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Seismic-upgrading of Existing Stacks of Nuclear Power Station using Structural Control Oil Dampers

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ABSTRACT :

This paper discusses a seismic-upgrading project for 100m-high steel stacks in a nuclear power station. For this upgrading, we reexamined seismic loads, and set up a new target earthquake that exceeds the original design loads when the stack was designed. First, we examined the possibility of conventional reinforcement by building a new supporting tower to surround the existing stack. It was, however, clarified that several problems would remain unsolved with such simple reinforcement. In order to provide high damping as well as higher strength, we planned to link the stack and the supporting tower via oil dampers. Numerical analysis results showed remarkable response reduction effects, but also clarified that the required damper's stroke would need to be over 200mm and its velocity almost 2.0m/sec, which beyond the performance of existing products. Thus, we developed a high-performance oil damper that meets these stringent specifications. This paper presents the upgrading plan, simulation results and the newly developed oil damper.

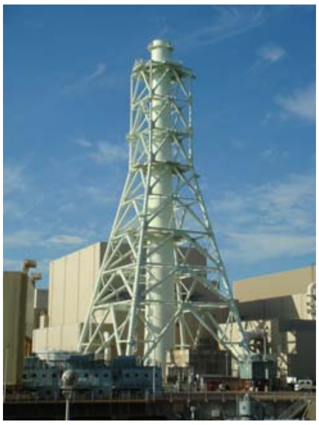
KEYWORDS: Structural control, Oil damper, Nuclear power plant, Stack, Damping augmentation

1. INTRODUCTION

Discussed here is a seismic-upgrading project for steel stacks in an existing nuclear power station, utilizing structural control technologies. The target Hamaoka nuclear power station consists of five reactor buildings, and is located in an area where a severe earthquake is expected in the future. Although the seismic safety was thoroughly examined when the each unit was designed, it has become very important to improve the plant's safety by utilizing up-to-date knowledge and technologies. Three stacks (units-3, 4 and 5) are included in this upgrading program, but this paper focuses on unit- 4. Figure 1 shows photos of the stack of unit-4 before and after upgrading project. Original tube-shaped stack was constructed about thirteen years ago, and is about 100m high, and stands without any supporting frames.

For this project, we reexamined the seismic loads, and set up a new target earthquake for structural design. This target design earthquake is much stronger than the original design loads when the stack was constructed. First, we examined the possibility of conventional reinforcement by building up a new supporting tower to surround the existing tube-shaped stack. It was, however, clarified that such simple reinforcement could not reduce the response stresses of the stack and its base to within their permissible values. In addition, the estimated reaction force of the supporting tower is very large, making it quite difficult to design and place its bases because the construction work would have to be carried out while the power station is running. Thus, a structural control technology that could reduce the seismic response became the key to solving these problems. In order to provide high damping as well as higher strength, we planned to link the existing stack and the supporting tower via oil dampers. Numerical analysis showed remarkable response reduction effects, but they also clarified that new oil dampers would need to be newly developed. This is because the analyses showed that the required damper stroke and velocity are about 200mm and 2.0m/sec respectively, which beyond the performance of existing products. Thus, we developed a high performance oil damper that meets these stringent specifications. This paper presents the upgrading project, simulation results and the newly developed oil damper.

(a) Before upgrading

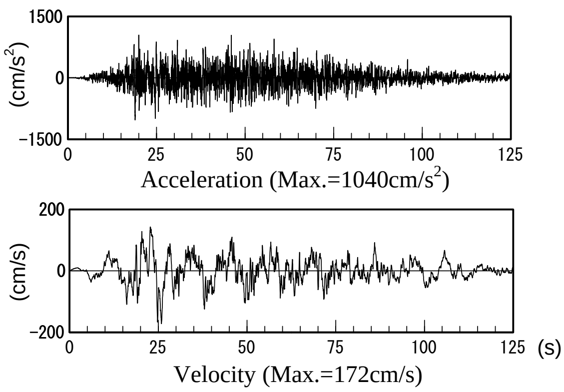


(b) After upgrading

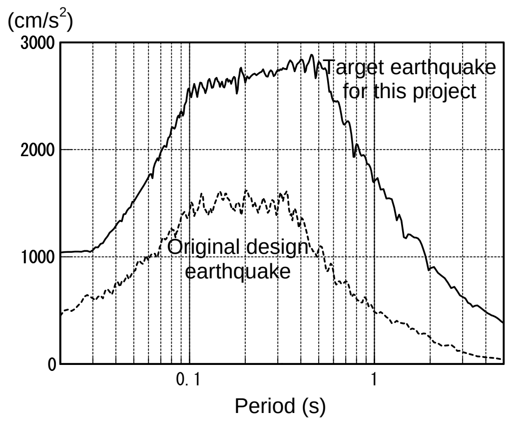
Figure 1 Photo of the stack (unit-4)

2. TARGET EARTHQUAKE

Figure 2 shows a newly-set-up target earthquake for this upgrading project. Figure 2(a) shows a time history which is evaluated at bedrock (FL-20m, Vs=700m/s). The peak acceleration is 1040cm/s^2 and the peak velocity is 172cm/s. Figure 2(b) shows an acceleration response spectrum (damping ratio h=0.05). The acceleration spectrum of an original design earthquake, which was used for designing the existing stacks, is also shown in Figure 2(b) for comparison. The spectrum of the new target earthquake is about twice as strong as that of the original design earthquake, which makes this seismic upgrading design very challenging.



(a) Time history



(b) Acceleration spectrum (h=0.05)

Figure 2 Target design earthquake

3. STRUCTURAL DESIGN UTILIZING OIL DAMPERS

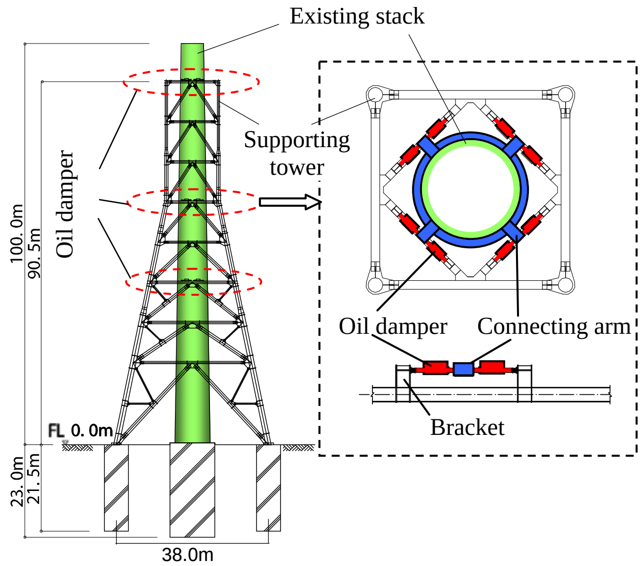
3.1. Structural Design Concept

Figure 3(a) shows an outline of the upgrading structural design. The existing tube-shaped steel stack is about 100m high with a diameter from 8.8m at the base to 5.6m at the top. We planned to build a new supporting tower 90.5m high to surround the existing stack, and to connect the two structures via oil dampers. The detail of the joint part is described in the figure. The damper is inserted between a connecting arm, which will be attached to the existing stack, and the bracket of the new supporting tower. We arranged three connecting levels (FL+90.5m, 60.5m and 40.5m) in considering various obstacle attachments of the existing stack. The oil damper generates a reaction force against a relative motion between the existing stack and the supporting tower, and augments the damping effect to both structures to reduce the response vibration.

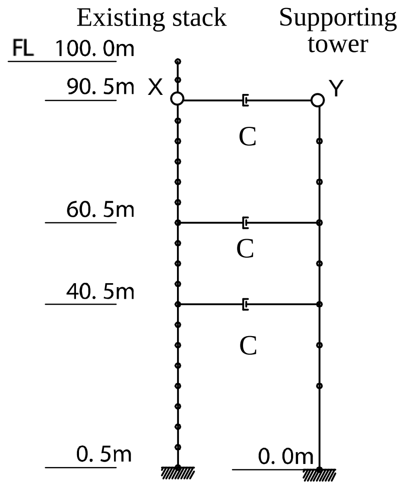
3.2. Study on Damper Parameters

The number of dampers and their parameters are determined considering both the damping ratio augmented to the structures and the response of the damper portion. The following outlines the strategy for determining the damper parameters.

Figure 3(b) shows a simplified vibration model used for this study. The existing stack and the supporting tower are modeled as lumped mass bending shear elements. The oil dampers are expressed as a dashpot. Although it is known that the dynamic characteristic of oil dampers is expressed as a Maxwell model, we simply model the oil damper as a dashpot here because the effect of the stiffness is small. We, however, consider its stiffness in the seismic response analyses shown in a later chapter. The natural periods of the existing stack and the supporting tower without oil dampers are 1.15sec and 0.38sec respectively. If the damper is replaced by a rigid spring, the period of the linked structure becomes 0.52sec.



(a) Damper installation



(b) Simplified vibration model

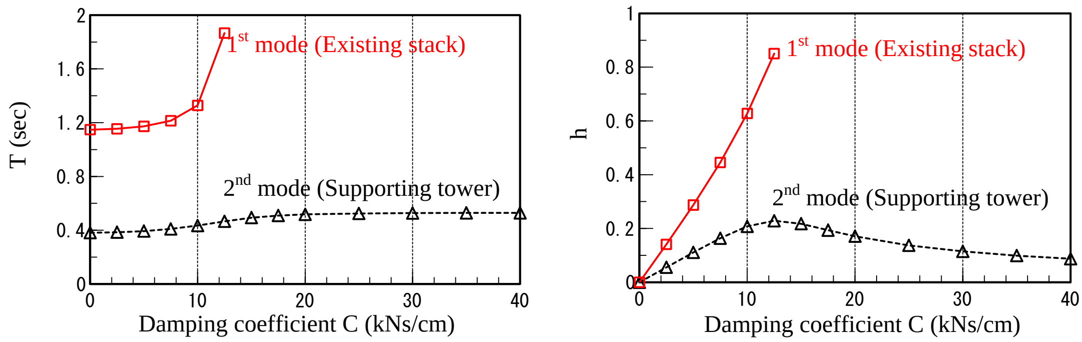
Figure 3 Outline of structural design

In order to grasp the relation between the damping coefficient of each damper and the vibration characteristics of the structure, we conducted complex eigenvalue analyses. For simplicity, we assumed that the damping coefficients at each connecting level are equal, and that the original damping of both structures is zero. Figure 4 shows the damping ratio and the eigenperiod of the fundamental modes obtained by the complex eigenvalue analyses. The horizontal axis shows a damping coefficient C at each level in Figure 3(b). From Figure 4, the following are recognized:

1. When C is smaller than about 10kNs/cm, two independent eigenvalues are obtained as fundamental modes. This means that the interaction between the existing stack and the supporting tower is small. In this region, the damping ratios h of both structures increase in proportion to C.
2. When C becomes 12.5kNs/cm, the stack's damping ratio reaches 1.0 and its eigenperiod suddenly becomes longer because of the relation $\omega' = \sqrt{1-h^2}\,\omega$. The damping ratio of the supporting tower also becomes a maximum.
3. When C is larger than 12.5kNs/cm, only one eigenvalue remains as a fundamental mode because the stack and the supporting tower strongly interact with the oil dampers. If C increases much more, the damping ratio gradually decreases and the eigenperiod approaches the value for the case where the two structures are rigidly linked.

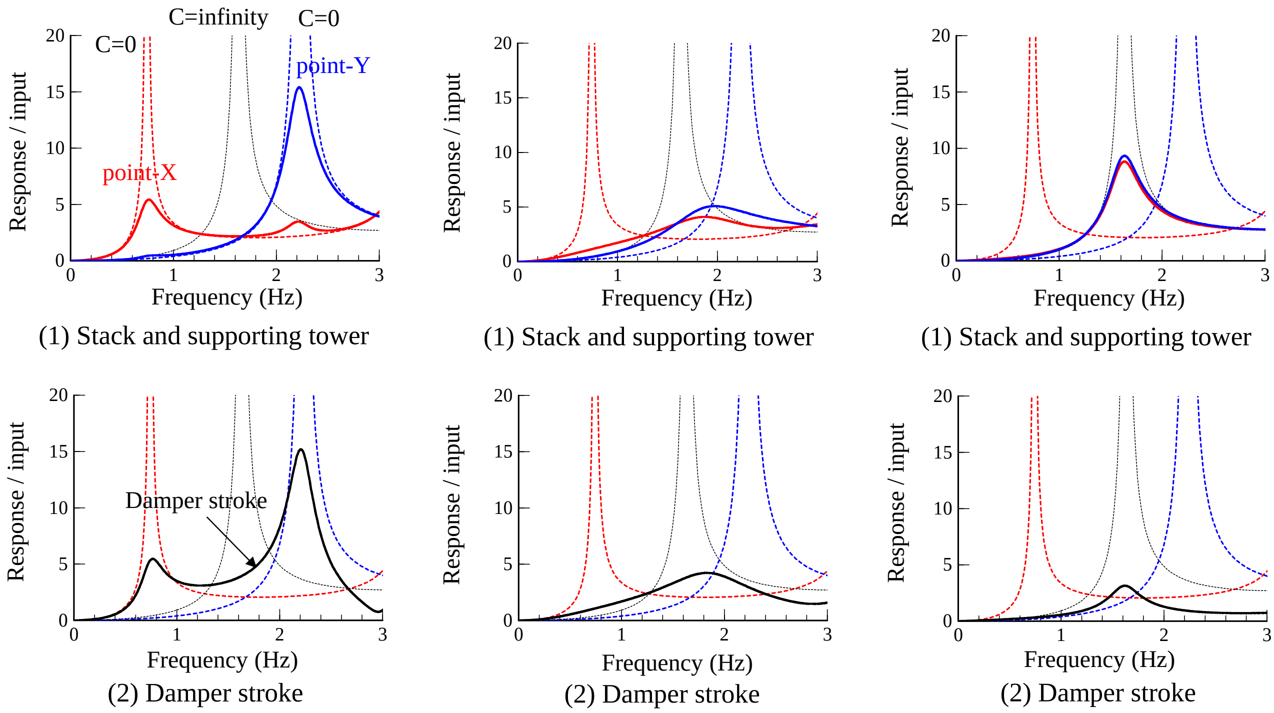
Therefore, it seems logical to set C for each level as 12.5kNs/cm if we focus on the damping augmentation of the fundamental vibration modes. However, we should take into account not only the damping augmentation but also the response of the damper portion in order to avoid the damper's specification becoming unrealistic.

Figure 5 shows resonance curves corresponding to three typical values of C in Figure 4. The upper figures (1) show the displacement amplitudes of the stack and the supporting tower (point X and Y in Figure 3(b)). The lower figures (2) show the displacement amplitude between point X and Y, which is equivalent to the damper stroke. From the viewpoint of response reduction of the structures, case-B seems to have the best setting. However, the resonance curve of damper response still extends over a wide frequency range. On the other hand, the damper response is kept small in case-C because the interaction between the two structures becomes stronger than in case-B. Compared with the case-B, the peak of the resonance curves of the stack and the supporting tower becomes a little higher. This, however, does not mean that the structure's response increases rapidly. Therefore, we decided to set the damping coefficient at each level to around 30kNs/cm considering not only structural response reduction but also damper stroke control.



(a) Eigen period T (b) Damping ratio h

Figure 4 Complex eigen-values of fundamental modes



(a) Case-A (C=2.5kNs/cm) (b) Case-B (C=12.5kNs/cm) (c) Case-C (C=40.0kNs/cm)

Figure 5 Resonance curves with various damper settings

3.3. Determined Damper Parameters

Table 1(a) shows the finally determined specifications of the oil damper. From the viewpoint of maintenance, it is rational to use the same device for all connecting levels of all units, but because the required strokes and velocities are very different, we chose two different specifications. The damper distribution is shown in Table 1(b). The eigenperiod and damping ratio evaluated by complex eigenvalue analyses for the final setting are 0.54sec and 0.12 respectively. As shown in a later chapter, these two types of dampers have the same force capacity but different stroke capacities and damping coefficients. The damping coefficient, or velocity capacity, is determined by the total capacity of housed valves. The two kinds of dampers, shown in Table 1, house the same sized valves, but different numbers of valves. For efficient development and future maintenance, using common components has several advantages.

Table 1 Damper specification and distribution

(a) Specification

Type	Damping coefficient	Stiffness	Permissible velocity	Stroke
L	5.0kNsec/cm	80kN/mm	180cm/s	±300mm
M	7.5kNsec/cm	110kN/mm	120cm/s	±200mm

(b) Distribution

Vertical level	Damper type	Number
FL 90.5m	L	16
FL 60.5m	M	8
FL 40.5m	M	8

3.4. Seismic Response Analysis

Figure 6 shows an example of the vibration model used for seismic response analyses. In order to consider soil-structure interaction, the soil portion is modeled as a multi-degree-of-freedom lumped mass model (MDOF parallel model [Onouchi and Tachibana 2005]). The viscous boundaries at the bottom, on the side and also in the depth dimension are applied as the boundary conditions when considering energy dissipation effects. The oil damper portion is modeled as a Maxwell model instead of a dashpot in Figure 3(b) to accurately take into account the effect of the damper's stiffness. In this analysis, we assume a structural damping ratio of 0.01 for the existing stack, 0.02 for the supporting tower, and 0.05 for the reinforced concrete base. The input earthquake motion at FL-100m for the MDOF parallel model is calculated using one-dimensional wave propagation theory for the target earthquake shown in Figure 2, defined at bedrock (FL-20m).

Figure 7 shows the maximum response distribution. Figure 7(a) shows the acceleration of the existing stack, (b) shows the bending moment of the existing stack, and (c) shows the bending moment of the supporting tower. For comparison, each figure includes the results of the case in which the existing stack and the supporting tower vibrate independently (without damper), and that in which the existing stack and the supporting tower are linked by rigid springs instead of oil dampers (conventional reinforcement). Although conventional reinforcement linking the two structures with a rigid spring can reduce the bending moment of the existing stack to some extent, the responses still exceed the permissible values. In addition, the responses of the supporting tower become so large that it becomes difficult to design the tower. However, with dampers, the bending moment of the existing stack meets the requirements, and the response of the supporting tower is reduced to almost half of that for the rigidly linked connection. Thus, the effect of structural control, which cannot be realized with conventional reinforcement, is clearly recognized from the results of simulation analyses. It is also confirmed that the damper responses meet the requirements shown in Table 1 (L-type maximum velocity: 120cm/s, stroke: 134mm).

In addition to the above, we conducted optional calculations by changing the damper's damping coefficient by plus or minus 20%, which represents the differences between the devices and the fluctuations caused by the temperature dependency. It is confirmed that all the response values in these optional cases also meet the requirements.

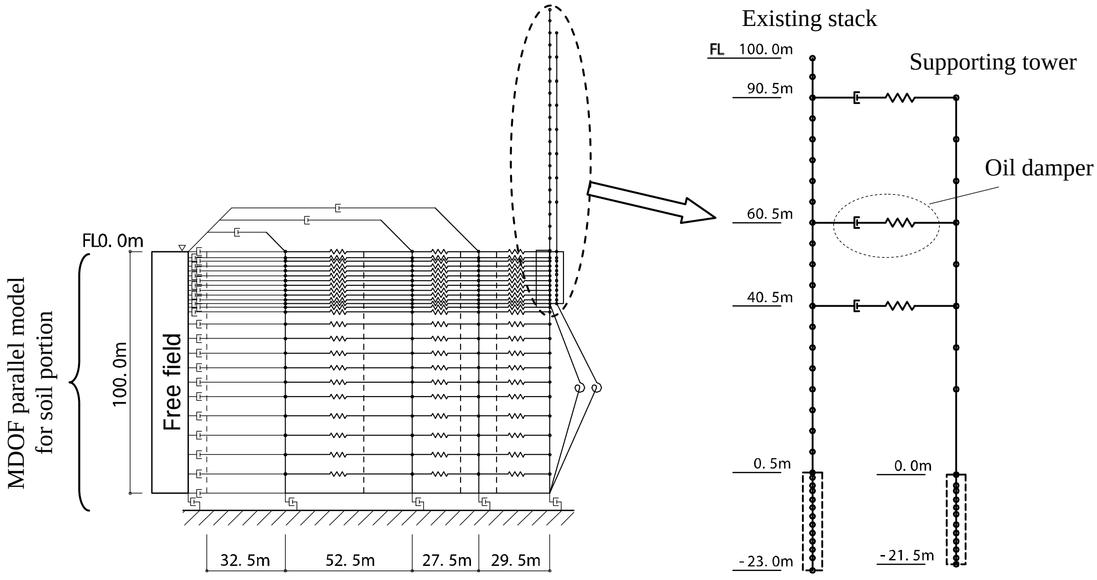


Figure 6 Vibration model for seismic response analysis

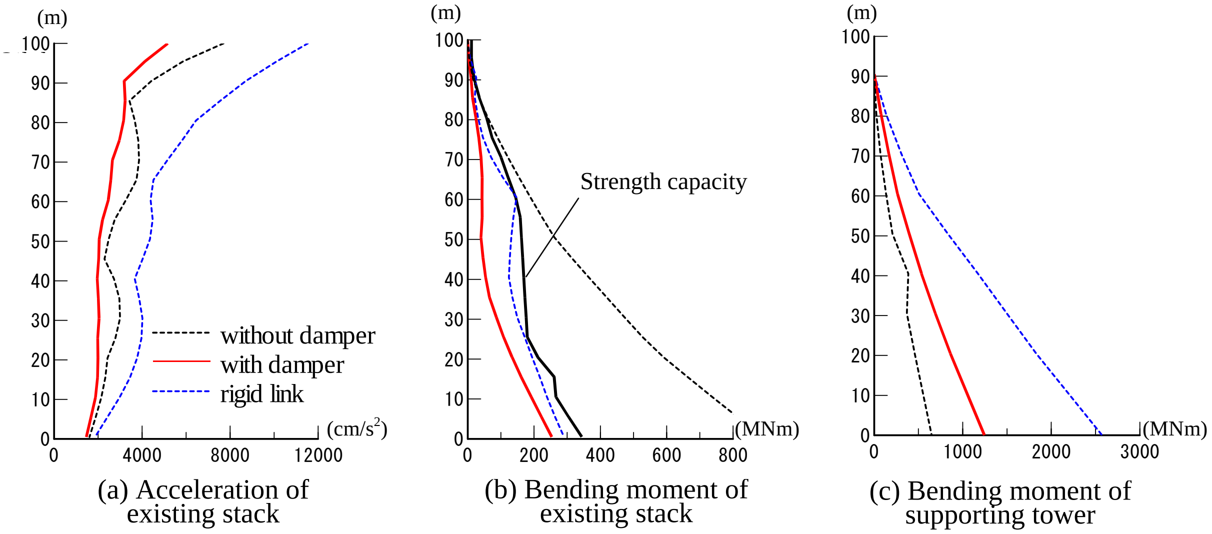


Figure 7 Maximum response values

4. DEVELOPMENT OF HIGH PERFORMANCE OIL DAMPERS

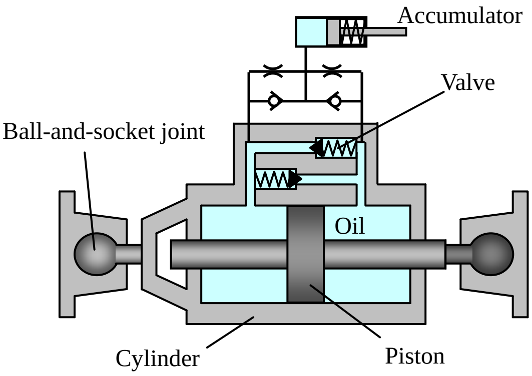
4.1. Basic Composition

Because the required specifications shown in Table 1 are beyond the capability of existing products, and high durability is indispensable when considering outdoor conditions and the importance of the target structure, we employ a newly developed high-performance oil damper designed for this project. Figure 8 outlines the inner mechanism of the oil damper and an outside view of a full-scale device. The device consists of a cylinder, a piston, a piston rod, valves, an accumulator, etc., and it uses the resistance when the oil in the cylinder passes the valve as a damping force. Both ends of the device house a ball-and-socket joint to follow a three-dimensional complicated motion during an earthquake. The accumulator is a kind of oil reserve tank that admits a change of oil volume caused by variations of temperature.

As shown in Table 1, two types of device, L-type and M-type, are adopted here. They have the same force capacity but different numbers of valves. Their lengths are about 2.4m (L-type) and 1.9m (M-type), and their weights are about 1000kg (L-type) and 750kg (M-type). To realize the required damping coefficient and velocity capacity, the L-type and the M-type devices employ six or four unit valves that can generate a linear damping force in proportion to a velocity of up to 30cm/s (Figure 9). As mentioned before, adjusting the damper parameter by only the number of common valves can streamline the development of the device because we only have to design and test one valve.

4.2. Performance Test on Full-scale Device

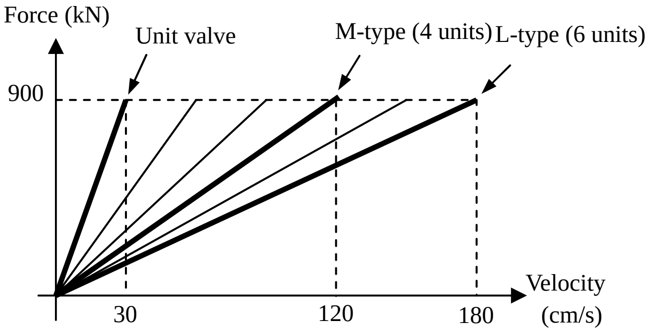
To verify the performance of the developed oil damper, we conducted dynamic loading tests on a full-scale M-type device. Because of the function attached to the valve, each valve unit can be externally controlled to be in operation or not. Figure 9(b) shows the relations between loading velocity and generated reaction force. Plots (A) are the results when one valve unit is in operation, and the plots include the results of four different valves. Plots (B) are the results when all four valves work together. We can see the same relation as that shown in Figure 9(a). The block line in Figure 9(b) indicates the target specification, and the two dotted lines indicate plus or minus 10% of it. From Figure 9(b), we can recognize that the difference between the valves is very small, and the highly linear characteristic, which meets the specification, is realized. Figure 10 shows another test results. Figure 10(a) shows a force-displacement relation for a sinusoidal loading with a frequency of 2.0Hz when only one valve unit is in operation. The oval force-displacement loops, which are associated with a linear viscous damper, are observed in accordance with the three levels of loading amplitudes. From this figure, it is also observed that this device has no mechanical gap. Figure 10(b) displays a change of damping coefficient under various temperatures of inner oil. The results are normalized by a value of 27 degrees. Although a slight temperature dependency is observed



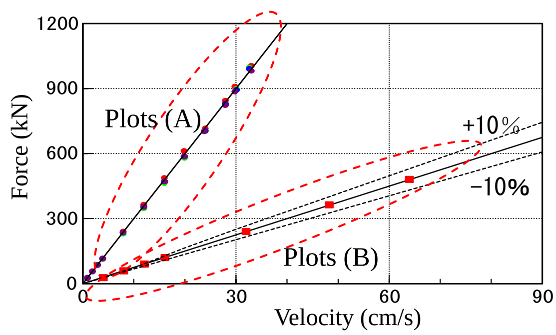
(a) Inner mechanism


(b) Outside view of full-scale device (M-type)

Figure 8 Outline of oil damper

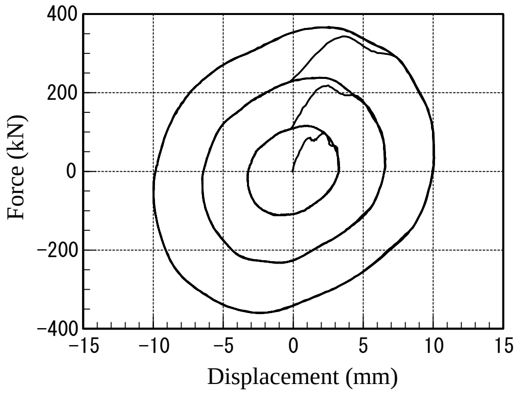


(a) Specification

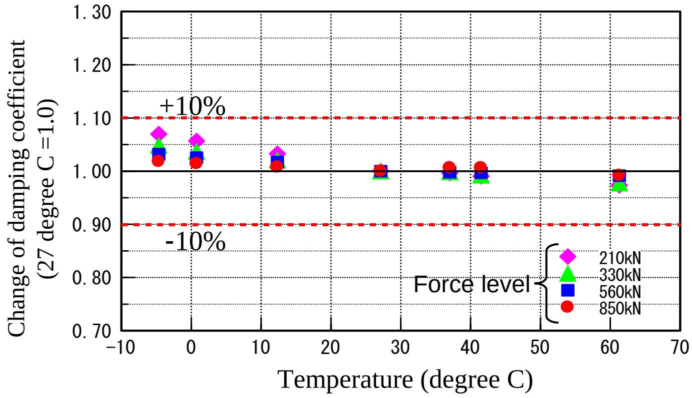


(b) Test results on full-scale device (M-type)

Figure 9 Force-velocity relation of oil damper



(a) Force-displacement relation for sinusoidal loading (2.0Hz)



(b) Temperature Dependency

Figure 10 Test results of full scale device (M-type)

for a small force, the percentage change is less than plus or minus 10% in the temperature range from -5 to 60 degrees. For a large force, which is important for seismic response control, the change of damping coefficient is very small. As mentioned in the former chapter, we considered a 20% fluctuation in damping coefficient in design. The test results indicate its validity when we take account of both the differences between the valves and the fluctuations due to temperature dependency.

5. CONCLUSION

This paper has presented a seismic upgrading project introduced for an existing stack using oil dampers that will become the first full-scale application of structural control technology to an actual nuclear power station facility in Japan. We planned to build a new supporting tower surrounding the existing tube-shaped stack and to link the two structures via oil dampers to augment damping ratio to the structures as well as to improve the strength. The damper parameters and allocation were carefully examined in considering the given conditions and the control effect. Numerical analysis results showed remarkable response reduction effects, which cannot be realized by conventional reinforcement. Because it was also clarified that the required damper specifications are beyond the capability of existing products, a high-performance oil damper has been developed for this project. Authorization was obtained for this upgrading project, and this project has been completed in December 2007. Before completion, large-scale forced vibration tests were conducted in order to examine the dynamic characteristic of the stack with oil damper. The test results including numerical simulation would be discussed in another paper.

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