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DEVELOPMENT OF 3-DIMENSIONAL SEISMIC ISOLATION SYSTEM FOR SODIUM-COOLED FAST REACTOR

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Abstract

A sodium-cooled fast reactor (SFR) which is characterized under the operation at a high temperature and a low pressure utilizes liquid sodium as a coolant. Components for the SFR have been designed as thin-wall structure to mitigate the thermal stress due to the operation at a high temperature. However, having thin wall structures, these components, such as a reactor vessel, have a disadvantage of the structural integrity for earthquake. To avoid this disadvantage, SFR will adopt seismic isolation system using laminated rubber bearings to reduce horizontal seismic loads to the reactor building and components. The authors already studied the horizontal seismic isolation system for SFR using laminated rubber bearing. As the results of previous studies, it is effective for this laminated rubber bearing to reduce and withstand the seismic loads.

However, it is important to reduce not only the horizontal seismic response but also the vertical seismic response in order to secure the structural integrity of components for the SFR and to realize high power by upsizing of the reactor vessel. To realize these requirements, the 3-dimensional seismic isolation system for the SFR had been studied. This isolation system requires a rocking suppression device to ensure the isolation performance and to mitigate the rocking motion. Therewith, this isolation system had resulted in the complicated structure and system. Accordingly, the authors propose a new 3-dimensional seismic isolation system for the SFR. This system consists of a laminated rubber bearing, vertical oil dampers and combined disc springs units. For the horizontal direction, the horizontal restoring force is provided by the laminated rubber bearing. Furthermore, for the vertical direction, the vertical restoring force is provided by the disc springs. The vertical damper provides the damping force for the vertical direction. This isolation system has three fundamental concepts. The first is to ensure the isolation performance that is required for a reactor vessel with a large diameter, which consists of simple isolation devices without a rocking suppression device. The second is to secure a layout, including the number of individual the isolation systems, of the 3-dimensional isolation system by maintaining the compressive stress and the installation size for the conventional 2-dimensional (horizontal) isolation system. The third is to secure the reliability for the 3-dimensional isolation system by employing a mechanical mechanism or an isolation device to be abundant track record in the seismic isolation field or the general industry field.

The authors conducted the static loading tests using full scale or half scale specimens to clarify the force-displacement relationships for each element of this 3-dimentional seismic isolation system, such as the rubber bearing, the disc spring units and the vertical oil dampers etc. Newly analytical models, which can capture the force-displacement relationships for each element obtained by test results, were created to improve the seismic prediction accuracy.

This paper describes the concept of the 3-dimensinal seismic isolation system and isolation performance obtained by the seismic response analysis.

Keywords: Sodium-cooled Fast Reactor; Seismic Isolation System; Rubber Bearing; Disc Spring; Oil Damper

1. Introduction

A sodium-cooled-reactor (SFR) which is characterized under the operation at a high temperature and a low pressure utilizes liquid sodium as a coolant. Components for the SFR have been designed as thin-wall structure to mitigate the thermal stress due to the operation at a high temperature. Having thin-wall structures, these components, such as a reactor vessel, have a disadvantage of the structural integrity for seismic events. To avoid the disadvantage mentioned above, the applicability of seismic isolation technologies not only for the SFR but also for light water reactors (LWRs) to reactor buildings has been investigated in many countries to ensure the safety margin, including residual risks, of components. The authors already studied the horizontal seismic isolation system for SFR using laminated rubber bearing [1]. As the results of previous studies, it is effective for this laminated rubber bearing to reduce and withstand the seismic loads.

However, for design seismic condition is severer in Japan, it is important to reduce not only horizontal seismic response but also vertical seismic response for structural integrity of SFR's components and to realize higher power by upsizing the reactor vessel. For this purpose, the 3-dimensional seismic isolation system for the SFR had been studied. This seismic isolation system required a rocking suppression device to ensure the isolation performance and to mitigate the rocking motion. To achieve these purposes, this system had resulted in the complicated structure and system [2]. Accordingly, the authors propose a new 3-dimensional seismic isolation system for the SFR [3]. This system consists of a laminated rubber bearing, vertical oil dampers and combined disc springs units. The authors conducted the static loading tests using full scale or half scale specimens to clarify the force-displacement relationships for each element of this 3-dimentional seismic isolation system. This paper describes the concept of the 3-dimensinal seismic isolation system and isolation performance obtained by the seismic response analysis.

2. System Configuration

The conceptual three-dimensional isolation system, which consists of thick rubber bearings, disc springs, and oil dampers, is shown in Fig. 1 [4]. This isolation system has three fundamental concepts as follows,

- ✓ To ensure the isolation performance that is required for reactor vessel with a large diameter, which consists of simple isolation devices without a rocking suppression device,
- ✓ To secure a layout, including the number of individual the isolation systems, of the three-dimensional isolation system by maintaining the compressive stress and the installation size for the conventional two-dimensional isolation system,
- ✓ To secure the reliability for the three-dimensional isolation system by employing a mechanical mechanism or an isolation device to be abundant track record in the seismic isolation field or the general industry field.

The three-dimensional isolation system was designed to provide 10,000 kN rated load with a horizontal natural frequency of 0.294 Hz (3.4 s) and a vertical natural frequency of 3 Hz. The dimensions of this isolation system are 2.5 m for the width and 2.2 m for the height. The functions of the isolation system are classified into the horizontal direction and the vertical direction. For the horizontal direction, the horizontal restoring force is provided by a thick rubber bearing, which was developed by the authors [1]. The horizontal damping force is given using oil dampers. For vertical direction, the restoring force is provided by disc spring units. Figure 2 is each component of three-dimensional seismic isolation system. Table 1 shows the specification of three-dimensional seismic isolation system.

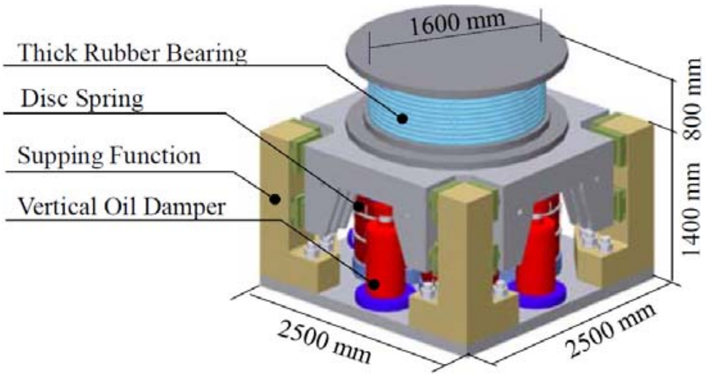
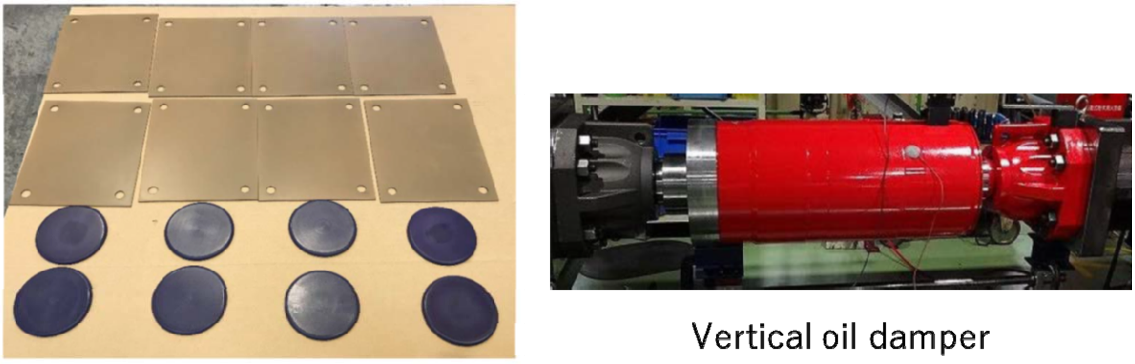


Fig. 1 – Schematic view of there-dimensional seismic isolation system [3]

Thicker laminated rubber bearing

Disc spring units



Vertical oil damper

Sliding elements

Fig. 2 – Each component of there-dimensional seismic isolation system

Table 1 – Specification

Component		
Thicker laminated rubber bearing	Material	Natural rubber and steel
	Horizontal natural period [s]	3.4
	Vertical natural period [s]	0.126

	Diameter [mm]	1,600
	Thickness of a layer [mm]	31
	Number of layers	10
Disc spring	External Diameter D [mm]	700
	Internal Diameter d [mm]	450
	Thickness t [mm]	34
	Free Height H0 [mm]	49.0
	Thickness of a layer [mm]	31
Vertical oil damper	Stroke [mm]	± 35
	Diameter [mm]	355.6
	Max damping force [kN]	2,000
	Max velocity [cm/s]	25
Sliding element	Diameter [mm]	140

As for thick rubber bearing, the proposed laminated rubber bearing is already studied for horizontal seismic isolation system for SFR as shown in Fig. 3 [5]. The first shape factor S1 of a rubber layer is about 12, which shows the ratio of the diameter of the rubber to the thickness of a rubber layer. The second shape factor S2 is about 5, which shows the ratio of the diameter of the rubber to the thickness of total rubber layers.

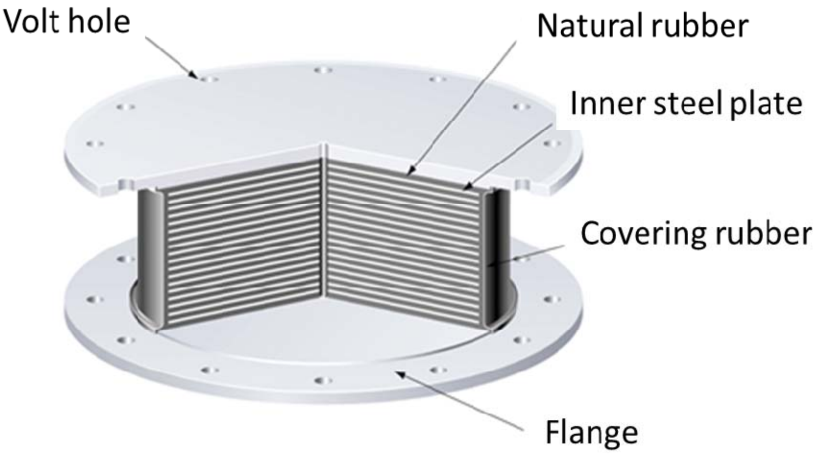


Fig. 3 – Schematic view of laminated rubber bearing [5]

As for disc springs, the principal dimensions are 700mm in external diameter, 450mm in internal diameter, 34mm in thickness and 15mm in initial cone height as the stroke as shown in Fig. 4 [6]. The product method of disc springs (specimens) in this study is different from the conventional ones, which are produced by one-shot press forming.

A disc springs' unit is set to be three stacks in parallel and six stacks in series, and a three-dimensional seismic isolation device is composed of four disc springs' units, which are installed under the rubber bearing. Since these disc springs are much thicker than the conventional ones and beyond the thickness limit of quenching, the heat treatment as spring steels would be a big problem on manufacturing. Moreover, it should be confirmed whether the design equations could be applied to thick disc springs.

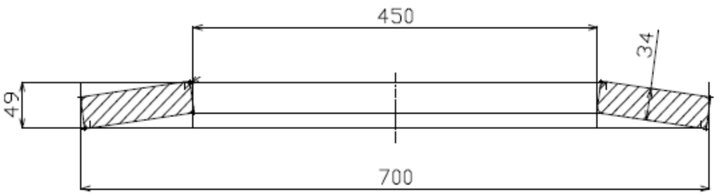


Fig. 4 – Schematic view of full-scale disc spring [6]

As for the vertical oil dampers as shown in Fig. 5 [6], there would be a geometric problem to install the oil dampers in a short and narrow space. Generally, the conventional vibration oil dampers are used in high rising buildings (skyscraper) with the low natural frequency of less than 0.5Hz, but the vertical oil dampers for the three-dimensional isolation system are used in the range of high frequency (about 3Hz). It is said that a frequency dependency appears from over 1Hz for the conventional oil dampers, and the damping performance would drastically deteriorate as higher frequency. Then the damping performance should be improved to be available at even higher frequency. Hence, the high-performance dampers with shortened and increased stiffness serving to the high-frequency should be developed.

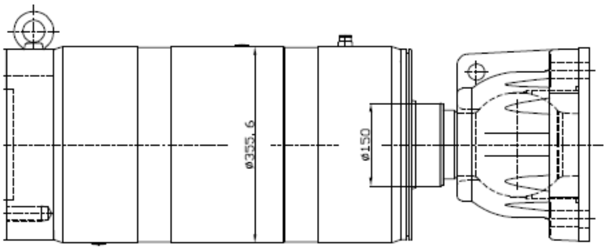


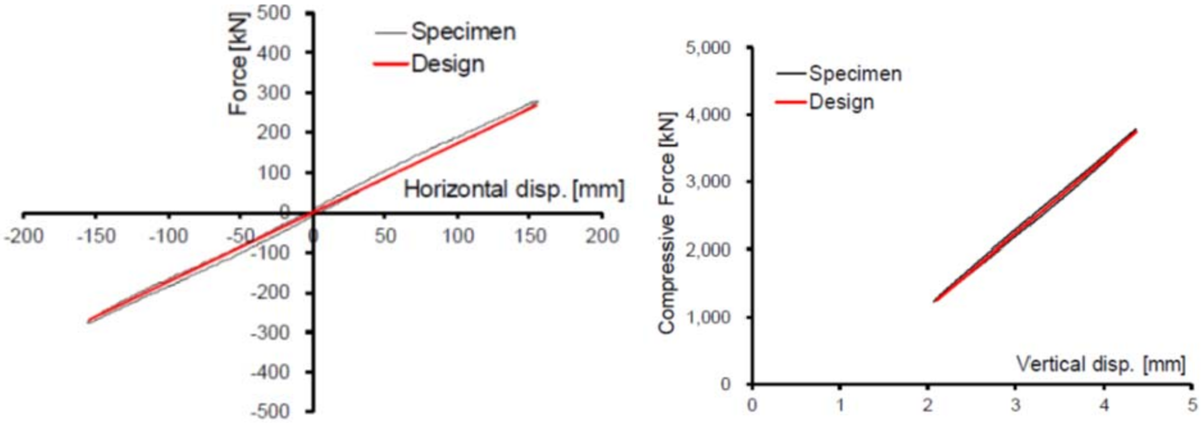
Fig. 5 – Schematic view of laminated rubber bearing [6]

3. Experimental results

The authors planed the experiments for each component. The experiment for horizontal damper will be carried out. This chapter describes the experimental results of each component.

3.1 Laminated rubber bearing

In the laminated rubber bearing experiment, the half-scale specimen (diameter 800 mm) is used. The objective of the tests on half-scale rubber bearings was to clarify their force-displacement relationships in the horizontal/vertical direction as an element. Additionally, it was also the objective to confirm the accuracy of manufacturing by comparing the horizontal and vertical stiffness of test results with the designed values. Figure 6 shows the comparisons between the typical hysteresis loop and the design stiffness plotted by the red-colored straight line. The design stiffness was defined to pass the original in the horizontal direction, or the middle point of two intersections of loading/unloading curves and the design supporting load in the vertical direction. The test results matched the design stiffness. It was confirmed that the rubber bearings had linear behaviors in the horizontal/vertical direction, and that thicker laminated rubber bearing was successfully produced with high accuracy.



(a) Horizontal direction (b) Vertical direction (-5 MPa±50 %)

Fig. 6 – Comparison between hysteresis loops and design stiffness [7]

3.2 Disc spring

In the assembled specimen of three-dimensional seismic isolation system, four disc spring units are installed under a thicker laminated rubber bearing, each of which has the three disc springs stacked in parallel and six disc springs stacked in series. The main objective of the loading tests was to clarify characteristics of a disc spring unit. As shown in Fig. 7, the loading apparatus for the full-scale disc springs is the uniaxial compressive static test machine by manual operation with the specification of the maximum loading 5,000kN.

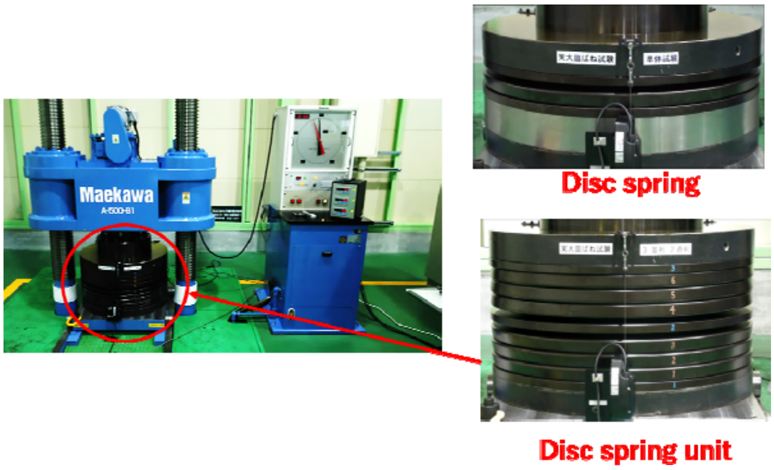
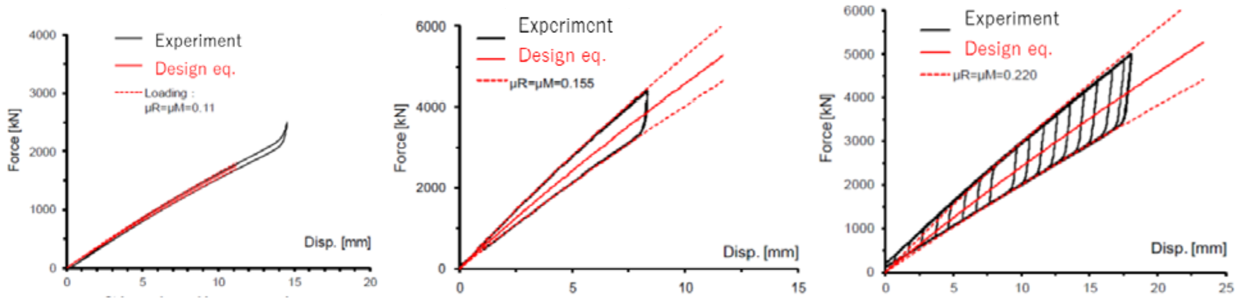


Fig. 7 – Loading apparatus for full-scale disc springs

In disc springs' experiments, three type of the experiments were carried out, single disc spring, 3 stacks in parallel and 1 stack in series and, 3 stacks in parallel and 2 stacks in series.

Figure 8 shows the comparison show the comparison between the Force-Displacement relationships and the design skeleton curves, where the friction coefficients for all tests were identified by the method of trial and error. Then the design equations seemed to be applicable even in the case of the thick disc springs.



(a)Single disc spring (b) 3 stacks in P and 1 stack in S (c) 3 stacks in P and 2 stacks in S

P: parallel, S: series

Fig. 8 – Comparison between test results and the design or the analytical model [7]

3.3 Vertical oil damper

In this study, the dynamic performance tests using sinusoidal waves or sweep waves with varied frequencies and velocities were carried out to investigate the damping performance. The authors developed two types of the oil damper (linear type and bi-linear type) for the three-dimensional seismic isolation system. And more, the seismic response wave tests were carried out to confirm the applicability of the analytical model. Figure 9 shows the specimen and the dynamic loading apparatus by automatic operation with the specification of the maximum force of 2,000kN and the maximum velocity of 0.3m/s [7].

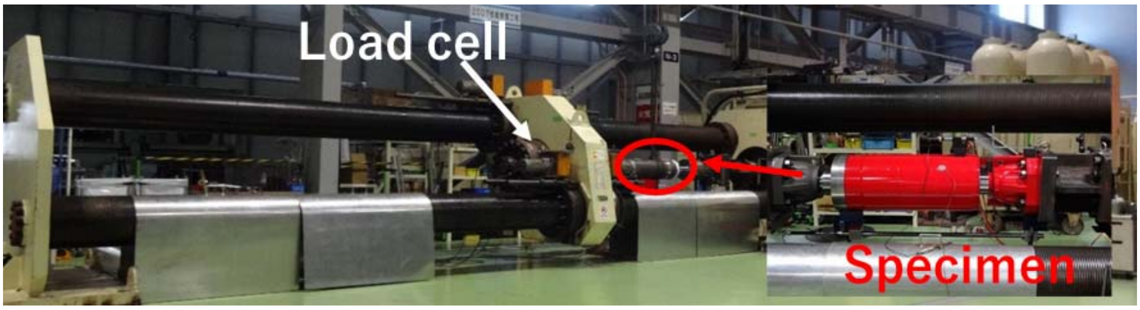
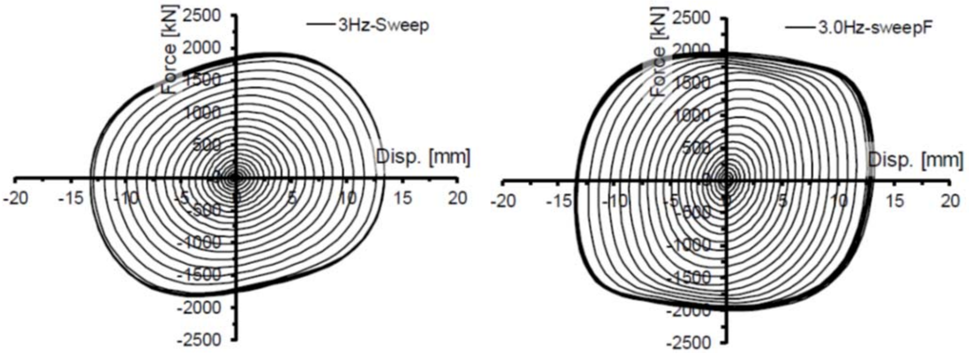


Fig. 9 – Loading apparatus for full-scale disc springs [7]

Figure 10 shows the typical F-D relationships for the linear and the bi-linear dampers by the sweep wave tests with the frequency of 3Hz. The feature of F-D relationships changed more remarkably as the velocity increased for the bi-linear damper, because the damping forces were at the ceiling when beyond the relief viscous velocity.



(a) Linear (b) Bi-Linear

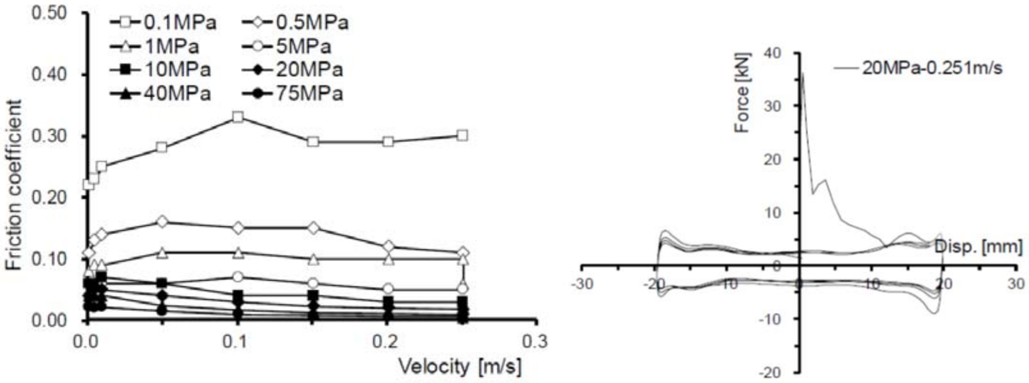
Fig. 10 – Typical sweep wave tests for frequency of 3Hz [7]

3.3 Sliding element

At the sliding elements of the horizontal support functions, the large horizontal load works during an earthquake. That is the combined forces of the horizontal force due to the horizontal seismic response and the reaction force of additional bending moment due to the vertical load under the horizontal deformation of the rubber bearing to generate the friction force. It is important that the sliding elements should be required under such conditions to move smoothly in the vertical direction without significant friction force influenced on the vertical response. Figure 11 shows the dynamic loading apparatus [7].

Fig. 11 – Dynamic loading apparatus [7]

Figure 12 shows that the dependence of dynamic friction coefficient on the velocity and the typical friction force-displacement relationship. The dynamic friction coefficient varied from 0.006 to 0.33. The friction coefficient at the same velocity became smaller as the compressive stress became higher. In the case that the velocity was increasing, the friction coefficient in the low range of the compressive stress was constant or slightly increasing. The sliding elements show a feature that a large static friction force occurs at the start of movement. Such great static friction force and the dynamic ones might make a significant vertical response.



(a) Dependence of dynamic friction coefficient (b) Typical friction Force-Displacement relationship

Fig. 12 – Results of Load-displacement experiment

3.4 Summary of experiment results of each component

The authors carried out the experiments for each component. For the thicker laminated rubber bearing, it was confirmed that they were produced with high accuracy for horizontal and vertical stiffness. For disc springs, the single and combination experiments were carried out. The results were matched with the design equations, For vertical oil damper, the two types of dampers with the maximum damping force of 2,000kN at the velocity of 0.25m/s, which have common body and the performance of linear or bi-linear by rearranging the valves, were manufactured. By the dynamic loading tests, both oil dampers were confirmed to function as designed in the range of practical use. For sliding elements, the polyamide sliding bearing had the finest and greatest performance as to the dynamic friction coefficient.

Based on the experimental results and analytical results of each component's modeling, the seismic response analysis was carried out. The detail description of that analysis is shown in the following chapter.

4. Seismic response analysis

The seismic response analyses utilizing a simple dynamic response analytical model are conducted to assess the seismic response of the three-dimensional isolation system. A simple analytical model for seismic response analysis incudes the influence on interaction of horizontal and vertical response. The simple dynamic response analytical model is shown in Fig. 13 [8]. This analytical model has a two degrees freedom system, which is modeled in a reactor building mass and a lower base mat mass, and consists of ten elements for the three-dimensional isolation systems in the horizontal and vertical directions. The simple analytical model for the seismic response analysis allows for the influence of the interaction with the horizontal and the vertical response. The assumed number of the three-dimensional isolation system is 500.

For the horizontal direction, the rubber bearings are modeled using the ten nonlinear-spring elements that can express the hardening and softening characteristics in horizontal and vertical direction. The horizontal damping force obtained by the whole number of the multiple-piston oil dampers is modeled with one element, which is the Maxwell model, representing all of the damping force.

For the vertical direction, the disc spring units are modeled using the ten nonlinear springs that can capture the hysteresis loops for the disc spring units. The vertical oil dampers are modeled using the 20 double dashpot models to capture the damping force characteristics under vertical seismic response that has relatively a high-frequency and a small displacement, as compared to the horizontal seismic response. The sliding materials are modeled using the four proposed friction model with respect to each three-dimensional isolation system. In addition, the interactions between the soil and the isolation system are considered using the soil spring elements and the soil dashpots in the horizontal and vertical directions.

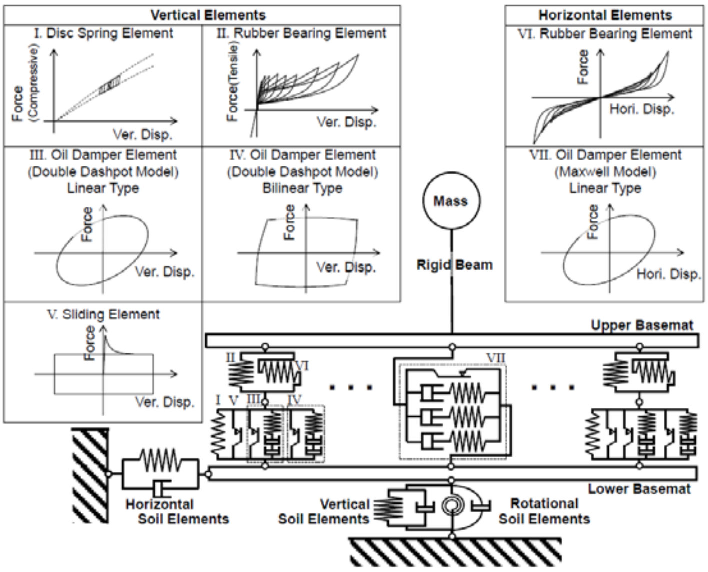


Fig. 13 – Simple dynamic response analytical model

The seismic response analyses were conducted as input acceleration levels up to two times larger than the design-basis ground motion Ss, which is referred to as 2.0 Ss, to assess the robustness of this three-dimensional isolation system. The vertical design-basis ground motion is two-thirds of the motion in the horizontal direction. Figure 14 indicates the target spectra, which are used in the seismic response analyses [8].

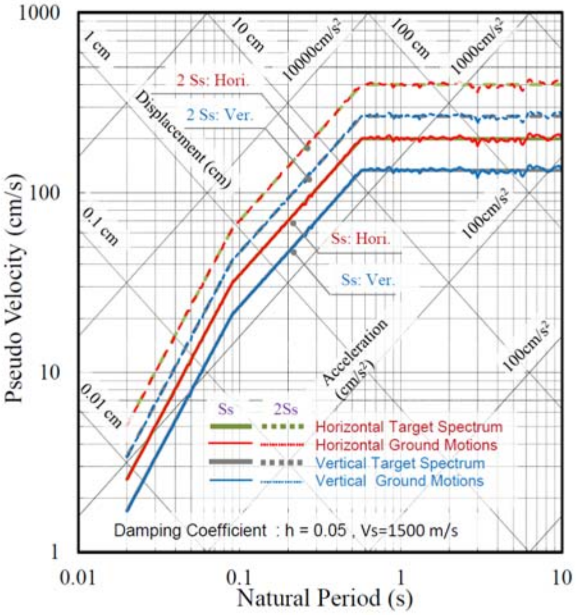
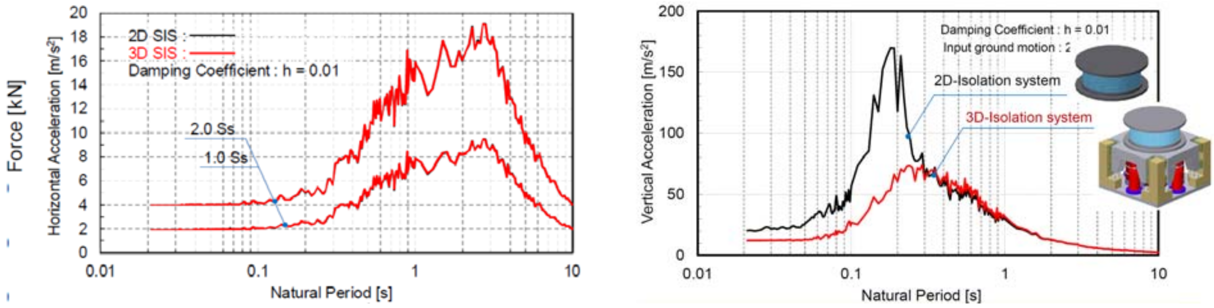


Fig. 14 – Target Spectra for Ground Motions

The results of seismic response analysis are shown in Fig. 15 [8]. Figure 15 (a) is the result of horizontal direction and (b) is that of vertical direction respectively. As the results of horizontal direction, the three-dimensional seismic isolation system has the same function as the two-dimensional seismic isolation system. And also, for the vertical direction, this system is found to be effective to reduce the vertical response.



(a) Horizontal direction (b)Vertical direction

Fig. 14 – Floor Response Spectrum Compared with 2D and 3D Isolation System

5. Conclusion

This paper described the development of new-type 3-demensinal seismic isolation system. This system consists of thicker laminated rubber bearing, coned disc spring and oil damper to secure the reliability for the three-dimensional isolation system by employing a mechanical mechanism or an isolation device to be abundant track record in the seismic isolation field or the general industry field. As the results of each experiment and analysis, it is useful for the reduction of seismic force to adopt the proposed three-dimensional seismic isolation system. Moreover, the results of seismic response analysis show that the three-dimensional seismic isolation device was found to reduce the vertical response without compromising the horizontal role.

In the next step, the system integrated experiment using half-scaled model will be performed for demonstration. And also, the authors aim for standardization of 3-demensional seismic isolation system.

6. Acknowledgements

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