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Shaking Table Test of Three-Dimensional Base Isolation System Using Laminated Thick Rubber Bearings

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ABSTRACT

In order to reduce horizontal and vertical seismic response of internal equipment in fast breeder reactor (FBR) plants, performance of three-dimensional (3-D) base isolation system using laminated thick rubber bearings as isolators is evaluated. Shaking table tests for scale models of base isolated structure are carried out. At first, horizontal and vertical shaking table tests are conducted independently for sinusoidal wave and white noise input to evaluate response characteristics of the model structures. Then an artificial earthquake and the natural earthquake motions are used for horizontal and vertical simultaneous shaking to evaluate the effect of the base isolation. Test results show that the horizontal response of the 3-D and the horizontal base isolation system is reduced similarly, and the vertical response of the 3-D base isolation system is reduced in the frequency range influential to internal equipment.

INTRODUCTION

In the case of FBR plants, reduction of the seismic loads is a matter of great concern in the design aspect, as internal pressure of the components is not a dominant load and structural design of components is strongly affected by seismic load. Three-dimensional (3-D) base isolation system, where seismic loads in both horizontal and vertical directions are to be reduced, is considered very effective, in order to reduce seismic loads for inner equipment in fast breeder reactor (FBR) plants.

In the last decade, researches on the application of horizontal (or two-dimensional, 2-D) base isolation systems to FBR have been conducted in Japan (e.g., Sawada, et al., 1989). In these studies, laminated thin rubber bearings (thin RBs) are supposed as seismic isolators. By using thin RBs, horizontal base isolation system is realized which can reduce horizontal seismic loads to superstructure and equipment, and the concept of horizontally base-isolated FBR plants using thin RBs have been widely accepted. Usually, the vertical stiffness of thin RBs used for horizontal base isolation system is far higher than the horizontal one and vertical response amplification is suppressed, but still vertical response cannot be reduced.

However, it is pointed out that the reduction of vertical seismic load as well as horizontal one can be effective to seismic design of some components of FBR (Yashiro et al, 1998), and various types of 3-D isolation systems have been proposed, which are classified into two types. One is the 3-D base isolation type where whole reactor building is three-dimensionally isolated, and the other is the partial 3-D isolation type where reactor building is supported by horizontal isolators and primary equipment in the building are supported by vertical isolators. In the former type, 3-D isolators such as thick RBs, or series combination of horizontal and vertical isolators (in this case, thin RBs are used as horizontal isolators and dish springs (Fujita, et al, 1995) or air springs (Tokuda, et al, 1995) are used as vertical isolators) are proposed. In the latter type, the building is horizontally isolated by thin RBs and the equipment are supported and vertically isolated by coil springs (Sonoda, et al, 1987) or dish springs (Morishita, et al, 1995). In these previous studies, vertical isolation period were chosen between 0.25 and 0.5 sec, which is considered effective to reduce vertical response of primary equipment. For 3-D isolation system with this vertical isolation period, maximum vertical acceleration (or ZPA: Zero Period Acceleration) of the reactor building is still larger than that of the ground motions, however, the maximum vertical acceleration response of the primary equipment is reduced compared to that in horizontally base-isolated reactor building. The 3-D isolation system with thick RBs proposed here is also based on the same principle.

In this research, authors conducted shaking table tests for scale models of the 3-D base isolation system, for the purpose of evaluating the effectiveness of the 3-D base isolation system using thick RBs. In the study on the horizontally base-isolated FBR plant, horizontal and vertical fundamental periods of the 2-D base isolation system are chosen to be 0.5 and 0.05 sec respectively (Sawada, et al., 1989). According to the study on the 3-D base isolation system (Yashiro, et al, 1998), when the vertical isolation period is set to be 0.25 sec, the 3-D base isolation system reduces vertical seismic load for internal equipment. Hence, in the reference plant in this study, horizontal and vertical isolation period are set to be 0.5 and 0.25 sec in 3-D base isolation system, and 0.5 and 0.05 sec in 2-D base isolation system, respectively.

EXPERIMENTAL MODEL

Base Isolated Model

Shaking table tests were carried out for three types of scale models shown in Table 1 (Model-1, 2 and 3), and these models were designed according to the law of similarity shown in Table 2. Each model is constructed of a rigid mass supported by four natural rubber bearings, with dampers for horizontal and vertical directions attached. Model-1 is the 3-D base isolation system, which is the high-rise rigid mass supported by thick RBs. In Model-2, a low-rise rigid mass of the same weight as used in Model-1 is supported by thick RBs, and Model-3 is the 2-D base isolation system in which the same rigid mass as Model-1 is supported by thin RBs, with dampers attached for horizontal direction only.

Fig.1 shows the high-rise model (Model-1 and Model-3) and the row-rise model (Model-2). Ratio of the height of the center of gravity of the rigid mass to the distance between isolators

Table 1 Specification of Models

Item	Model-1 3-D Isolation	Model-2 3-D Isolation	Model-3 2-D Isolation
Superstructure	High Rise	Low Rise	High Rise
Weight(tonf)	8.86	9.00	9.00
Isolator	Thick NRB	Thick NRB	Thin NRB
Damper Hori.	Attached	Attached	Attached
Vert.	Attached	Attached	Not-Attached

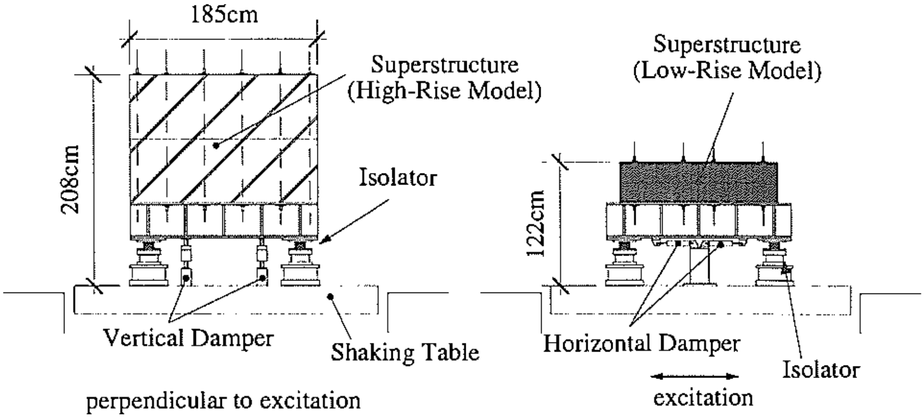

Fig.1 Experimental Models

for high and low-rise model is 0.6 and 0.3, respectively.

Isolator

The prototype thick RB is natural rubber bearing and its dimensions are; diameter = 101cm, total thickness of rubber = 24.6cm, number of rubber sheets = 3, design vertical load = 190 tonf, primary shape factor (= loaded area / force-free area) S1 = 3.1 and secondary shape factor (= diameter / total thickness of rubber) S2 = 4.1, respectively. Scale models of thick RB were made according to the law of similarity depicted in Table 2.

Table 2 Low of Similarity

Parameter	Prototype	Model
Displacement	1	1/9.4
Acceleration	1	1
Force	1	9.4
Vertical Pressure	1	1
Time	1	$1/\sqrt{9.4}$

Table 3 shows dimensions of thick and thin RBs. In this table, horizontal period and vertical frequency are evaluated from the loading test results of RBs. Transforming from the

Table 3 Dimensions of Isolators

Item		Thick NRB	Thin NRB
Loading Weight	(tonf)	2.25	2.25
Hori. Spring Const.	(tonf/cm)	0.201	0.244
Hori. Natural Period	(sec)	0.672	0.609
Vert. Spring Const.	(tonf/cm)	24.9	129.4
Vert. Natural Freq.	(Hz)	16.57	37.78
Rubber Layers	(cm x num)	6.5 x 4	2.6 x 10
Diamater	(cm)	10.7	10.7
Shear Modulus of Rubber	(kg/cm2)	6	6

scale model to real plant, the horizontal isolation period and the vertical isolation frequency of thick RBs became 2.1 sec and 5.4 Hz, and those of thin RBs became 1.9 sec and 12.3Hz, respectively. Vertical natural frequency of thick RBs were slightly higher, and that of thin RBs were lower, than specified values.

Damper

Cylindrical oil dampers were used as damping device in horizontal and vertical directions, and attached to the basement of the rigid mass and to the shaking table with hinges. The damping force which is proportional to the axial velocity was selected so that the modal damping factors of the scale models would become 20% for the 1st natural frequency of both horizontal and vertical directions.

TEST METHOD

Input Motion

A shaking table was used, which could generate horizontal (one direction) and vertical motions simultaneously.

At first, in order to evaluate fundamental dynamic characteristics of the base-isolated models, horizontal and vertical shaking were given independently to the models using sinusoidal wave (1-30Hz, table acceleration 50gal) and white noise (1-50Hz, table acceleration 200gal).

Then, in order to confirm the performance of the models under earthquake motions, an artificial earthquake and the natural earthquake motions such as El Centro (1940) and JMA Kobe (1995) were used for horizontal and vertical simultaneous shaking. Fig.2 shows target response spectra (Sv, h=5%) of the artificial earthquake, which takes into account slightly long period contents (Ishida, et al., 1989). The artificial earthquake are synthesized to fit the target response spectra with phase components of earthquake records at La Union (1985 Mexico Earthquake), and the ratio of the vertical target response spectrum to the horizontal one is assumed to be 0.6. Fig.3 shows response spectra calculated from the original records of El Centro and JMA Kobe. The acceleration amplitude for El Centro and JMA Kobe was set to be 1.0 and 0.5 times the original records respectively. For the input motion of the shaking table, time scale of these waves were reduced by 1/3.1 according to the law of similarity.

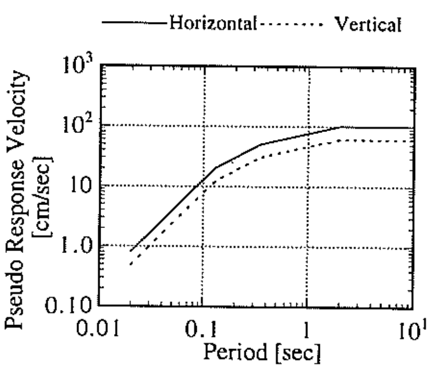

Fig.2 Design Response Spectra for Artificial Earthquake Motion

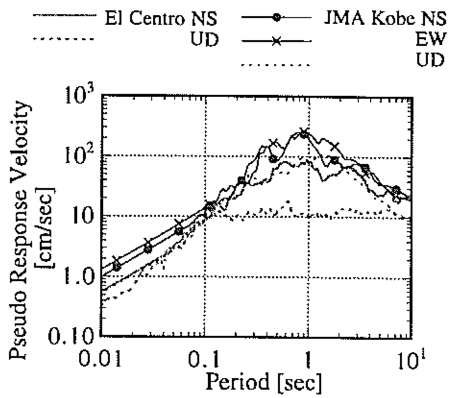

Fig.3 Response Spectra of Natural Earthquake Records

Response Reduction

Maximum acceleration of the shaking table and the models at the center of gravity, and their ratios are shown in Table 4. As for horizontal response, maximum acceleration response of the scale models (Model-1, 2, 3) is reduced compared to that of shaking table. On the other hand, as for vertical response, in Model-1, Model-2 and Model-3, maximum acceleration response is amplified compared to that of shaking table, except for the case of Model-1 and Model-2 of El Centro wave input. This result indicates that 3-D base isolation system with the thick RBs cannot necessarily reduce vertical maximum acceleration response in term of peak value. Exceptions in the case of El Centro wave input can be explained because the dominant frequency components of this wave lie in the frequency range over 25Hz where response reduction effect appears.

Table 4 Maximum Acceleration of Input Motions and Responses of Model Structures

	Model-1			Model-2			Model-3		
	Inp.	Resp.	Resp./Inp.	Inp.	Resp.	Resp./Inp.	Inp.	Resp.	Resp./Inp.
Horizontal Responses									
Artificial Earthquake	332	225	0.68	320	214	0.67	304	227	0.75
El Centro(NS-UD)	311	134	0.43	312	129	0.41	298	169	0.57
JMA Kobe(NS-UD)	319	90	0.28	328	88	0.27	303	117	0.38
JMA Kobe(EW-UD)	395	161	0.41	402	137	0.34	405	218	0.54
Vertical Responses									
Artificial Earthquake	210	327	1.56	197	358	1.81	182	221	1.21
El Centro(NS-UD)	192	141	0.73	209	146	0.70	168	431	2.56
JMA Kobe(NS-UD)	117	208	1.78	157	243	1.55	183	230	1.25
JMA Kobe(EW-UD)	158	249	1.58	166	231	1.39	182	221	1.21

Horizontal floor response spectra (FRS) at the center of gravity (CG) and the bottom are shown in Figs.7 and 8 respectively. As shown in Fig.7, three FRS curves for scale models at CG are almost the same. On the other hand, as shown in Fig.8, three FRS curves for the models at the bottom show slightly difference in the period range less than 0.1 sec. FRS curves for Model-1 and Model-3 have peaks between 0.04 and 0.1 sec and between 0.02 and 0.03 sec respectively. These peaks seem to be affected by the rocking mode, and the FRS curve for Model-2 which is the low-rise model dose not have a significant peak by the rocking mode.

Vertical FRS for Model-1 and Model-3 are shown in Figs.9 and 10, and the vertical natural frequencies of the primary equipment exist in the period range shorter than 0.04 sec (in real plant; more than 8 Hz). It is noted that vertical components of the input waves in these cases are not in good agreement with each other, because the shaking table was affected by the response of the model structure. As shown in Fig.9, FRS of the three-dimensionally base-isolated Model-1 is larger than that of the shaking table in the period range between 0.04 and 0.1 sec, however, in the period range less than 0.04 sec it dose not hold true. On the other hand, as shown in Fig.10, FRS of the horizontally base-isolated Model-3 agree with the response spectrum of the input motion in the period range longer than 1.0 sec, however, in the period range between 0.01 and 0.02 sec FRS of the model is larger than the response spectrum of the input motion.

Measurement

Fig.4 shows arrangement of measuring instruments on the models. Displacement transducers were set to measure relative displacement between shaking table and the bottom of the superstructure (rigid mass), and force transducers were installed between the shaking table and the isolators, to measure shear and axial forces acting on each isolator.

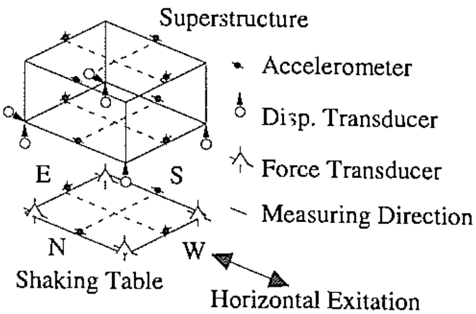

Fig.4 Arrangement of Instruments

TEST RESULTS

Dynamic Characteristics of Scale Models

Fig.5 shows horizontal resonance curves at the top of the models obtained from the sinusoidal shaking test. The 1st horizontal resonance frequencies of Model-1 and Model-2 are 1.4-1.5Hz, and that of Model-3 is 1.7 Hz. From theoretical transfer functions fitting these experimental curves, the horizontal damping factors for the 1st mode of the models are estimated 20-22%. The 2nd horizontal resonance frequencies of Model-1 and Model-2 estimated from phase curves in this figure are 17Hz and 26 Hz respectively, which agree well with the theoretical rocking frequencies (17.6 Hz and 25.9 Hz) using the design parameters. By the same calculation, the theoretical rocking frequency of Model-3 is estimated 42.6 Hz.

Fig.6 shows vertical resonance curves at the top of the scale models obtained from the white noise excitation. The 1st vertical resonance frequencies of Model-1 and Model-2 are 16-17 Hz, and that of Model-3 is 37 Hz. The 1st vertical damping factors of Model-1 and Model-2 are 11-13%, and that of Model-3 is 6%, which are estimated in the same way as the horizontal damping factors. In the case of Model-1 and Model-2, where vertical dampers were attached, vertical damping factors by the experiment prove smaller than the designed one (20%), which is because the vertical relative displacement of the models was so small that enough damping force of the damper could not be obtained.

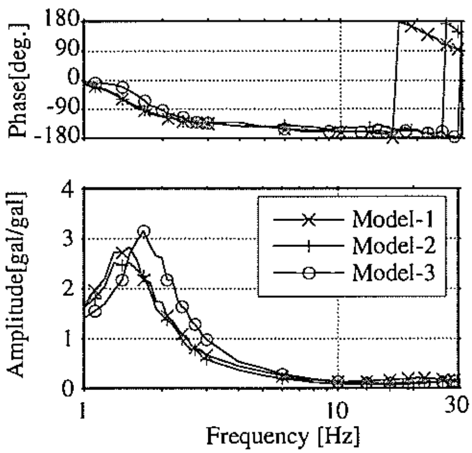

Fig.5 Horizontal Frequency Respose

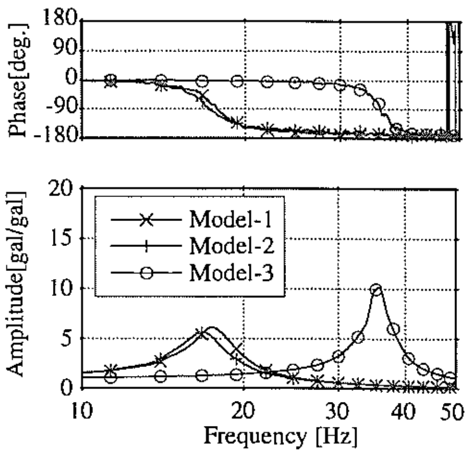

Fig.6 Vertical Frequency Response

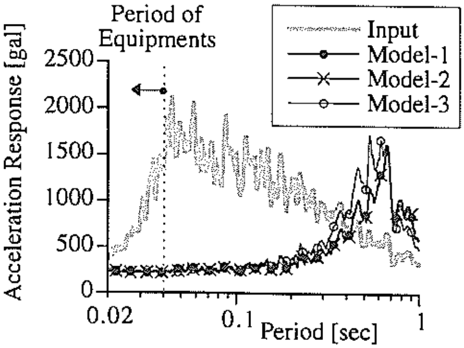

Fig.7 Horizontal Response Spectra
at the Center of Gravity of Models

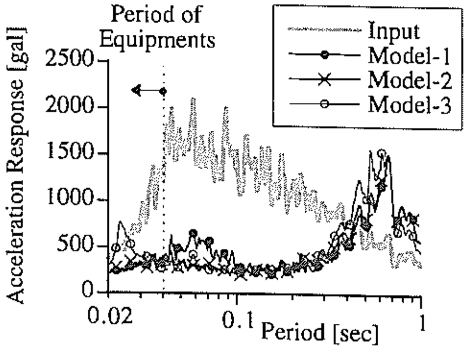

Fig.8 Horizontal Response Spectra
at the Bottom of Models

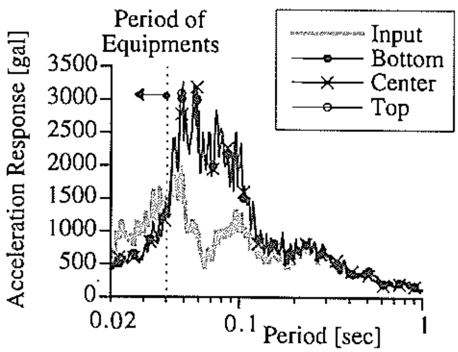

Fig.9 Vertical Response Spectra
of Model-1

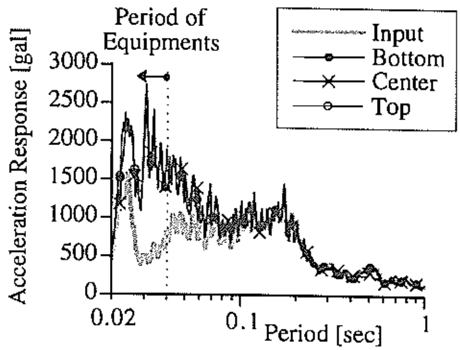

Fig.10 Vertical Response Spectra
of Model-3

Above results indicate that the vertical seismic load for the equipment can be reduced, by setting the vertical isolation frequency appropriately considering the vertical dominant frequency of the equipment or ground conditions. Thus the vertical isolation frequency is selected between the maximum and minimum limit specified from several factors (e.g., stability, manufacturability). For example, if the dominant vertical frequencies of the primary equipment exist over 8 Hz, the vertical acceleration response of these equipment can be reduced by 3-D isolation system with the thick RBs whose specifications for the reference plant were presented in this paper.

Rocking Motion of Isolated Models

Rocking ratios of the the models under the earthquake excitations are shown in Table 5, where the rocking ratio r is defined as the follows.

$$r = Xr / Xmax \times 100 \ [\%] \tag{1}$$

where Xr is the horizontal displacement at the top of the model due to rotational motion when the maximum horizontal displacement occurs, Xmax is the maximum horizontal displacement at the top of the models.

The rocking ratios of Model-1 (3-D) is about three times as large as those of Model-3 (2-D), however, the rotational angle is assessed at 3.48×10^{-4} rad in the case of the artificial earthquake input, and the rotational motion is considered quite small.

Table 5 Ratios of Rocking Motion

	Mode-1	Model-2	Model-3
Artificial Earthquake	3.28	1.63	1.09
El Centro (NS-UD)	3.21	1.63	1.06
JMA Kobe (NS-UD)	3.12	1.88	1.16
JMA Kobe (EW-UD)	3.02	1.52	1.08

CONCLUDING REMARKS

The results of this research are summarized as follows.
(1) As for the horizontal response, 3-D base isolation system using thick rubber bearings shows similar performance to that of 2-D system using thin rubber bearings, and for both systems rocking response is very small.
(2) It is shown that the vertical response of the 3-D base isolation system can be reduced in term of floor response spectrum in the specific frequency range where the vertical response of the internal components are affected. And the effectiveness of the 3-D base isolation system using the thick rubber bearings is proved from the experiment.

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