Shaking Table Test on Base Isolated FBR Plant Model
Part 2 Simulation Analysis

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1 INTRODUCTION

As a part of seismic safety verification test program for the base isolated fast breeder reactor (FBR) plant, a shaking table test using a simplified scaled model and subsequent simulation analyses of the test results were conducted. This paper describes the simulation analyses of the test results, whose objective is the verification for the adequacy of response analysis methods as used for design level earthquake inputs. In particular, modeling methods for the nonlinear characteristics of isolators and those effects on the calculated results were evaluated.

Isolators whose test results were analytically simulated in this study were following three types, i.e., lead rubber bearing(LRB), high damping rubber bearing(HRB) and multi-layered rubber bearing with steel bar damper. However, only the modeling methods and analytical results of LRB and HRB are described in this paper.

2 MODELING FOR ANALYSES

The outline of the analytical model for one directional excitation is shown in Fig. 1. The steel frame of superstructure and the isolator layer were modeled by shear-flexural beam elements, and a nonlinear shear spring with a linear rocking spring, respectively. The modeling method of nonlinear shear spring for the isolator layer was discussed below.

The isolator layer of the test specimen was composed of a set of nine isolator elements. In modeling process, the isolator layer was modeled by a single nonlinear shear spring and a single linear rocking spring that represent those nine isolator elements. The basic characteristics of isolator elements were obtained in advance by a preliminary element test of the isolator elements. The horizontal nonlinear characteristics model of isolators was determined by using the following method.

The nonlinear characteristics of isolators were determined from an engineering point of view so as to meet the values of both equivalent stiffness(Keq) and equivalent viscous damping ratio(Heq) which were calculated based on the results of the preliminary element test for steady state displacement cases. Fig. 2 shows how to determine the bilinear characteristics from the restoring loops obtained in the preliminary element test of isolator elements using this engineering method. Bilinear characteristics which satisfy both Keq and Heq as obtained from the preliminary element test results must meet the following conditions.

- The primary curve of the bilinear hysteresis loop must pass point C shown in Fig.2, which corresponds to a specified target displacement δd, so that this bilinear primary curve characteristics satisfy a target Keq.
- The points on the primary curve of the bilinear hysteresis loop must correspond to a set of yielding shear displacement δy and yielding shear force Qy in order for the area of bilinear loop ΔW to be the same as that obtained from the element test results so that this bilinear hysteresis loop satisfies a target Heq.

In these relationships, numerous sets of yielding horizontal displacement δy and yielding shear force Q_y which satisfy the specified value of ΔW could exist on a line A − B which is parallel to line O − C as shown in Fig. 2. To select one particular set of δ_y and Q_y, a loop fitting method was used in this study. In this method, the sum of square of differences between the assumed bilinear loop and the loop obtained in the test results(solid circular marks in Fig. 3) was calculated at selected values of δ_y in a range of 0 to δ_d and the one which gives the least value for the sum of square of differences was selected for δ_y in the bilinear primary curve. In this study, the displacement δ_d was determined to be the maximum displacement of isolator element recorded in the shaking table test.

Four different types of nonlinear model used in the simulation analyses are as follows(see Fig. 3):

(a)Bilinear model:the model properties can be determined by the method shown in Fig. 2. This model satisfies the required Heq solely by hysteretic damping, therefore, this model has no damping for the displacement less than δ_y.

(b)Bilinear + Linear model:LRB consists of laminated rubber bearing and lead plague. To consider internal viscous damping of laminated rubber bearing in the analysis model, this model has both the linear characteristics with the equivalent Keq and Heq of laminated rubber bearing alone and the bilinear characteristics which represent the nonlinear characteristics of lead plague. The bilinear characteristics were calculated by subtracting the linear characteristics(linear stiffness and equivalent hysteresis area corresponding to viscous damping) from the bilinear characteristic defined in (a).

(c)Overlay model:The model characteristics defined in (a) and (b) satisfy the target Keq and Heq for a specified displacement amplitude. The Overlay model[1] described here was developed by combining several elasto-plastic characteristics which simultaneously satisfy ΔW for different displacement amplitudes and nonlinear elastic characteristics which simultaneously satisfy a number of Keq. As an example of overlay model, Keq and Heq calculated from the element test results of LRB, which were used to determine the overlay properties for LRB, and the nonlinear characteristics of a set of shear springs whose combination produces a overlay model were shown in Table 1 and Table 2, respectively. Furthermore, Fig. 4 shows the hysteresis loops of HRB subjected to gradually increasing displacement steps when the overlay model was used.

(d)Nonlinear Elastic + Damper model:It is known that Heq of HRB has little dependence on displacement amplitude. In this model, the nonlinear elastic characteristics which satisfy Keq for different displacement amplitudes were combined with the viscous dampers which satisfy Keq and Heq for a specified displacement amplitude δ_d.

3 ANALYTICAL CASES

Type of isolator device, modeling method of isolator device and input level of earthquake motion were selected as the parameters of analyses as shown in Table 3. The earthquake motion used in the shaking table test is an artificial earthquake motion developed in this study[2]. Three types of modeling method were applied for each isolator device which was tested on the shaking table. The maximum displacements of isolator device recorded in the shaking table test and the target displacements, δ_d, as used for modeling were also shown in Table 3.

It should be mentioned that the analysis cases of A-3 and C-3 used a overlay model of the same properties in spite of different input earthquake levels applied to these two cases.

4 ANALYTICAL RESULTS

Fig. 5 shows the time history waveforms recorded in the test and those of analysis for comparison. The analytical results show a good agreement with the test results for both response acceleration and response displacement waveforms. However, in the test results, the acceleration responses at RF and 1F levels contain some high frequency components. The maximum acceleration profiles and the floor response spectra at 2F level(corresponding to the reactor location in an actual plant) for cases of LRB isolator subjected to S1 level earthquake input are shown in Fig. 6 and Fig. 7, respectively. The analytical results for cases in which the nonlinear properties satisfy both Keq and Heq at the amplitude around the maximum displacement recorded in the shaking table test show a good agreement with the test results. As for the floor response spectra, the maximum peak values and the overall shapes of peak obtained from the analyses are in a good agreement with the test results in the period range of 0.1sec to 1.0sec where the mode of isolator displacement becomes dominant. The maximum acceleration profiles and the floor response spectra for cases of HRB isolator under S1 level earthquake input are shown in Fig. 8 and Fig. 9 , respectively. As for the maximum acceleration profiles, the result of the analysis case B-2 shows the best agreement with the test result. In comparison of floor response spectra, the analytical results of all three analysis cases show a good agreement with the test results in the period range of 0.1sec to 1.0sec. The hysteresis loops of LRB and HRB isolator layers under S1 level earthquake input are shown in Fig. 10 and Fig. 11, respectively. Although there is a tendency that the maximum displacements of analyses are slightly smaller than those of test results, an overall comparison between the analytical results and the test results is satisfactory. The maximum acceleration profiles and the floor response spectra for cases of LRB isolator subjected to 1.5S1 level earthquake input are shown in Fig. 12 and Fig. 13, respectively. As input earthquake level increases, differences in the analytical results become noticeable due to different isolator modeling methods. In particular, a difference in the analytical results was found on the floor response spectra. The result of the analytical case C-3 which used an overlay model is in a good agreement with the test result for both the maximum displacement profiles and the floor response spectra. The hysteresis loops of LRB isolator layer subjected to 1.5S1 level earthquake input are shown in Fig. 14. The maximum displacement of the analytical case C-1 which used a bilinear model is smaller than the corresponding test value.

5 ANALYSIS OF TWO DIRECTIONAL INPUT

The one way nonlinear properties were extended to the horizontal in-plane nonlinear properties by using Multiple Shear Spring (MSS) model[3]. An analytical case of LRB isolator for multi-directional inputs of S1 level earthquake was performed. The concept of MSS model is shown in Fig. 15. The nonlinear properties of each direction used in this analysis is the same as those of the analytical case A-2. Fig. 16 shows the relative horizontal displacement orbit of isolator. The analytical results properly simulated the behavior of isolators in the horizontal plane as observed in the shaking table test.

6 CONCLUSION

The analytical results are in a good agreement with the test results in case of S1 level earthquake input for the lowest mode in which the isolator deformation was dominant. Therefore, the adequacy of modeling methods for nonlinear properties was confirmed in this study. Using the overlay model which satisfies Keq and Heq simultaneously for different steady-state displacement levels, a single nonlinear analytical model can adequately simulate the test results of different input earthquake levels, i.e., S1 and 1.5S1.

7 ACKNOWLEDGMENTS

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[2]Ishida,K. et al. (1990),"Shaking Table Test on Base Isolated FBR Plant Model (Part 1:Shaking Table Test Results)", 11th SMIRT.

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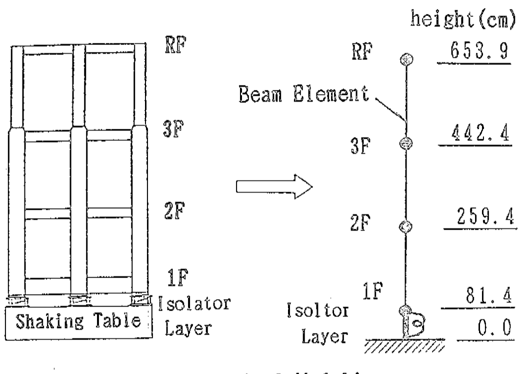


Fig. 1 Analytical Modeling

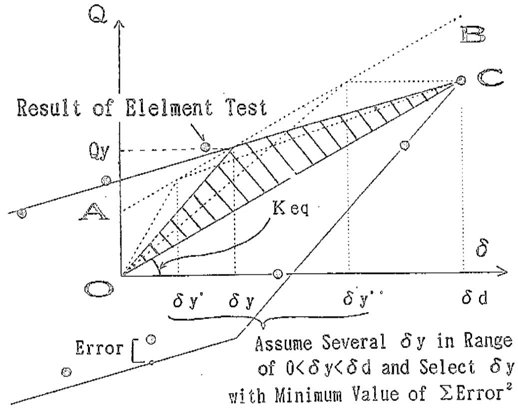
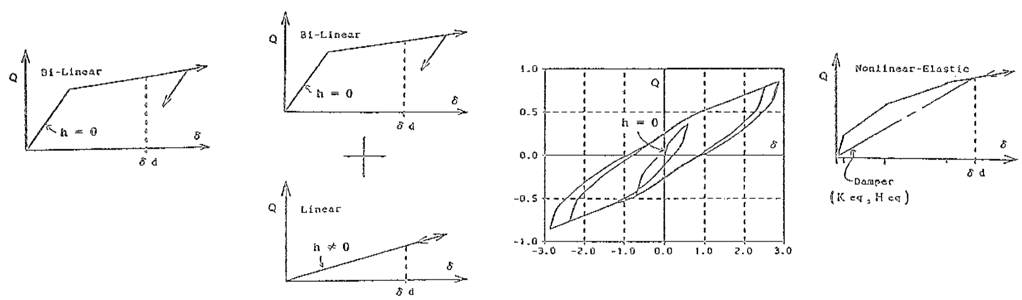


Fig. 2 Loop Fitting Method



(a) Bilinear (b) Bilinear + Linear (c) Overlay (d) Nonlinear Elastic + Damper

Fig. 3 Types of Nonlinear Properties used in Analyses

Tabel 1 Element Test Results

HORIZONTAL STRAIN γ (%)	HORIZONTAL DISPL. δ (cm)	Keq (ton/cm)	heq (%)
25	0.375	0.629	14.57
50	0.750	0.542	13.33
100	1.500	0.428	11.93
150	2.250	0.363	10.63

Table 2 Nonlinear Properties of Overlay Model Component

STIFFNESS CHANGING POINT(cm)	NON-LINEAR ELASTIC (ton/cm)	BI-LINEAR (1) (ton/cm)	BI-LINEAR (2) (ton/cm)	BI-LINEAR (3) (ton/cm)	BI-LINEAR (4) (ton/cm)	TOTAL STIFFNESS (ton/cm)
	2.499	11.090	1.292	0.471	0.078	15.380
0.051*						
	2.302	0.000	↑	↑	↑	4.143
0.375						
	3.546	↑	0.000	↑	↑	4.095
0.750						
	2.748	↑	↑	0.000	↑	2.826
1.500						
	2.097	↑	↑	↑	0.000	2.097

*The 1st stiffness changing point was calculated by hysteresis loop fitting of horizontal strain of 25%.

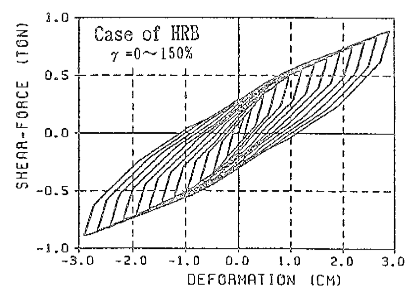


Fig. 4 Example of Overlay Model

Table 3 Analytical Cases

TEST CASE	ISOLATOR	INPUT LEVEL	MAXIMUM DISPL. (TEST:cm)	ANALYTICAL CASE	TYPE OF ANALYSIS MODEL	DISPLACEMENT USED TO DETERMIN MODEL PROPERTIES (cm)
A	LRB	S1	1.13 1.07	A-1	(a)Bi-linear	0.750
				A-2	(b)Bi-linear + Linear	
				A-3	(c)Overlay*	0.375, 0.750, 1.50, 2.25
B	HRB	S1	0.93 0.87	B-1	(a)Bi-linear	0.966
				B-2	(d)Nonlinear Elastic + Damper	
				B-3	(c)Overlay	0.483, 0.966, 1.93, 2.90
C	LRB	1.5S1	1.73 1.72	C-1	(a)Bi-linear	1.50
				C-2	(b)Bi-linear + Linear	
				C-3	(c)Overlay*	0.375, 0.750, 1.50, 2.25

*Analytical case A-3 and C-3 use same analysis property model.

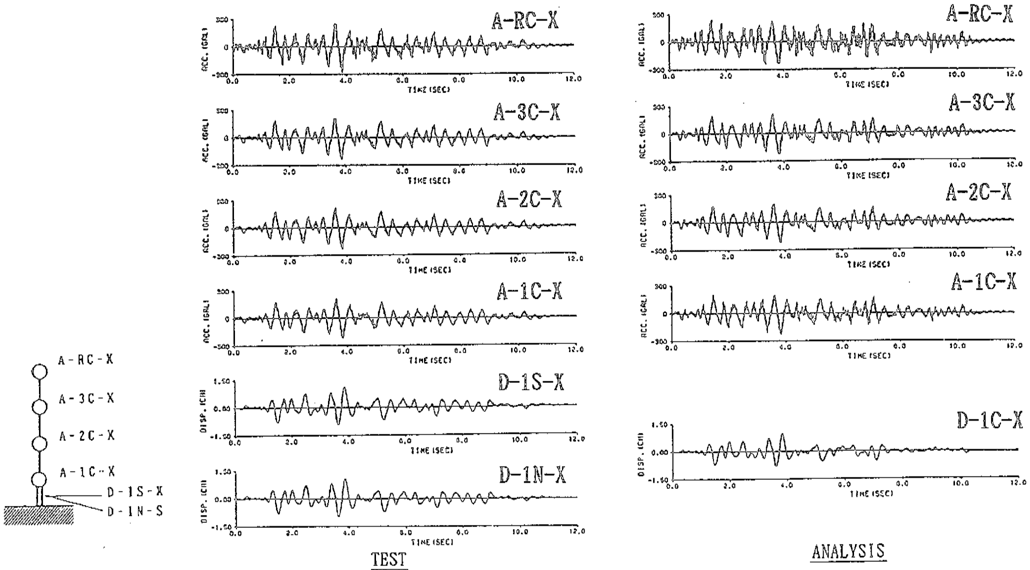


Fig. 5 Waveforms of Test Results and Analytical Results(A-2)

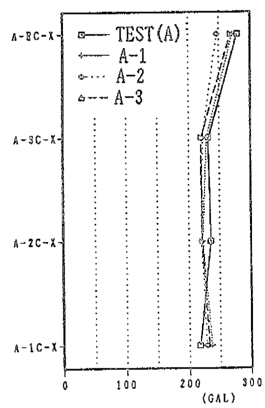


Fig. 6 Maximum Acceleration Profiles(LRB:S1)

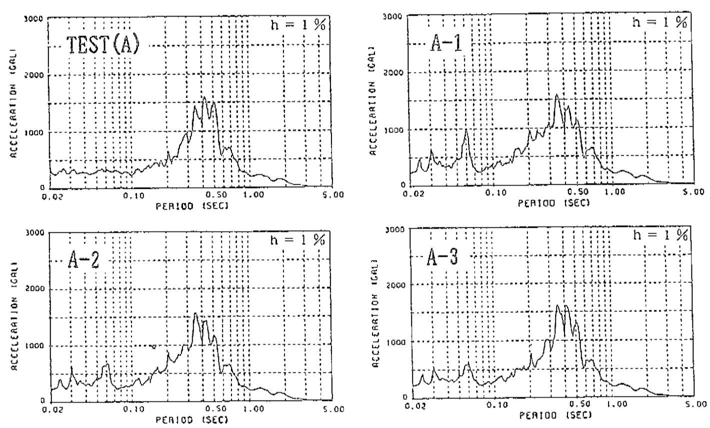


Fig. 7 Floor Response Spectra(LRB:S1)

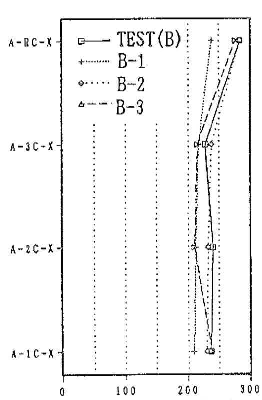


Fig. 8 Maximum Acceleration Profiles(HRB:S1)

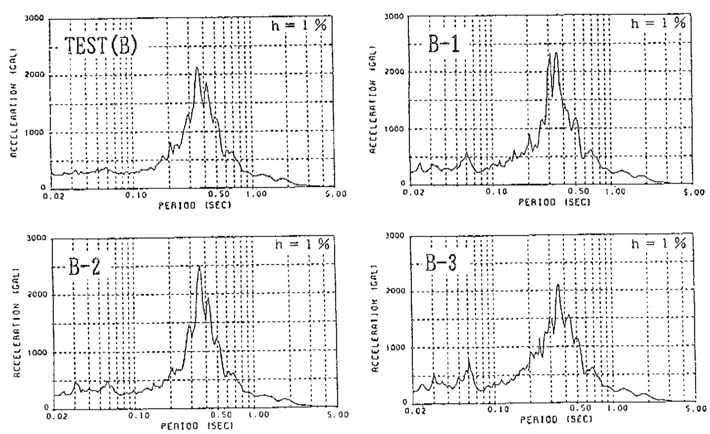


Fig. 9 Floor Response Spectra(HRB:S1)

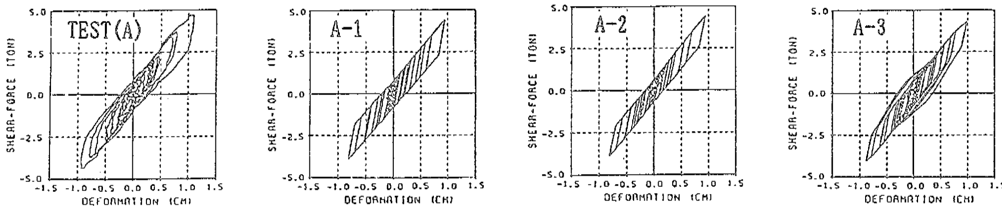


Fig. 10 Restoring Hysteresis Loop(LRB:S1)

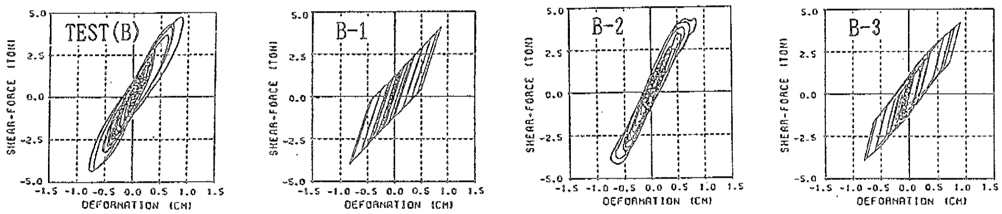


Fig. 11 Restoring Hysteresis Loop(HRB:S1)

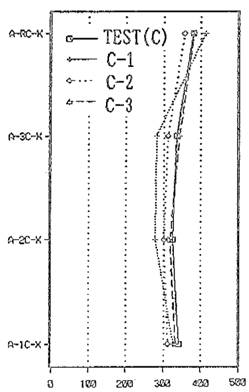


Fig. 12 Maximum Acceleration Profiles(LRB:1.5S1)

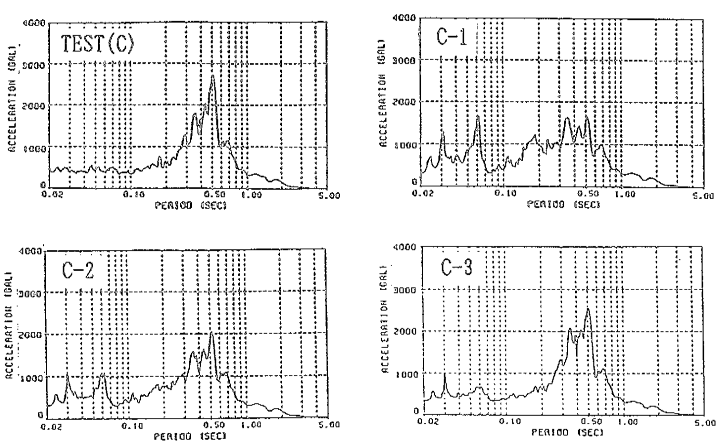


Fig. 13 Floor Response Spectra(LRB:1.5S1)

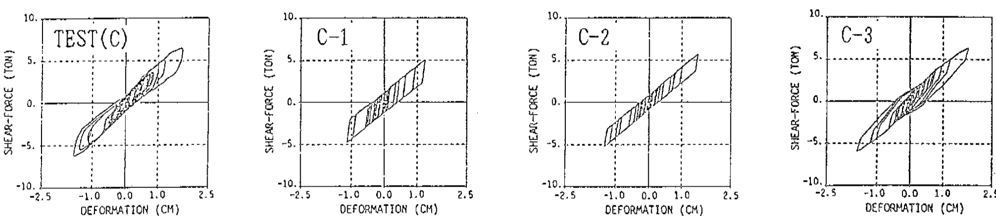


Fig. 14 Restoring Hysteresis Loop(LRB:1.5S1)

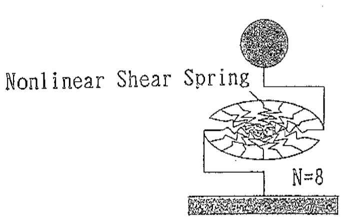


Fig. 15 MSS Model

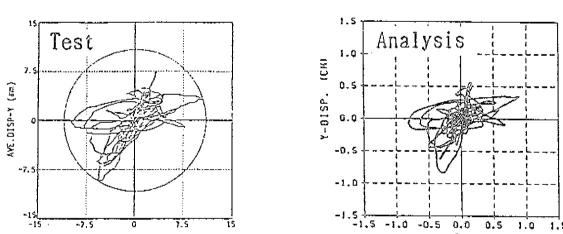


Fig. 16 Orbits of Isolator Layer