SHAKING TABLE TEST AND ANALYSIS ON BASE ISOLATED FBR PLANT MODEL WITH HIGH-DAMPING RUBBER BEARING

Yukio WATANABE[1], Asao KATO[2], Takahiro SOMAKI[3], Katsuhiko UMEKI[4] And Nobuhisa SATO[5]

SUMMARY

As for the high damping laminated rubber bearing(HRB) which was nominated as one of three base isolation devices to be applicable for the demonstration FBR plant(DFBR) in Japan, the shaking table tests to verify the seismic safety for the design earthquake(S2-M) with the 5% damping response velocity spectrum to be uniform 200kine(Vmax) in long periods from 2 seconds to 10 seconds and simulation analyses were conducted. The test parameters were the isolated natural period-2.0 / 2.83 seconds, and the phase properties of earthquake ground motion. The difference was the axial stress value, that is to say, the number of isolation devices for 2.83 seconds was half for 2.0 seconds. Regarding the test results, the responses for 2.0 seconds were kept within the linear domain, but ones for 2.83 seconds exceeded the linear domain because of the insufficient damping capacity. The simulation analyses for both cases were conducted, but the test results for 2.83 seconds were placed to ones of the half intensity input(100kine) of design earthquake(S2-M), which were within the linear domain. The test results were simulated by the non-linear seismic response analysis, as usual, using the simple bilinear model for HRB. Moreover, the modified bilinear model for HRB, in which the shear strain and frequency dependency were considered, gave closer results.

INTRODUCTION

High damping laminated rubber bearing(HRB) was considered as one of three types of base isolation systems for the base-isolated demonstration Fast Breeder Reactor (DFBR) plant in Japan, which were the natural laminated rubber bearing with steel damper (NRB+SD), the natural laminated rubber bearing with a lead plug(LRB) and HRB. In the beginning of the design of the DFBR plant, the seismic isolation specifications of these prototype devices were the initial period T1=1.0 second, the isolated natural period T2=2.0 seconds and the yield strength ratio to the total building weight β=0.1. And the design axial capacity of these devices was 500tonf, of which the axial stress was 32.3kgf/cm^2. But the verification of productivity and seismic safety by testing of these prototype devices had not been conducted yet. And it was appeared to be essential for reducing the number of devices since it was required too many 500 tonf devices to support the DFBR. And recently, it was strongly required to reduce the construction cost by adopting the devices with the higher axial stresses. So a series of shaking table tests by the scaled model were conducted for the purpose of verifying the seismic safety of the higher axial devices, including the prototype devices. And the applicability of analytical method for the design of superstructure and HRB were studied by simulation analyses of the shaking table tests with several parameters of seismic isolation specification.

[1] *THE JAPAN ATOMIC POWER COMPANY 1-6-1 Otemachi Chiyoda-ku Tokyo Japan E-mail:yukio-watanabe@japc.co.jp*
[2] *THE JAPAN ATOMIC POWER COMPANY 1-6-1 Otemachi Chiyoda-ku Tokyo Japan E-mail:asao-kato@japc.co.jp*
[3] *OBAYASHI CORPORATION 1-19-9 Tsutsumitoori Sumida-ku Tokyo Japan E-mail:t.somaki@o-net.obayashi.co.jp*
[4] *OBAYASHI CORPORATION 1-19-9 Tsutsumitoori Sumida-ku Tokyo Japan E-mail:umeki@o-net.obayashi.co.jp*
[5] *KAJIMA CORPORATION 6-5-30 Akasaka Minato-ku Tokyo Japan E-mail:shuoh@psa.kajima.co.jp*

SHAKING TABLE TESTS

Outline of the shaking table tests

a. Test cases

The parameters of test models for HRB are shown in Table 1. Test parameters are the T2 of HRB and the phase properties of earthquake ground motion. The T2 is set 2.0 and 2.83 seconds in actual time, which correspond to 0.51 and 0.72 seconds respectively in scaled time for testing. The ratio β of an yield strength to supporting load is set 0.1 for case 1(T2=2.0seconds) and expected to be 0.1 for case 2(T2=2.83seconds). The T2 is elongated to be 2.83 seconds by increasing the supporting load due to reducing the devices.

b. Shaking table test model and Specimen of HRB

The shaking table test model is shown in Fig.1. This model represents the dynamic characteristics of the DFBR building in Japan. The scale of the model to a prototype is 1/15.3, and both acceleration and stress are equal to those of the prototype. The superstructure, of which the proportion is the same as the DFBR, consists of three-story steel frame, and the center of gravity is located on the second story.

The configuration of the specimen of HRB is shown in Fig. 2. The diameter is 92mm. The rubber thickness totals up to 16mm(1mm thickness times 16 sheets).

c. Input motion

The maximum probable earthquake ground motion (S2-M)[1)] with the phase property of La Union record in Mexico earthquake 1985, of which response velocity spectrum with 5 % damping in long periods from 2 seconds to about 10 seconds is 200kine(Vmax), is used as an input motion to a shaking table test in this study. And more two input motions with the same spectra are considered, which are different in phase properties, Taft record 1952 and random phases. Each HRB is designed to have a margin against a hardening point in a load - deformation curve by this input motion S2-M.

d. Measuring instruments

The axial and shear forces acting on HRB are measured by load cells installed under each HRB and steel damper. The relative horizontal displacements between the shaking table and the superstructure, accelerations and velocities on shaking table and the superstructure are also measured.

Test results

a. Responses of isolation devices

Fig.3 shows the maximum responses of horizontal displacements and shear forces for HRB in comparison with the results of NRB+SD and LRB. The solid lines indicate the skeleton curves of design specification, and the subscript like 1028 describes T1 and T2 in seconds respectively. The maximum response shear strains of HRB for T2=2.0 seconds(Case 1) are almost the same as that of NRB+SD, and those of HRB for T2=2.83 seconds (Case 2) reach from 220% to 260% which are larger than the response strain 100% to 200% of the other devices.

Hysteresis loops of the shear force and the horizontal displacement of HRB are shown in Fig.4. The broken lines signify the design specification. The response of HRB for T2=2.83 seconds(Case 2) exceeds the strain hardening point(nearly 170%), since the yield strength of HRB for T2=2.83 seconds is not achieved as was expected. And the strain hardening in deformation might be small in comparison with other devices(over 250%). As shown in Fig.4(c), in the case of half intensity input(Vmax=100kine) of design earthquake, the response of HRB for T2=2.83 seconds is within the linear domain.

Accordingly, in case of using an HRB whose T2 is set longer by increasing axial stress, it is necessary to confirm whether it has sufficient damping. In the following simulation analyses for T2=2.83 seconds, the test results within the linear domain are selected.

b. Responses of superstructure

Distributions of the observed maximum response acceleration of the superstructure are shown in Table 2. It is found that the maximum response acceleration on all floor levels are smaller than on the shaking table, so the effectiveness of isolation system in case of each HRB is confirmed. As for the floor response spectra which are very important for the design of equipment and piping, the higher natural mode(0.035sec) of the superstructure is less excited than other devices(see Fig.9).

SIMULATION ANALYSES

Analytical cases and analysis model

Analytical cases are shown in Table 3. The influence of phase properties of each earthquake ground motion is evaluated in the analyses for T2=2.83 seconds.

The analysis model for simulation analyses is shown in Fig.1. The model of the superstructure is 3-lamped mass model composed of shear springs, bending springs and axial springs. The detail of each spring is determined based on the sweep(sine wave input) tests. The damping factor of the superstructure and the axial springs of isolation devices are 1% and 2%, respectively.

As for the analysis model of HRB, three models are considered, which are the design-base model with the bilinear and two simulation analysis models with the bilinear/the modified bilinear. The property of each model is shown in Table 4. The yield strength ratio of design specification for T2=2.83 seconds is set 0.05, referring to Fig.4(c). And the difference between the bilinear and the modified bilinear is whether the shear strain dependency is considered or not.

Generally speaking in the design of HRB, the 2nd stiffness K2 and the dissipating shear force Qd are easy to be controlled, however the initial stiffness K1 is essentially too difficult to be done. Therefore, the ratio of K1 to K2 for the design-base model is given in a range of 3 to 6 in the guideline[2)], not to be specified. In this study, that ratio is chosen to be 3 with closer analysis results.

The modified bilinear model is usually used in the design of the isolated building with HRB. The initial stiffness K1 is usually calculated by 2nd stiffness K2, the dissipating shear force Qd and the equivalent damping Heq based on the static element tests which are conducted for all devices as manufacturing inspections. But in this study, K1 is evaluated by relationship with K2 based on the shaking table test directly because K1 has remarkable influence on the floor response spectra in short range period. In Fig.5, the static element test results, the shaking table test results and the calculated Heq are compared. The calculated Heq from the modified bilinear model almost corresponds with the shaking table test results, and the insufficiency is considered as an internal viscous damping. Moreover, the influence of the frequency dependency is evaluated by the shear strain velocity rate tests (Frequency: 0.01, 0.5, 1.0, 2.0Hz) for some devices right after the static element tests, and the coefficient of 1.09 to 1.1 for K2 and 1.08 to 1.15 for Qd are considered in the simulation analysis models.

Results

a. Responses of isolation devices

Fig. 6 and Fig.7 show the comparison of the maximum response displacement and the hysteresis loop of isolation devices of the tests and analyses, respectively. The design-base model overestimates the maximum response displacement. On the other hand, the modified bilinear model can simulate closer. However, it dose not simulate the K2 of hysteresis loop well, even the frequency dependency is considered in the simulation models. The insufficient simulation is thought to be caused by the difference between in the element test for the individual device and the shaking table tests for the assembly, and also by the restoring property to the initial state.

b. Responses of superstructure

Fig. 8 shows the comparison of the distribution of the maximum response acceleration between tests and analyses in case of T2=2.0 seconds and 2.83 seconds. Though the test results in the case of T2=2.83 seconds can be analysed sufficiently by any models, ones in the case of T2=2.0 seconds is not so well. It is considered that the former was within the linear domain but the latter was slightly within the strain hardening.

Fig. 9 shows the typical floor response spectra(FRS) of the 2nd-story with damping factor h=1%. The FRS can be roughly analysed by any models. But focusing on the FRS in the vicinity of period 0.035sec, which has significant influence on the design of important equipment and piping, the modified bilinear model brings closer results. Through the simulation analyses, it is found that the initial stiffness K1 is the most effective factor on

FRS estimation. So the bilinear model considering the ratio of K1 to K2, which is based on several loops of the shaking table test results, brings closer results as the same as the modified bilinear model dose.

CONCLUSION

1) Since the damping factor of HRB was to be smaller than the assumed value that the yield strength ratio of seismic isolation specification was to be 0.1, the displacement response of HRB was greater than NRB+SD and LRB. Moreover, since the strain hardening in deformation was small in comparison with other devices, HRB was apt to exceed the linear domain.

2) The results of the shaking table test within the linear domain response can be simulated sufficiently by the non-linear seismic response analysis method as usual. As for the restoring characteristics of HRB, the test results can be simulated sufficiently by the bilinear model based on the static element tests(inspection), and more closely by the modified bilinear model based on the shaking table tests. However, the design-base model can not analyse the response spectra sufficiently.

3) Regarding HRB, of which isolated natural periods are set longer by higher axial stresses, it is necessary to confirm whether it has sufficient damping to reduce the horizontal relative displacement.

ACKNOWLEDGEMENT

This study was carried out as a part of the FBR common research of the electric power companies in Japan, entitled "Conceptual Design of DFBR". And this study was based on the support of Professor T. Fujita of Institute of Industrial Science, University of Tokyo, whom the authors gratefully acknowledge.

REFERNCES

1) Kato, M. et al. "Design study of the seismic-isolated reactor building of demonstration FBR plant in Japan," *Trans. of the 13th SMiRT,* Vol.3, Division.K, pp579-584, Brazil, August, 1995.

2) Ishida, K. et al. "Study on Design Method for Seismically Isolated FBR Plants," *Abiko Research Laboratory Rep.No.U34 of Central Research Institute of Electric Power Industry,* p III-97, December, 1998. (In Japanese)

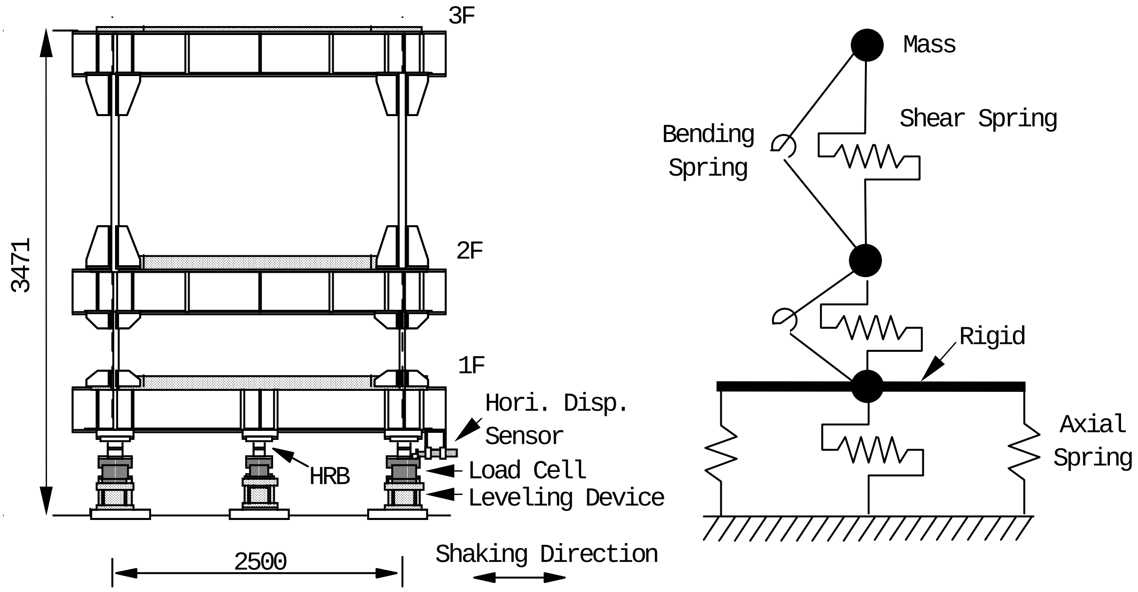
Table 1 Parameters of Test Models

Case No.	Initial Natural Period (T1 second)	Isolated Natural Period (T2 second)	Yield Strength Ratio β	Number of Isolation devices	Total Weight (tonf)	Axial Stress (kgf/cm^2)
1	1.0	2.0	0.1	8	17.2	32.3
2	1.0	2.83	0.1	4	17.2	64.7

Table 2 Test Results of Maximum Response Acceleration(Unit:Gal)

Mass Point	Case-1 (T2=2.0sec)			Case-2 (T2=2.83sec)		
	S2-M	TAFT	RANDAM	S2-M	TAFT	RANDAM
3rd Story	533	472	479	539(174)	515(187)	415(157)
2nd Story	514	349	401	438(161)	426(175)	362(148)
1st Story	442	385	416	383(165)	373(191)	332(154)
Shaking Table	832	926	890	866(417)	919(453)	911(460)

Note: The numerical value in brackets are the results by half intensity input(Vmax=100kine) of design earthquake.



(a) Shaking table test model **(b) Analysis Model**

Fig.1 Shaking Table Test Model and Analysis Model(Unit:mm).

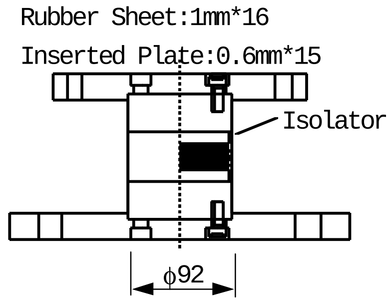
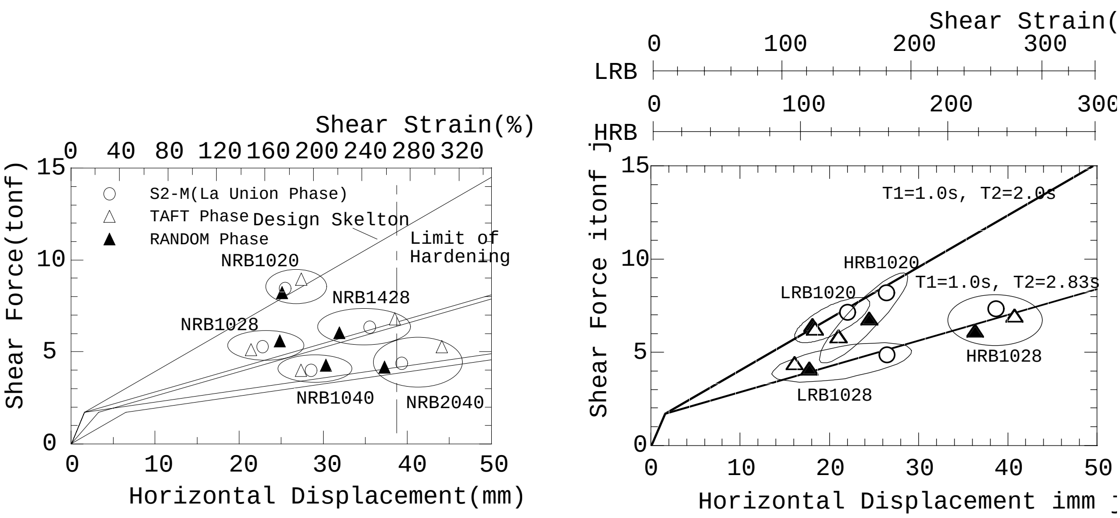
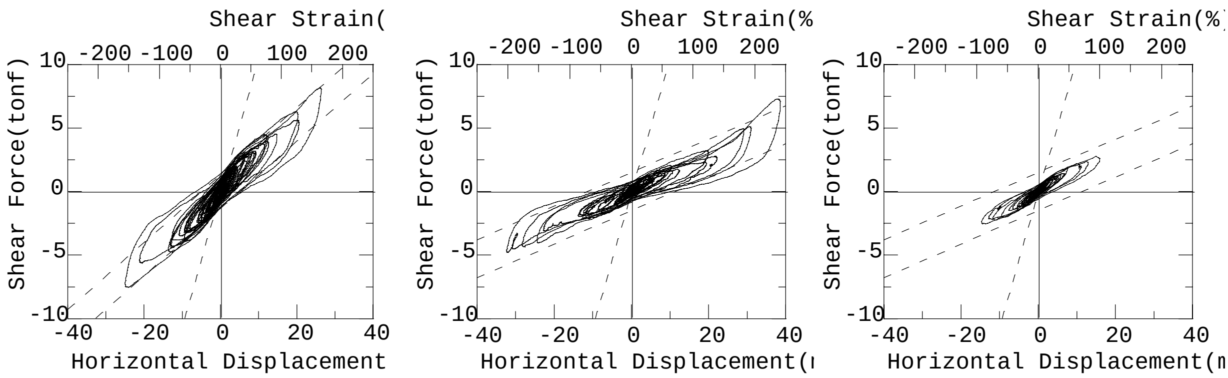


Fig.2 Specimen of HRB



(a) Test results for NRB+SD **(b) Test results for LRB and HRB**

Fig.3 Maximum Responses of Shear Force and Horizontal Displacement.



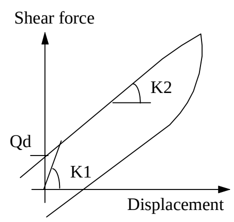
(a) T=2.0seconds for S2-M **(b) T=2.8seconds for S2-M** **(c) T=2.8seconds for S2-M*1/2**

Fig.4 Hysteresis Loops of Shear Force and Horizontal Displacement of HRB.

Table 3 Analytical Cases

Case No.	Design Specification and Parameters				Earthquake Ground Motion			
	Isolated Natural Period T2 (second)	Yield Strength Ratio β	Number of Isolators	Axial Stress (kgf/cm^2)	S2-M (200kine)	S2-M*1/2 (100kine)	TAFT*1/2 (100kine)	RANDAM *1/2 (100kine)
1	2.0	0.1	8	32.3	✓	-	-	-
2	2.83	0.05	4	64.7	-	✓	✓	✓

Table 4 Detail of Analysis Model for HRB

Item	Design-base Model	Simulation Analysis Model		Note
	Bilinear	Modified Bilinear	Bilinear	
Initial Stiffness K1	K1=3*K2	K1=α(γ)*K2 α(γ) is due to the regression of the shaking table test.	K1=2.4 to 3.2*K2 with reference to Modified Bilinear.	
2nd Stiffness K2 (Isolated Natural Period) / Dissipating Shear Force Qd	K2=constant Qd=constant K2 is due to the design equation at shear strain γ=100%, and Qd is based on K1, K2 and β.	K2 and Qd depend on the shear strain due to the regression of the static element tests.	K2=constant Qd=constant are based on the static element tests.	
Vertical Stiffness Kv	Kv=constant is due to the design equation.	Kv=constant is based on the static element tests.	Kv=constant is based on the static element tests.	

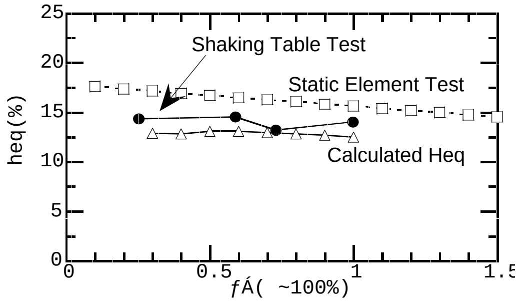


Fig.5 Comparison of Heq.

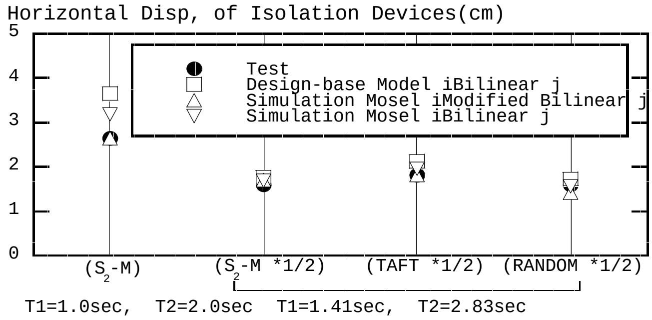
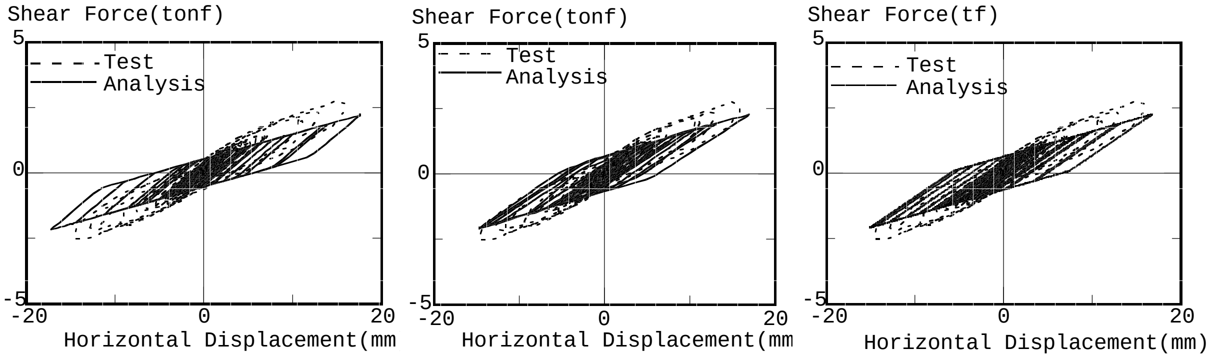
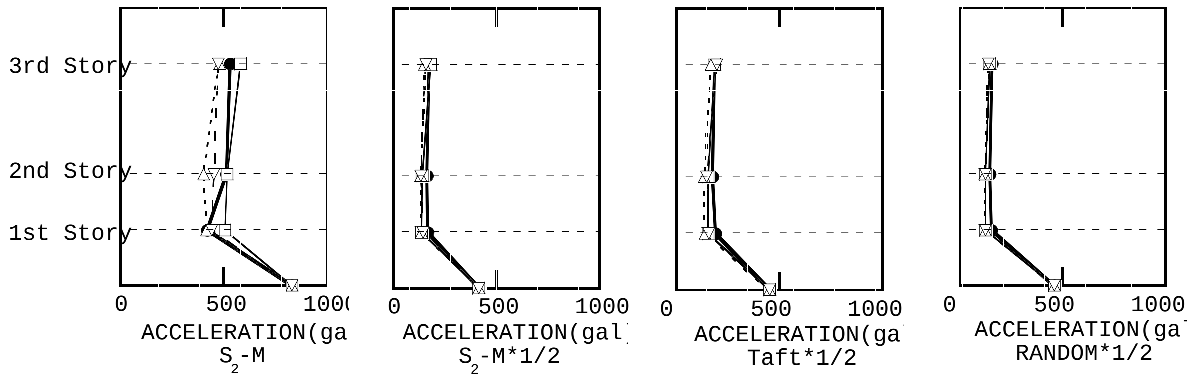


Fig.6 Comparison of Maximum Response Displacement of HRB.



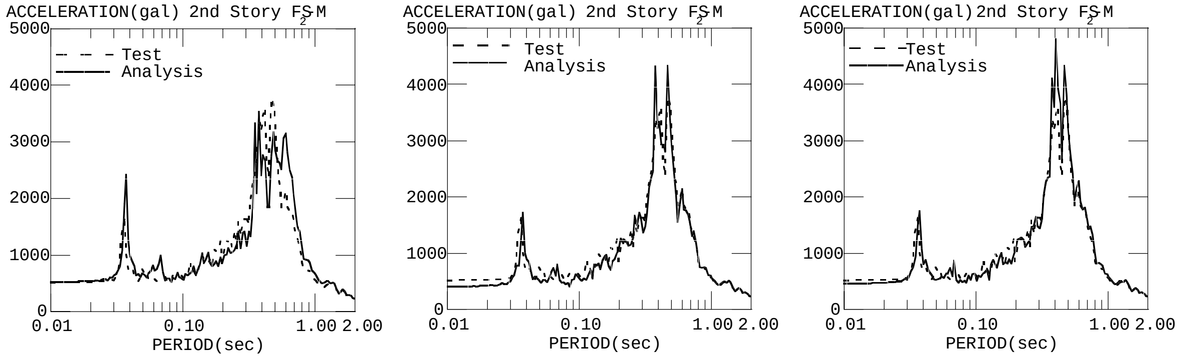
(a) Design-base Model (bilinear) **(b) Simulation Model (Modified bilinear)** **(c) Simulation Model (bilinear)**

Fig.7 Comparison of Hysteresis Loops between Tests and Analysis Models.



(a) T2=2.0seconds (S2-M) **(b) T2=2.83seconds (S2-M*1/2)** **(c) T2=2.83seconds (TAFT*1/2)** **(d) T2=2.83seconds (RANDAM*1/2)**

Fig.8 Comparison of Distributions of Maximum Response Acceleration.



(a) **Design-base Model (bilinear)** **(b) Simulation Model (Modified bilinear)** **(c) Simulation Model (bilinear)**

Fig.9 Typical Floor Response Spectra with Damping Factor h=1% at 2nd Story between Tests and Analyses for T2=2.0seconds and S2-M Input.