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DEVELOPMENT OF DISPLACEMENT SUPPRESSION OIL DAMPER BY INTRODUCING KINETIC ENERGY LIMITATION SYSTEM

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Abstract

In 2006, the 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 NPP facilities. The Base-isolated Important Building of the Fukushima Dai-Ichi NPP was completed in March 2010. Based on evaluation analyses of observation records of the 2011 off the Pacific coast of Tohoku Earthquake by Hijikara et al. [1], it was confirmed that the Base-isolated Important Building functioned as expected and demonstrated a seismic isolation effect during this disaster. Since this earthquake, however, the Nuclear Regulation Authority of Japan has required the safety of NPP facilities to be ensured against extremely large earthquakes that greatly exceed the level in notification for general buildings. As a result, the deformation of a seismic isolation layer would become large, and a possible collision with a moat wall during such extremely large earthquakes would become a concern. A common measure to prevent such a collision is to provide additional oil dampers. Installing a large number of oil dampers, however, sacrifices the seismic isolation effect for medium or smaller earthquakes. In addition, when using a conventional oil damper in a base isolation system, it is necessary to keep not only displacement but also velocity within the allowable range of the oil damper, which is often a more severe limitation.

This paper presents a newly developed passive oil damper for seismically isolated buildings subjected to extremely large earthquakes such as those considered for Nuclear Power Plant (NPP) facilities. Two major characteristics of the developed damper are its high velocity capacity and a kinetic energy limitation system. The kinetic energy limitation system can switch its damping coefficient from low to high passively at a specified velocity to limit a building's kinetic energy. This system can prevent a collision between a moat wall and a seismically isolated building and can achieve both displacement suppression and a seismic isolation. It was originally developed by Kurino et al. [2, 3] as a stroke control system of a tuned mass damper (TMD) system for a high-rise building in Tokyo.

First, we present the features and the target specifications of the developed damper, and show its effectiveness through seismic response analyses. The analysis results show that the developed damper can achieve both displacement suppression and seismic isolation. Next, we show results of dynamic loading tests conducted on a full-scale prototype device. They show that hardening characteristics can be realized by passively switching two hydraulic flow paths. Finally, results of simulation analyses are shown, and it is confirmed that the dynamic characteristics of the damper can be accurately simulated by a nonlinear Maxwell model.

Keywords: Oil Damper; Displacement Suppression; Kinetic Energy Limitation System; Dynamic Loading Test

1. Introduction

In 2006, the 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 seismic isolation systems to NPP facilities. An extremely large ground motion was observed at the Kashiwazaki-Kariwa NPP during the Niigataken Chuetsu-oki Earthquake in 2007, but there was no serious damage that affected the safety system. However, owing to damage to non-structural members such as doors and ceilings, the emergency response center, which was housed in a conventional seismic building, could not perform adequately. Based on this experience, it was recognized that the emergency response center should be housed in a building called a Base-isolated Important Building that is provided with a base isolation system. The Base-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. [1], it was confirmed that the Base-isolated Important Building functioned as expected and demonstrated a seismic isolation effect during this disaster.

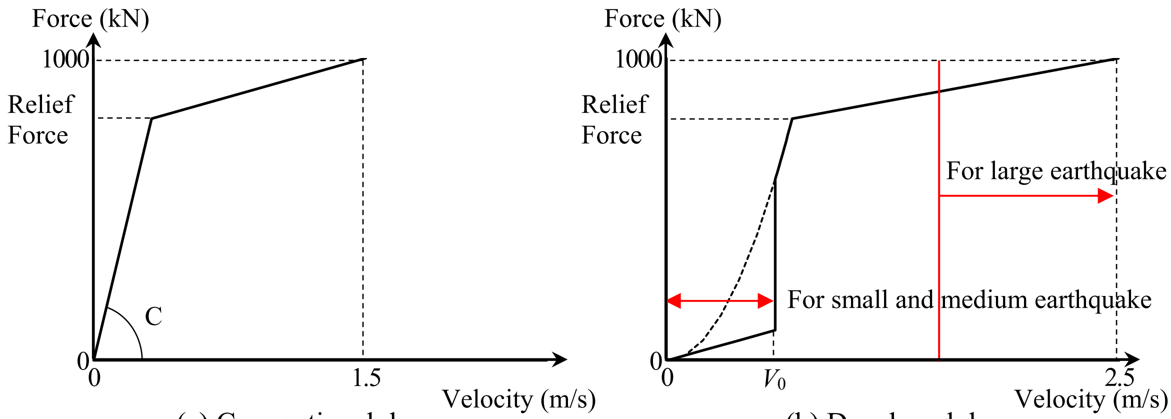
Since this earthquake, however, the Nuclear Regulation Authority of Japan, which was reorganized by the Nuclear Safety Commission, has required the safety of NPP facilities to be ensured against extremely large earthquakes that greatly exceed the level in notification for general buildings. As a result, the deformation of the seismic isolation layer would become large, and a possible collision with a moat wall during such extremely large earthquakes would become a concern. A common measure to prevent such a collision is to provide additional oil dampers. Installing a large number of oil dampers, however, sacrifices the seismic isolation effect during medium or smaller earthquakes. In addition, when using a conventional oil damper in a 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 seismically isolated buildings subjected to extremely large earthquakes such as those considered for NPP facilities. First, we present the features and the target specifications of the developed damper, and show its effectiveness through 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 is thus confirmed that the dynamic characteristics of the damper can be accurately simulated by a nonlinear Maxwell model.

2. Specifications and advantages of developed damper

2.1 Target Performance

Typical force-velocity relations of a conventional oil damper used in a seismic isolation system in Japan are linear or bi-linear, as shown in Fig.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 and smaller earthquakes. In order to achieve both the seismic isolation effect for medium and smaller earthquakes and the displacement suppression effect for extremely large earthquakes, it is necessary to limit the velocity, i.e., kinematic energy, only for large earthquakes to avoid a collision with a moat wall. Specifically, as shown in Fig.1(b), the damping force should increase sharply when the damper's velocity reaches a predetermined velocity V_0, and recover immediately to the original damping coefficient when the damper's velocity falls below V_0. This characteristic is the same as that given to the large-size TMD by Kurino et al. [2, 3], and it can also be expected to suppress the increase in overall layer shear force, which is equivalent to the upper structure's acceleration. In addition, the maximum velocity of conventional oil dampers used for seismic isolation systems in Japan is 1.5 m/s at most, which requires an increase in the number of dampers. Therefore, the maximum velocity of the developed damper is set to 2.5 m/s.

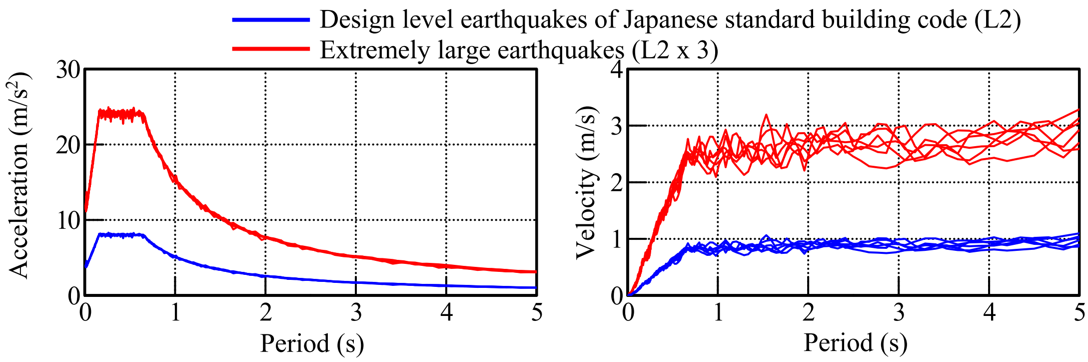


(a) Conventional damper (b) Developed damper

Fig. 1 – Force-velocity relationship of oil dampers

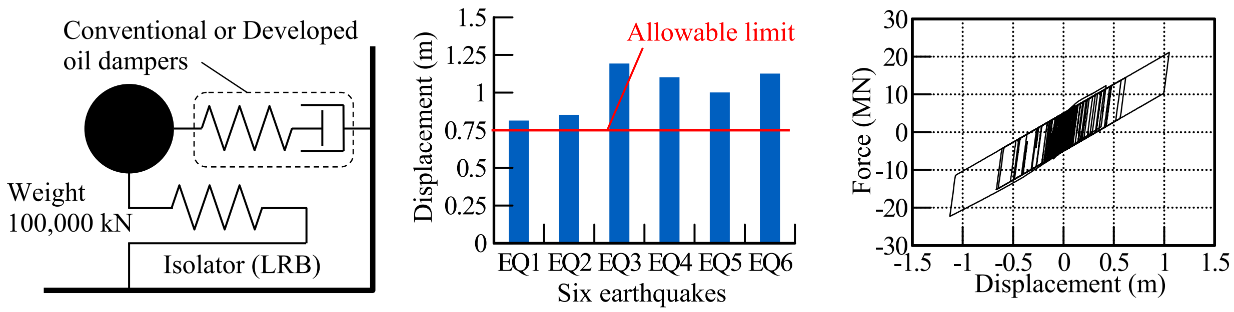
2.2 Seismic response analysis

To demonstrate the advantages of the developed damper, seismic response analyses were conducted for a seismically isolated building. Six design earthquake motions used for seismic design of ordinary seismically isolated buildings and high-rise buildings in Japan were selected for input ground motions as the moderate earthquake level (L2) in this study. As the extremely large earthquake for the study, we tripled the acceleration of those design earthquake motions (L2 x 3.0). The response acceleration and velocity spectrum of the extremely large earthquake (L2 x 3.0) and the moderate earthquake (L2) are shown in Fig.2. The velocity spectrum of the extremely large earthquake with damping ratio h=5% is around 2.5 m/s, which 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. [4].



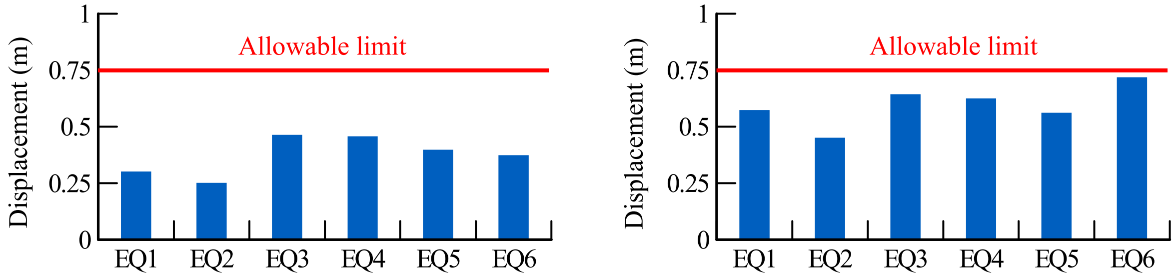
(a) Acceleration spectrum (b) Velocity spectrum

Fig. 2 – Response spectra of input earthquake waves (L2x3 level, h=0.05)



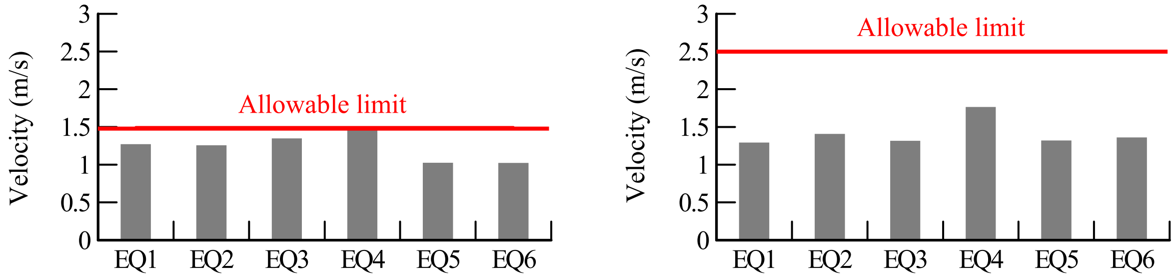
(a) Mechanical model (b) Maximum deformation of LRB (c) Hysteresis of the LRB

Fig. 3 – Model of seismically isolated building and seismic response without oil dampers



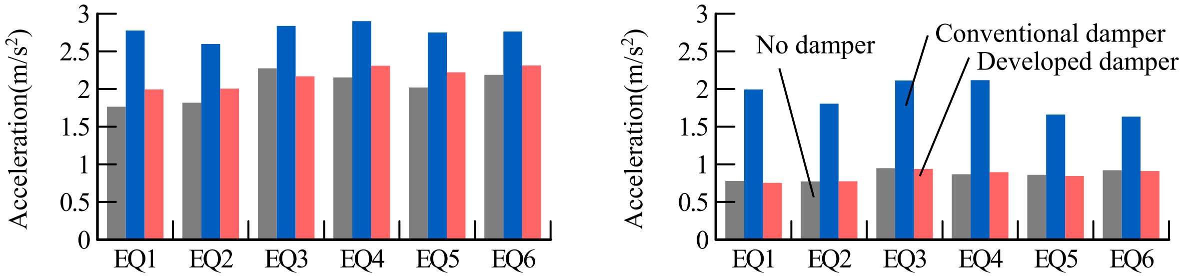
(a) Conventional dampers (20 units) (b) Developed dampers (11 units)

Fig. 4 – Maximum response displacement for extremely large earthquakes (L2 x 3)



(a) Conventional dampers (20 units) (b) Developed dampers (11 units)

Fig. 5 – Maximum response velocity for extremely large earthquakes (L2 x 3)



(a) Extremely large earthquake (L2 x 3.0) (b) Moderate earthquake (L2)

Fig. 6 – Maximum response acceleration

The analytical model is a single-degree-of-freedom model with one elastoplastic spring that represents the base isolation device and one Maxwell model that represents oil dampers, as shown Fig.3(a). Lead Rubber Bearings (LRB) are used as the isolator spring. The conventional damper is a typical type on the market in Japan. Its largest velocity capacity is 1.5 m/s and its damping characteristic is as shown in Fig.1(a). The initial damping coefficient C in Fig.1(a) is 2500 kNsec/m. The damping characteristic of the developed oil damper is shown in Fig.1(b). Relief forces of both dampers are 800 kN. The developed damper has a relatively small damping coefficient in the low- to medium-velocity region, which maintains a good base isolation effect for medium and smaller levels of ground shakings even if quite a few dampers are used for extremely large earthquakes to prevent collisions between seismically isolated buildings and moat walls. The developed damper sharply increases 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. The maximum velocity of the developed damper is set at 2.5 m/s so it can be used during extremely large earthquakes for NPPs. The maximum response deformation of the LRB against extremely large earthquakes without oil dampers are shown in Fig.3(b) and an example of a hysteresis of an isolator spring is shown in Fig.3(c). In all six waves, it exceeds 0.75 m, which is the criterion described later.

First, we determined the number of dampers necessary for extremely large earthquakes based on the seismic response analysis. The required number of dampers was determined so as not to exceed a linear limit of shear strain of the LRB, and 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% linear limit of shear strain of the 0.3 m total rubber thickness of the LRB. The velocity limit is 1.5 m/s for the conventional damper and 2.5 m/s for the developed damper.

Fig.4 and Fig.5 show the maximum response displacement and velocity, respectively, for the extremely large earthquake level (L2 x 3.0) with oil dampers. Through parametric earthquake response analyses, it was determined that the required number of dampers was 20 for the conventional damper and 11 for the developed damper. The number of conventional dampers was derived from the velocity limit (1.5 m/s), and its maximum response velocity occurs for an EQ4 input earthquake. The number required for the developed damper was derived from the displacement limitation of rubber bearings (0.75 m), and its maximum response displacement occurs for an EQ6 input earthquake. The maximum response velocity for the developed damper was 1.76 m/s, which is much less than the velocity limit of 2.5 m/s. The required number of developed dampers is almost half that of conventional dampers, which is one of the advantages of the developed damper.

Fig.6 shows the maximum response acceleration for the moderate earthquake level (L2) and the extremely large earthquake level (L2 x 3.0). For a certified product, in addition to that fact that the initial damping coefficient per unit is large, the number of units installed is also large due to the velocity limitation, so it can be seen that the seismic isolation effect for the Level 2 earthquake is greatly deteriorated. On the other hand, the maximum acceleration of the seismically isolated building with developed dampers is almost the same as that without dampers, which shows that the seismically isolated building with developed dampers maintains good isolation effect. Through the earthquake responses of the isolated building with developed dampers and conventional dampers, the advantages of the developed damper are clearly identified, showing that the developed damper is very effective in both suppressing excessive displacement for extremely large earthquakes and providing good base isolation effect for moderate earthquakes.

3. Full-scale experiment and simulation analysis

3.1 Development of full-scale damper

An external view of the full-scale prototype of the developed damper is shown in Fig.7, and the specifications are shown in Table 1 and Fig.8. It is equipped with a damping coefficient switching system that sharply increases the damping force when it reaches a predetermined velocity. The conventional oil damper that has obtained the Minister's approval as a seismic isolation device in Japan has a maximum velocity capacity of 1.5 m/s. However, our developed damper can handle a higher level of earthquake motion, having a velocity capacity of 2.5 m/s. The maximum load was set to 1000 kN. A hydraulic system consisting of oil tanks and external valve blocks is provided on both side of the cylinder. It is a single-rod-type damper with a mounted length of about 4.6 m and a weight of about 3200 kg. The mounted portion employs a clevis having a spherical bearing that allows it to follow up and down behavior in addition to deformation in two directions in a plane.

Table 1 – Specification of developed damper

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

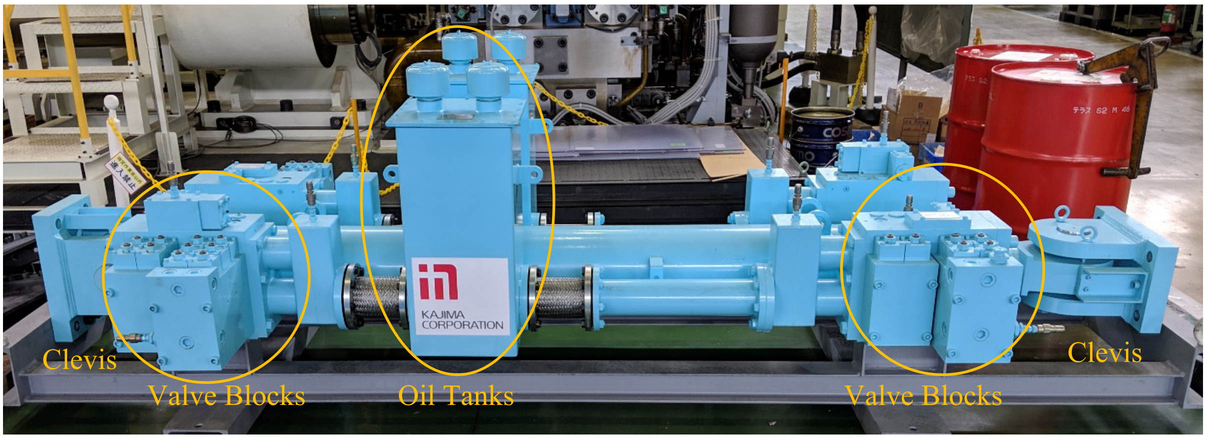


Fig. 7 – External view of full-scale developed damper

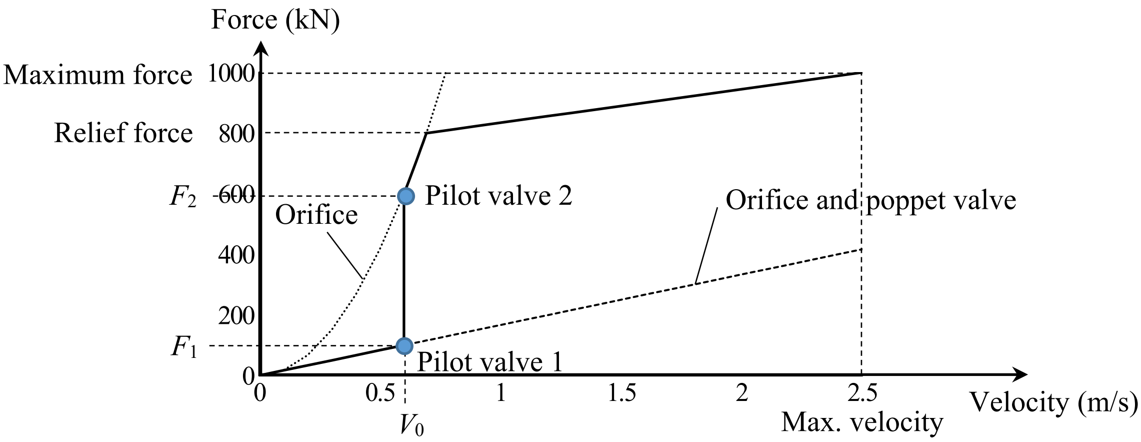


Fig. 8 – Target performance of developed damper

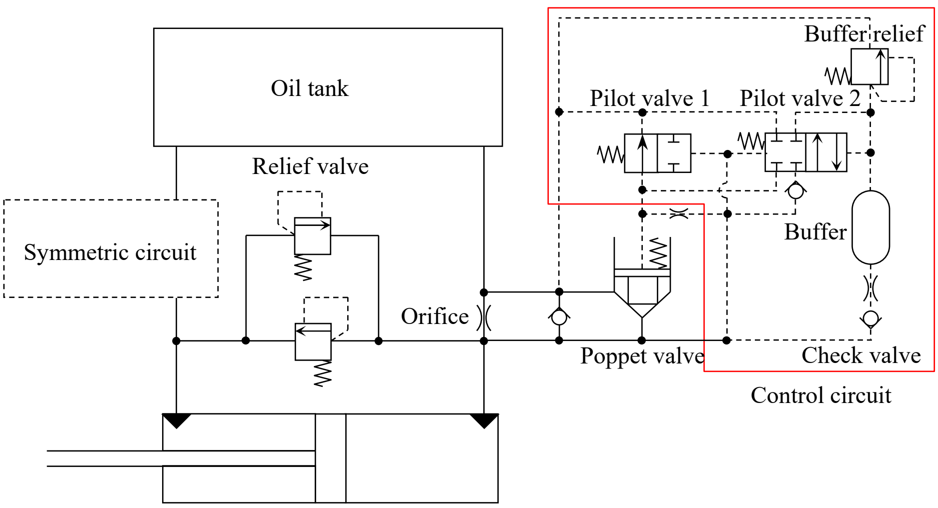


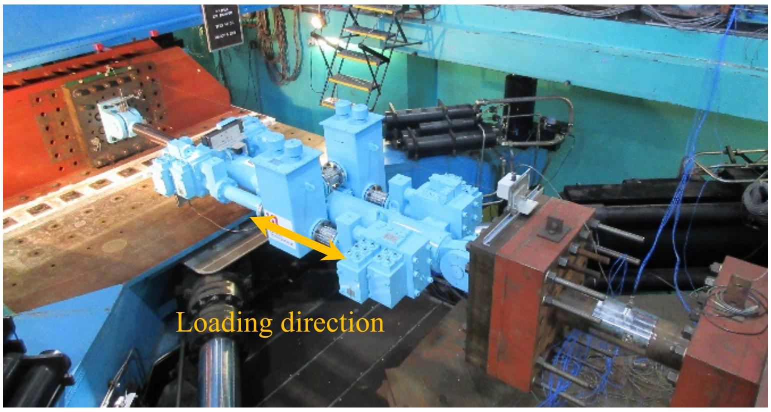
Fig. 9 – Hydraulic circuit

To realize the damping characteristics of Fig.8, we propose an oil damper with the unique hydraulic circuit shown in Fig.9. The oil damper with this hydraulic circuit automatically switches its damping coefficient using the inner pressure (damper force). The hydraulic circuit includes two main flow paths, an orifice, a poppet valve, and a control circuit. When the damper force is lower than F_1, corresponding to the predetermined velocity V_0, the 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 pilot valve 1, pilot valve 1 closes causing the poppet valve to close, and the damping coefficient switches to the high characteristic of the orifice.

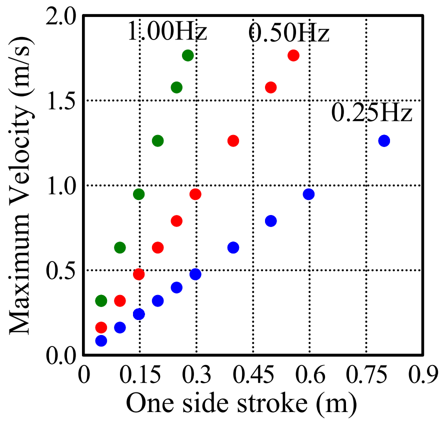
On the other hand, if the pressure starts to decrease and the damper force becomes lower that F_2, pilot valve 2 opens via the control circuit, which was developed in the research of a switching oil damper for damping structures by Kurino et al. [5]. The specific mechanism of the control circuit is as follows. When the cylinder pressure increases, the buffer pressure also increases, but if the pressure is greater than the initial stress of the buffer relief valve, the buffer relief valve opens and the buffer pressure becomes saturated. Thereafter, when the cylinder pressure decreases below the buffer pressure, 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.

3.2 Dynamic loading test

To confirm the dynamic performance of the developed damper, we conducted experiments on the full-scale prototype specimen. These verification experiments were performed using a Seismic Response Modification Device (SRMD) at the University of California, San Diego (UCSD). This loading device is a large-

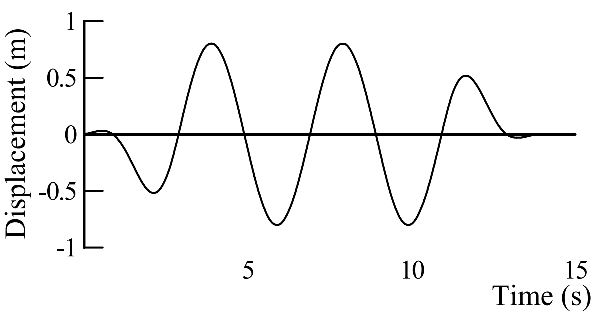


(a) Experimental Setup

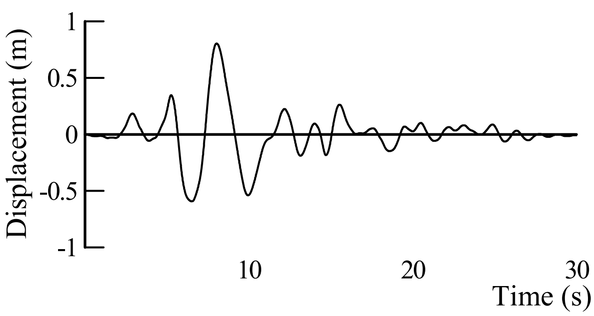


(b) Test cases

Fig. 10 – Experimental setup and test cases

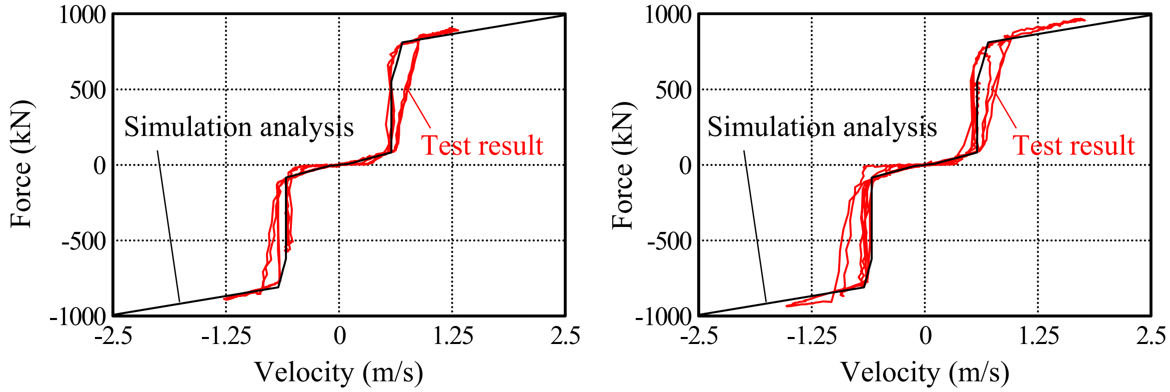


(a) Sinusoidal loading



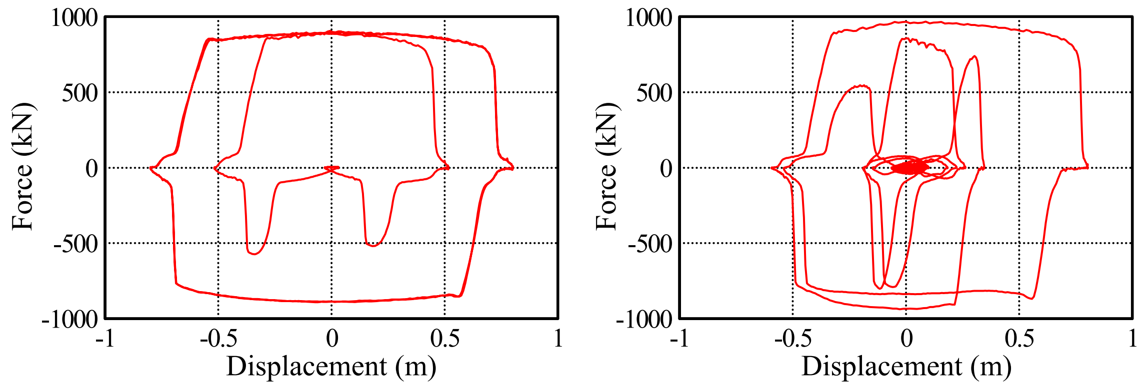
(b) Non-stationary loading

Fig. 11 – Examples of loading displacement waves



(a) Sinusoidal loading (b) Non-stationary loading

Fig. 12 – Force-velocity relationship of test results



(a) Sinusoidal loading (b) Non-stationary loading

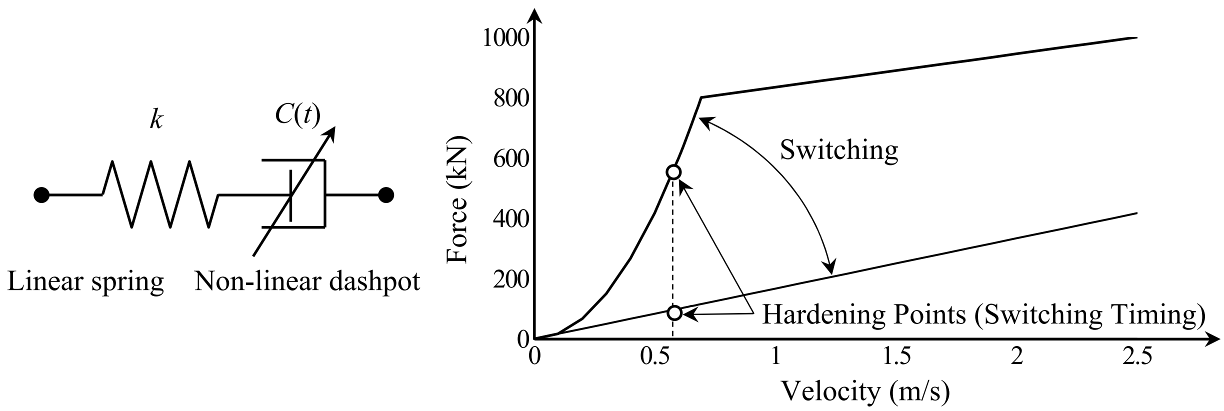
Fig. 13 – Force-displacement relationship of test results

scale dynamic test device that can excite up to ±1.22 m and 1.78 m/s with four actuators arranged horizontally. First, we conducted sinusoidal loading tests with parameters of amplitude and frequency to evaluate the basic characteristics of the developed damper. Fig.10 shows the experimental setup and sinusoidal loading cases. Also, to examine the dynamic behavior under non-stationary excitation, dynamic loading tests was conducted using seismic response waves of the building model.

Experimental results of sinusoidal loading (0.25 Hz, maximum displacement 0.8 m, maximum velocity 1.26 m/s) and non-stationary loading (maximum displacement 0.8 m, maximum velocity 1.78 m/s) are shown as representative. Fig.11 shows the loading displacement, Fig.12 shows the force–velocity relationship, and Fig.13 shows the force–displacement relationship. The black lines in Fig.12 indicate the characteristics set for simulation analysis described later. The developed damper can realize hardening characteristics at the predetermined velocity of 0.6 m/s for not only sinusoidal loading but also seismic response wave loading. The changing behavior of the damping coefficient was very smooth. The expected behavior including unloading from hardening was confirmed from the low-velocity region to the high-velocity region of 1.78 m/s.

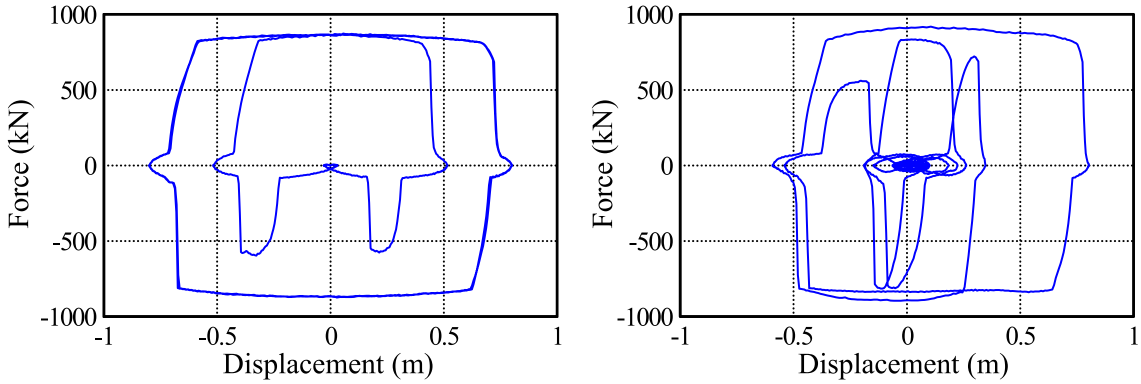
3.3 Simulation analysis

To design a building using the developed damper, we developed a numerical analysis model. In order to verify the validity of this model, we conducted a simulation analysis of the dynamic loading tests mentioned above. The mechanical model of the developed damper is expressed as a Maxwell model as shown in Fig.14(a). It has a non-linear dashpot that can be switched at hardening points. Its characteristics are shown in Fig.14(b).



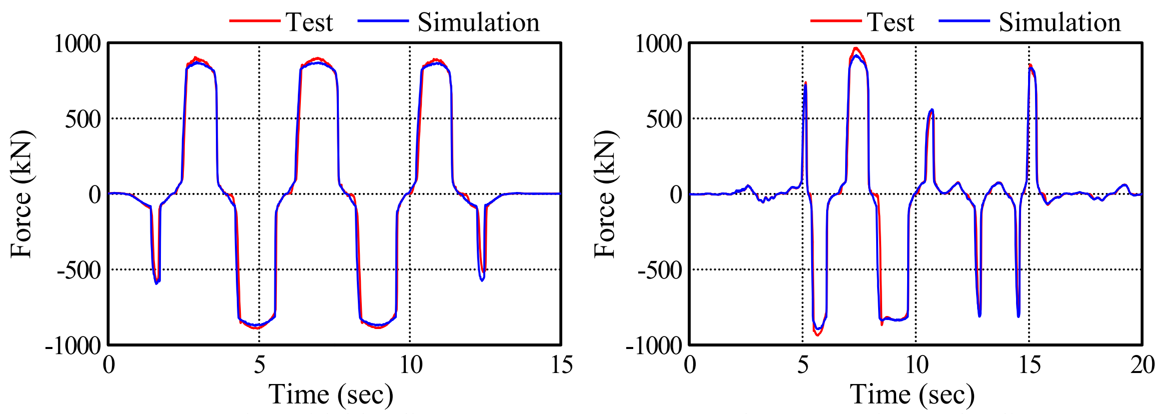
(a) Mechanical Model (b) Force–velocity relationship

Fig. 14 – Analysis model and damping characteristic of non-linear dashpot



(a) Sinusoidal loading (b) Non-stationary loading

Fig. 15 – Force-velocity relationsihps of analysis results



(a) Sinusoidal loading (b) Non-stationary loading

Fig. 16 – Comparison of load time histories of analysis results and test results

The simulation analysis was performed by discretizing the compatibility condition of the Maxwell model's velocity expressed in Eq. (1) in the time domain. 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 the simulation analysis was performed using the velocity obtained by numerical differentiation of the displacement as an input $\dot{x}$.

$$\frac{\dot{F}}{k}+\frac{F}{C(t)}=\dot{x} \tag{1}$$

Analysis results of sinusoidal loading (0.25 Hz, maximum displacement 0.8 m, maximum velocity 1.26 m/s) and non-stationary loading (maximum displacement 0.8 m, maximum velocity 1.78 m/s) are shown as representative. Fig.15 shows the force–velocity relationship corresponding to the test results in Fig.13, and Fig.16 compares the force time histories of the experimental results and the analysis results. It is thus confirmed that the experimental results and the simulation analysis results agree very closely, and that complex behavior including hardening can be appropriately expressed by this analytical model.

4. Conclusion

This paper has presented a newly developed oil damper for nuclear power plant facilities that require a high safety level during extremely large earthquakes. This damper has hardening characteristics that achieve both high seismic isolation effects for small and moderate earthquakes and displacement limitation during extremely large earthquakes. In addition, the 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 presented the features of the developed damper and clarified its target performance using seismic response analysis. Next, we presented the specifications of the damper and the hydraulic circuit that achieved the hardening characteristic passively. To confirm the dynamic performance of the developed damper, we conducted experiments on a full-scale prototype. The results of the experiment showed that the developed damper 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. The results of simulation analysis of the dynamic loading tests using the developed mechanical model confirmed that the experimental results and the simulation analysis results agreed very closely, and that the complex behavior of the developed damper including hardening can be appropriately expressed by this analytical model.

5. Acknowledgements

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6. References

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