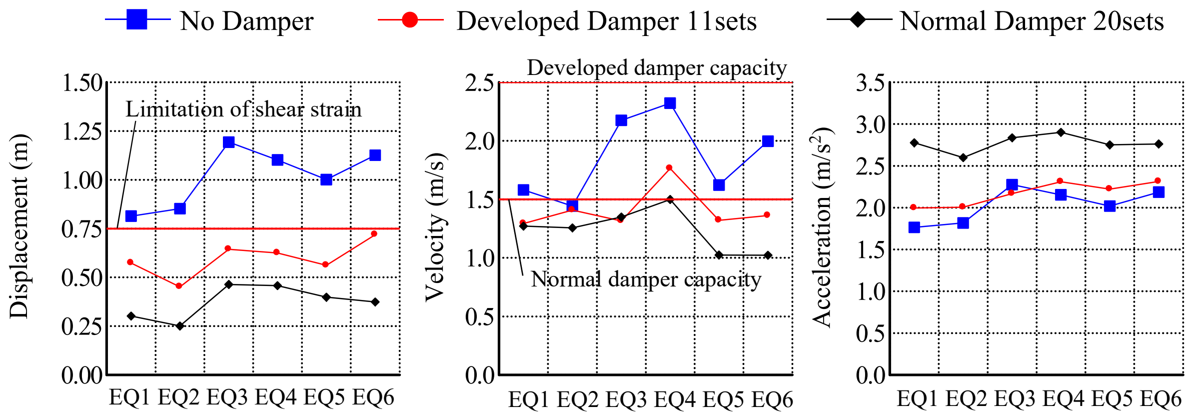
(a) Model (b) Hysteresis of the isolator (LRB)

Figure 2. Model of a base isolated building for earthquake response analyses



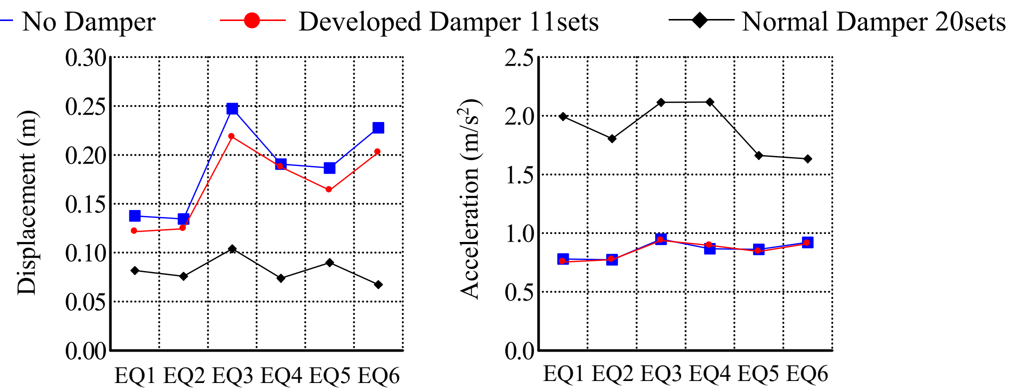
(a) Acceleration spectrum (b) Velocity spectrum

Figure 3. Response spectra of input earthquake waves (L2x3 level, h=0.05)



(a) Displacement (b) Velocity (damper) (c) Acceleration

Figure 4. Maximum response for extremely large earthquakes (L2x3 input level)



(a) Displacement (b) Acceleration

Figure 5. Maximum response for moderate earthquakes (L2 input level)

Figure 4 shows maximum response results for the extremely large earthquake level (L2 x 3.0). Through parametric earthquake response analyses, obtained required number of damper is twenty for the normal damper, and eleven for the developed damper. The number of normal damper is derived from the velocity limit (1.5 m/s), and its maximum response velocity occurs at EQ4 input earthquake. While on the other hand, the number of developed damper is derived from the displacement limitation of rubber bearings (0.75m), and its maximum response displacement occurs at EQ6 input earthquake. As for the developed damper, its maximum response velocity is 1.76 m/s and there remains much allowance to velocity limit of 2.5 m/s. The necessary number of developed damper is almost half than that of normal damper, which is one of the advantage for using the developed damper.

Figure 5 shows maximum response results for the moderate earthquake level (L2). Maximum acceleration of the base isolated building with developed dampers is almost the same as that of without damper, which means the base isolated building with developed dampers is holding a good isolation effect. Through the earthquake responses of the isolated building applied developed dampers and normal dampers, advantages of the developed damper are clearly identified that the developed damper is very effective both to suppress excessive displacement for extremely large earthquakes and to exert good base isolation effect for moderate earthquakes.

DEVELOPMENT OF PROPOSED DAMPER

The external view of the full-scale prototype of the developed damper is shown in Figure 6, and the specifications are shown in Table 1 and Figure 7. This developed damper equips a damping coefficient switching system that increases the damping force sharply when it reaches a predetermined velocity. In addition, although the velocity capacity of a typical oil damper that has obtained Minister's approval of seismic isolation materials as a designated building material in Japan is 1.5 m/s at maximum, this damper can handle a further higher level of earthquake motion, so the maximum velocity is 2.5 m/s. The maximum load was set to 1000 kN. The hydraulic system of the oil tank and the external valve block is provided on both sides of the cylinder, and it is a single rod type damper with a mounting length of about 4.6 m and a weight of about 3200 kg. The mounting portion employs a clevis having a spherical bearing so as to follow up and down behavior in addition to deformation in two directions in a plane.

To realize the damping characteristics of Figure 7, we propose an oil damper with a unique hydraulic circuit shown in Figure 8. The oil damper with this hydraulic circuit automatically switches its damping coefficient using the inner pressure (damper force). This hydraulic circuit includes two main flow paths, an orifice and a poppet valve, and a control circuit. When the damper force is lower than F_1, which corresponding to the predetermined velocity V_0, poppet valve opens and realizes the initial low damping coefficient. When the damper force reaches F_1 or the pressure becomes larger than the initial stress of the pilot valve 1, pilot valve 1 closes and the poppet valve closes consequently, and the damping coefficient switches to high characteristic of the orifice.

On the other hand, if the pressure starts to decrease and the damper force becomes lower than F_2, pilot valve 2 opens via the control circuit, which has been developed in the research of a switching oil damper for damping structures by Kurino et al. (2004). The specific mechanism of the control circuit as follows. When the pressure in the cylinder increases, the pressure in the buffer also increases, but if the pressure is greater than the initial stress of the buffer relief valve, the buffer relief valve opens and the pressure in the buffer is saturated. Thereafter, when the pressure of the cylinder decreases below the pressure of the buffer, the pilot valve 2 is driven to open the poppet valve. This mechanism enables the damping coefficient to switch at the predetermined velocity V_0. In addition, relief valves between the cylinder chambers protect buildings and oil dampers from excessive load.

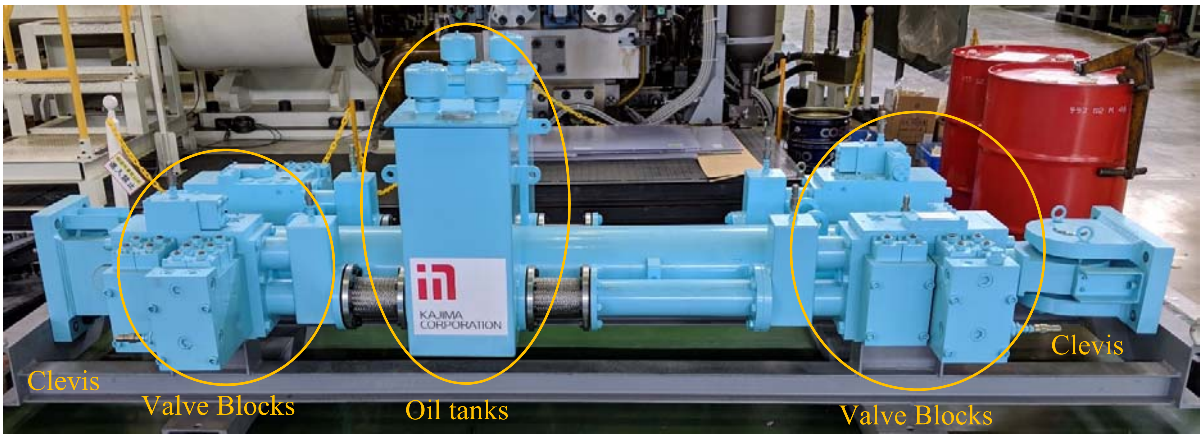


Figure 6. External view of the full-scale developed damper

Table 1: Specification of the developed damper

Item	Specification
Maximum Force [kN]	1000
Relief Force [kN]	800
Maximum Velocity [m/s]	2.5
Maximum Stroke [m]	±1.0
Initial Damping Coefficient [kNs/m]	167
Mounting Length [m]	4.6
Mass [kg]	3200

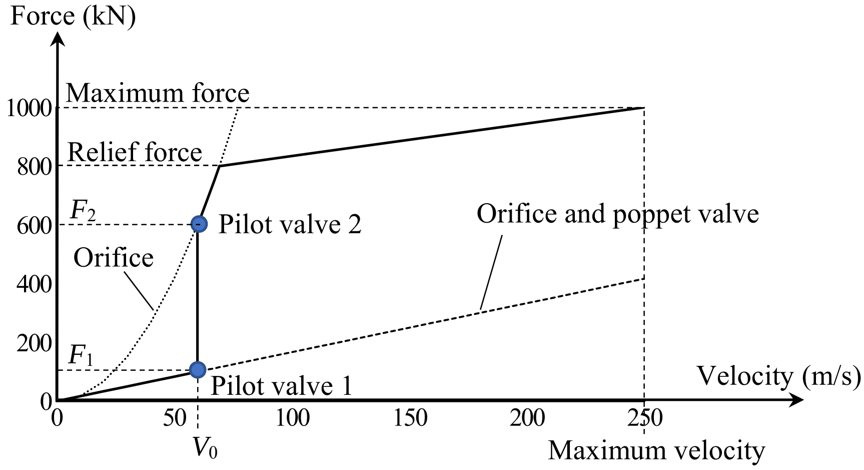


Figure 7. Target performance of the developed damper

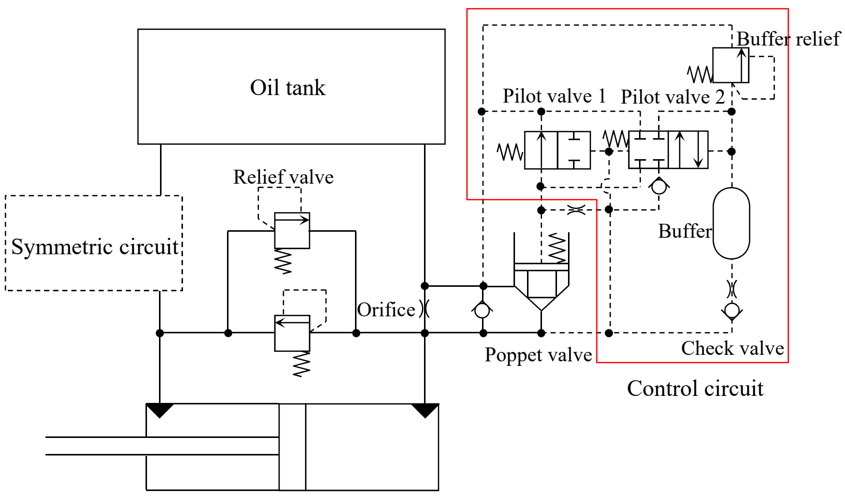


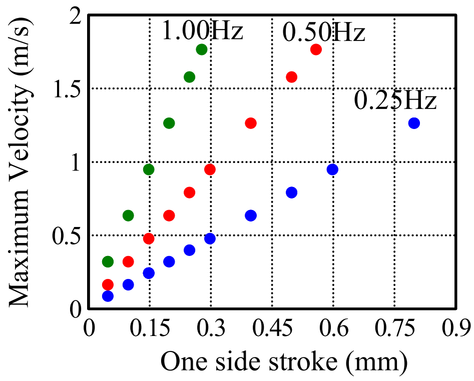
Figure 8. Hydraulic circuit

DYNAMIC LOADING TEST

To confirm the dynamic performance of the developed damper, we conducted experiments on the full-scale prototype specimen. This performance verification experiments were performed using Seismic Response Modification Device (SRMD) at the University of California, San Diego (UCSD). This device is a large-scale dynamic test device that can excite up to ± 1.22 m and 1.78 m/s by four actuators arranged horizontally. First, we conducted sinusoidal loading tests with parameters of amplitude and frequency for evaluation the basic characteristics of the developed damper. Figure 9 shows the experimental setup and sinusoidal loading cases. And also, to examine the dynamic behavior under non-stationary excitation, dynamic loading tests was conducted using seismic response waves of building model.

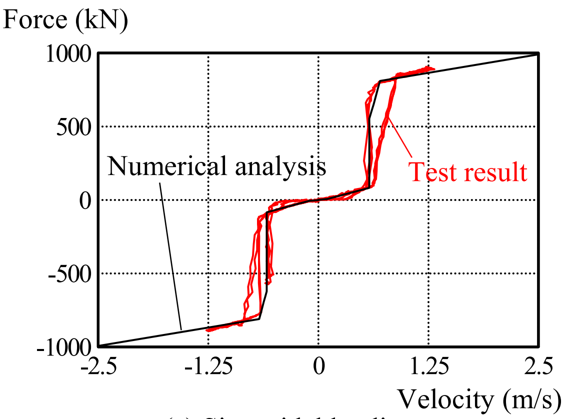
Experimental results of sinusoidal loading (0.25 Hz, maximum amplitude 0.8 m, maximum velocity 1.26 m/s) and earthquake response excitation (maximum amplitude 0.8 m, maximum velocity 1.78 m/s) are shown as a representative. Figure 10 shows the load–velocity relationship, and Figure 11 shows the load–displacement relationship. The black lines in Figure 10 are the characteristics set by numerical analysis to be described later. The developed damper can realize the hardening characteristics at the predetermined velocity 0.6 m/s for not only sinusoidal loading but also seismic response wave loading. The expected behavior including unloading from hardening was confirmed from the low velocity region to the high velocity region of 1.78 m/s.

(a) Experimental Setup

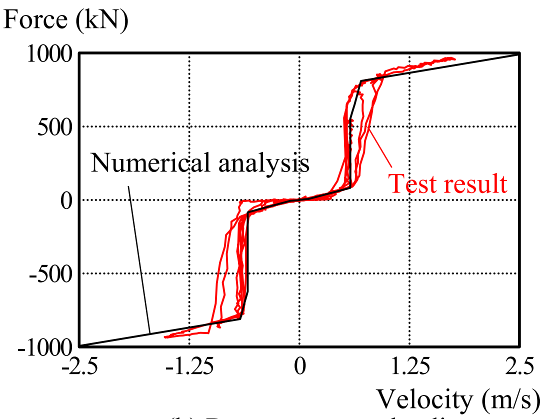


(b) Test cases

Figure 9. Experimental setup and test cases

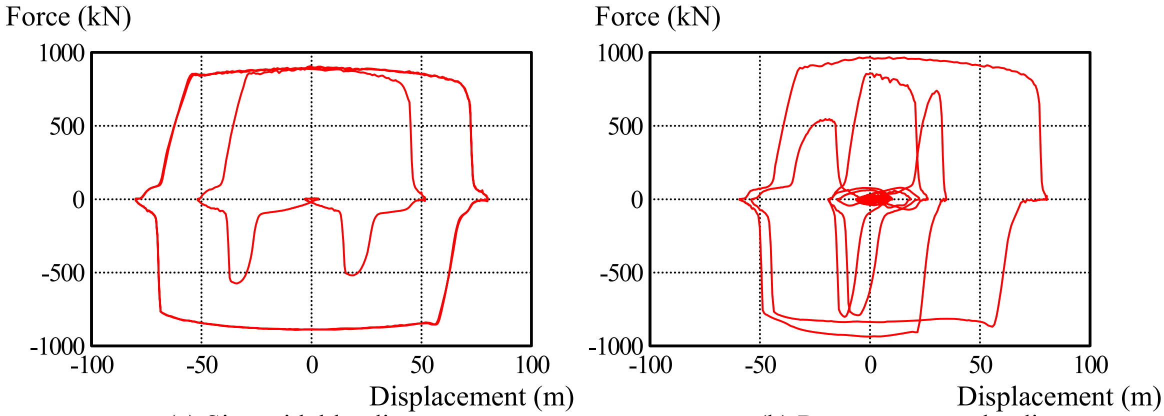


(a) Sinusoidal loading



(b) Response wave loading

Figure 10. Load–velocity relationship of the test results



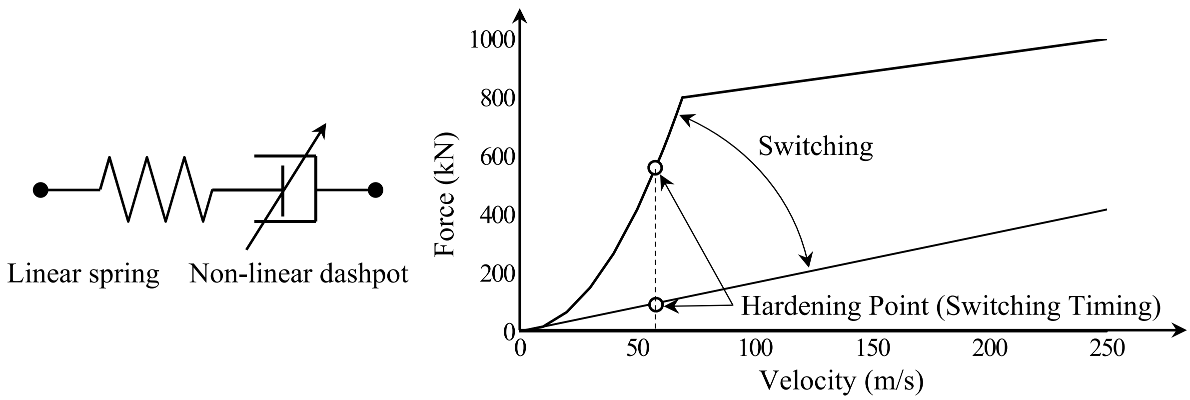
(a) Sinusoidal loading (b) Response wave loading

Figure 11. Load–displacement relationship of the test results

SIMULATION ANALYSIS

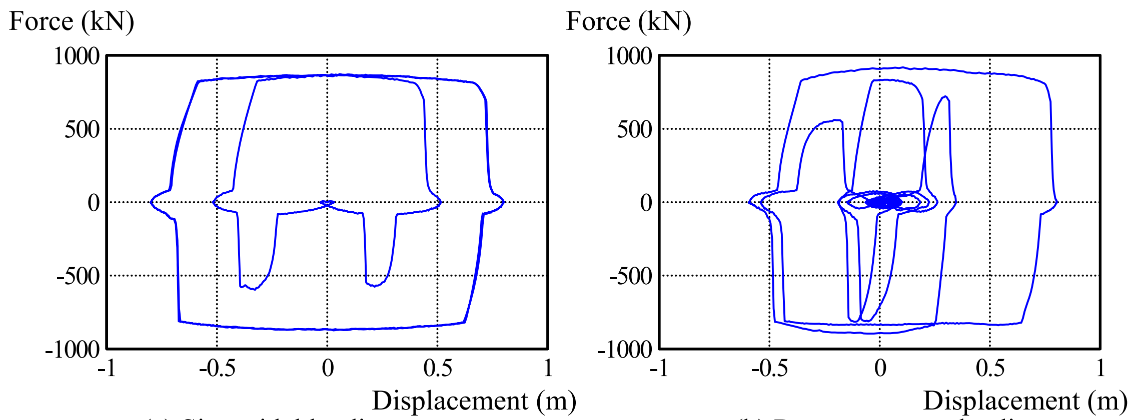
To design a building using a developed damper, we developed a numerical analysis model. In order to verify the validity of the analysis model used in the design, we conducted the simulation analysis of the dynamic loading tests mentioned above. The mechanical model of the developed damper is expressed as Maxwell model as shown in Figure 12(a). This model has non-linear dashpot and the damping coefficient can be switched as shown in Figure 12(b). The observed displacement at both ends of the damper were smoothed using a low-pass filter with a cut-off frequency of 100 Hz, and simulation analysis was performed using the velocity obtained by numerical differentiation of the displacement as an input.

Analysis results of sinusoidal loading (0.25 Hz, maximum amplitude 0.8 m, maximum velocity 1.26 m/s) and earthquake response excitation (maximum amplitude 0.8 m, maximum velocity 1.78 m/s) are shown as a representative. Figure 13 shows the load–velocity relationship, and Figure 14 shows the comparison of the load time histories of the experimental results and the analysis results. It was confirmed that the experimental results and the simulation analysis results agree very accurately, and that complex behavior including hardening can be properly expressed by this analytical model.



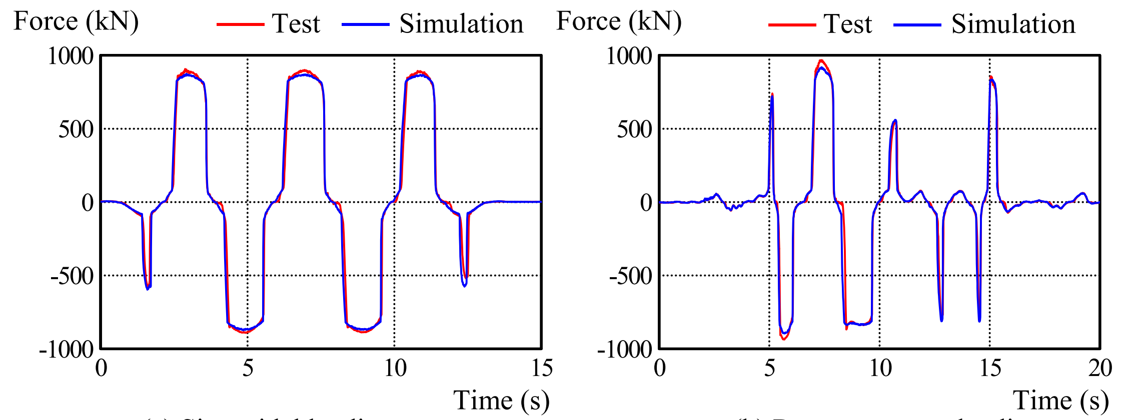
(a) Mechanical Model (b) Force–velocity relationship

Figure 12. Analysis model and the damping characteristic of the non-linear dashpot



(a) Sinusoidal loading (b) Response wave loading

Figure 13. Load–velocity relationships of the simulation analyses



(a) Sinusoidal loading (b) Response wave loading

Figure 14. Comparison of the load time histories of the analysis results and the test results

CONCLUSION

This paper presented a newly developed oil damper for nuclear power plant facilities which is required high safety during extremely large earthquakes. The developed oil damper has hardening characteristics that achieves both high seismic isolation effects for small and medium earthquakes and displacement limitation during extremely large earthquakes. In addition, maximum velocity of the developed damper is 2.5 m/s, which is much higher than that of a conventional seismic isolation oil damper. First, we present the features of the developed damper and clarified the target performance using seismic response analysis. Next, we presented the specifications of the damper and the hydraulic circuit that achieve the hardening characteristic passively. To confirm the dynamic performance of the developed damper, we conducted experiments on the full-scale prototype specimen. The results of the experiment showed that the developed damper had realized the hardening characteristics owing to the hydraulic circuit, and the expected behavior including unloading from hardening was confirmed from the low to high velocity region. According to the results of simulation analysis of the dynamic loading tests using the developed mechanical model, it was confirmed that the experimental results and the simulation analysis results agree very accurately, and that complex behavior of the developed damper including hardening can be properly expressed by this analytical model.

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