



## Shaking Table Tests on Failure Characteristics of Base Isolation System

Yukio Watanabe<sup>1)</sup>, Asao Katoh<sup>1)</sup>, Masaaki Ohba<sup>1)</sup>, Yasuaki Fukushima<sup>2)</sup>, Nobuhisa Satoh<sup>2)</sup> and Masao Iizuka<sup>2)</sup>

1) *The Japan Atomic Power Company, Japan*

2) *Kajima Corporation, Japan*

### ABSTRACT

A series of shaking table tests were conducted for reduced scaled model of a base isolated demonstration Fast Breeder Reactor (FBR) plant in Japan for the purpose of verifying the seismic safety of systems. Three types of base isolation systems: natural rubber bearing with steel damper (NRB+SD), lead rubber bearing (LRB), and high damping rubber bearing (HRB) were concerned. As a result of these tests, NRB+SD, LRB and HRB were within stable domain (not hardening) at S2 input, and were nearly hardening at  $2 \times S2$  input. All types of the rubber bearings did not break at  $3 \times S2$  input which was the level of design limit. And these bearings broke at over  $4 \times S2$  input.

### Introduction

A demonstration FBR plant in Japan is to be planned as a base isolated building in the horizontal direction. The authors have already presented the results of the three breaking tests consisting of four, nine and twenty-five NRBs using a shaking table at 12th SMiRT Conference. In this paper seismic safety and dynamic characteristics of the rubber bearing breaks of three types of reference design base isolation system, NRB+SD, LRB and HRB for the demonstration FBR plant in Japan were confirmed by conducting shaking table tests.

### 1. Test Methods

#### a. Input condition

The test cases are shown in table.1. Four excitation levels were set up in these tests. Those were on the design level, the hardening level, the level of the design limit, and the target breaking level of the laminated rubber bearing. The time scale were reduced one-fourth by the Similarity Law where the reduced scale of acceleration and stress of the isolation system was the same as full scale.

#### b. Test model

Test model and its size ,about 2500(wide)•2000(deep) •3500mm(high), was about one-sixteenth, the scale of the base isolated FBR building model. The model consisted of an upper structure and a base isolation system. The outline of the model is shown in fig.1.

(a) the upper structure

The upper structure had three floors and was made of steel. Its total weight was about 17 tonf. The second floor of the upper structure was modeled as the reactor support floor of DFBR. And the first-story column was made of high strength steel so as to remain elastic through the experience, because shaking table tests were conducted to evaluate failure characteristics three times.

(b) the isolation system

The vertical stress of the rubber bearing was 50 kgf/cm<sup>2</sup>. The period corresponding to initial stiffness of the isolation system was equal to 1.0 second for full scale building, the period corresponding to second stiffness was equal to 2.0 seconds, and the ratio of yield shear stress to design vertical stress of the rubber bearing was 0.05, which is a standard design for DFBR in Japan. The total thickness of the rubber sheet of the three types of the rubber bearings, NRB, LRB and HRB, was 7mm (NRB and LRB), and 8mm (HRB). The outline of these rubber bearings were shown in fig.2. Four rubber bearings were placed under the upper structure columns in each test.

The property of the steel damper that was used for NRB+SD is also shown in fig.2. Two steel dampers were placed in the isolated layer so as not to be twisted. The spherical bearing was placed over the joint of the steel damper of the upper structure to make the steel damper be a cantilever type. The steel dampers were replaced every test.

(c) The safety frame

The safety frame, shown in fig.1, was set so that the upper structure would not be damaged when the rubber broke because the breaking tests were conducted using the same upper structure three times. The frame was designed based on the result of the preliminary analysis, considering safety during the tests.

c. The shaking table

The six degree-of-freedom shaking table was used.

## 2. Measurements

Horizontal accelerations were measured at each floor and the top of the shaking table. Horizontal relative displacement and shear force of the isolated layer were also measured. As a result of these tests measurements, dynamic characteristics of the upper structure and the isolation system can be evaluated. Vertical relative displacement and vertical force of the rubber bearing were measured especially for analyzing the failure mode of the rubber bearing. Moreover, instruments were chosen for their durability throughout the tests, meaning being strong enough to receive the vibration whenever the rubber bearing breaks.

## 3. Static tests of the laminated rubber bearing

- 1) The quality of the rubber bearings were confirmed from the results of static tests for every specimen in a factory before the shaking table test. The outline of the static tests were as follows:

parameter	: shear strain	= 100,150,200%
	: the vertical stress=	50kgf/cm <sup>2</sup> (design value)
loading	: 4 times cyclic loading	under a design vertical load.

measurements : Mean shear modulus and mean force at 0 displacement for the third cycle are shear stiffness (KH) and characteristic dissipator shear strength (Qd) of the rubber bearing respectively.

The results were shown in fig.3. The variation between data was approximately within  $\pm 10\%$  of the design value.

- 2) Static breaking tests by a monotonic load under a design vertical stress were conducted. Using the result of the tests, the shear strain linear limit of each type of the laminated rubber bearing could be calculated[1]. When the linear limits were calculated, the characteristic dissipator shear strength were used for the results of the former tests (shear strain 200%). The calculated shear strain linear limit of NRB was about 290%, about 310% for LRB, and about 260% for HRB. The test results were also compared with the shaking table tests.
- 3) Static failure limit tests using two directional loads for calculating breakage bound were conducted. The outline of the static tests were as follows:
  - number : five test pieces for each type of the rubber bearings
  - test cases : i.shear breaking test in the compression zone (vertical stress :  $250\text{kg/cm}^2$ )
    - ii.shear breaking test under non vertical loading
    - iii.shear breaking test in the tension zone (vertical strain : 25%)
    - iv.shear breaking test in the tension zone (vertical strain : 50%)
    - v. tensional breaking test
  - method : static monotonic loading

As a result of static break tests using a monotonic load under a design vertical stress and static failure tests using two directional loads, static breakage bound of each type of the laminated rubber bearing was confirmed. And the breakage bound is compared with the shaking table tests. Test results and the breakage bound were shown later.

#### 4. Test results

##### a. Input motion of the shaking table

Acceleration response spectra of the shaking table for example in case of 1S2 and 4S2 inputs were shown in fig.4. This figure shows that response spectra of NRB was almost the same as that of other rubber bearings. In the case of other level inputs the floor response spectra was also almost the same as in the case of 1S2 input. The result means that input motions of the shaking table of the three types of isolation systems were almost the same. There was a slight difference in the short period of response spectra at more than 4S2, but acceleration response spectra were almost the same as other bearings in the period of 0.25 to 0.5 seconds, where the period corresponding to the second stiffness of each rubber bearing was within the period region.

##### b. Shear force - Horizontal displacement hysteresis curve of isolation layer

The hysteresis behavior of shear force - horizontal displacement at 1S2, 2S2, and 4S2 inputs in case of NRB+SD, at 5S2 input in the case of LRB and HRB is shown in fig.5. The hysteresis in the three quadrant areas were rotated at 180 degree. This figure also shows the breaking point of the rubber bearing and the results which were four times as much as the stress of the static breaking tests under a monotonic load.

##### 1) NRB+SD

Max. horizontal shear strain of the isolator at 1S2 input was about 130%. This strain was under the linear limit which could be calculated from the static breaking

tests by a monotonic load. Max. horizontal shear strain of the isolated layer at 2S2 input was about 340% which was more than the linear limit. Horizontal shear strain of the isolated layer at 3S2 input was about 490%, but all the NRBs did not break. One of the NRBs (C3 in fig.1) broke at about the maximum strain which was 600% at 4S2 input, but the steel dampers did not break then.

When the hysteresis was compared with the static breaking tests, the slip phenomena could be seen from the hysteresis at 4S2 input, so the breaking strain of the shaking table test was larger than the static breaking tests.

That means the NRB was within the stable domain (not hardening) at 1S2 input, reached hardening at 2S2 input, was sound at 3S2 input which was the level of the design limit, and the rubber bearing broke at 4S2 input.

### 2)LRB

Max. horizontal shear strain of the isolator at 1S2 input was about 80%. This strain was under the linear limit. The maximum strain was less than other isolation systems. That was because characteristic dissipator shear strength and first stiffness of LRB were larger than other isolation systems. Max. horizontal shear strain of the isolated layer at 2S2 input was about 310% which was almost the linear limit. Max. horizontal shear strain of the isolated layer at 3S2 input was about 490%, but all the LRBs did not break. One of the LRBs (A3 in fig.1) broke at about the maximum strain which was about 640% at 5S2 input. Immediately after that the rest of the rubber bearings broke on the opposite side.

When the hysteresis was compared with the static breaking tests, the slip phenomena could be seen from the hysteresis at 4S2 input, the breaking strain of the shaking table test was larger than the static breaking tests as well as NRB+SD.

### 3)HRB

Max. horizontal shear strain of the isolator at S2 input was about 110%. This strain was under the linear limit. Max. horizontal shear strain of the isolated layer at 2S2 input was about 280% which was more than the linear limit. Max. horizontal shear strain of the isolated layer at 3S2 input was about 420%, but all the HRBs did not break. One of the HRBs (A1 in fig.1) broke at about maximum strain which was about 630% at 5S2 input. Immediately after that the rest of the rubber bearings broke on the opposite side.

When the hysteresis was compared with the static breaking tests, the shear strain of the shaking table tests were larger than the static breaking tests at 1S2 to 3S2 input. That was because of the shear strain velocity rate dependency of HRB which Dr. K.Ishida etc. pointed out[2]. The shear strain of the shaking table tests was less than the static breaking tests at the same stress input level of 4S2 and 5S2, so the slip phenomena could be seen from the hysteresis. But HRB were more gentle than other bearings and the maximum response was almost the same as the static breaking tests. That was because the slip phenomena and the shear strain velocity rate dependency of this HRB occurred simultaneously.

### c. Failure mode

The failure mode for the rubber bearings were shown in fig.6. In the vertical stress - horizontal shear strain relation and the vertical strain - horizontal shear strain relation, the breakage bound which was calculated by the static breaking tests was included.

The vertical stress at the breakage of the rubber bearing which broke first among the four elements was 30 - 40 kgf/cm<sup>2</sup> on the tension side, the vertical strain was 10 - 15% for the three types of rubber bearings as shown in fig.6. That is to say all types of

the rubber bearings broke in the tension-shear zone. The breaking strain of all the rubber bearings which broke at the shaking table tests was larger than that of static breaking tests and the strain was also beyond the breakage bound.

**d. Maximum response at 1S2 input**

The maximum response acceleration of each floor for the three isolation systems was shown in fig.7. All the maximum response accelerations at 1S2 input of the upper structure were less than 500 gal which was the design target level of the isolation system for three types of isolation systems. The maximum response shear force and the shear coefficient of each floor is also shown in fig.7. This figure shows that the response acceleration and the shear force of third floor for LRB were a little greater than for other bearings. That was because yield stress and initial stiffness of LRB was greater than for the others, as mentioned above

## **5. Conclusions**

The results of the shaking table tests were summarized as follows.

- 1) The maximum response acceleration of the upper structure for the three types of the isolation system was less than the design target level of the isolation at 1S2 input.
- 2) The three types of isolation system were within the stable domain (not hardening) at 1S2 input, and were nearly hardening at 2S2 input. All types of laminated rubber bearings did not break at 3S2 input which was the design limit.
- 3) All types of the laminated rubber bearing broke at more than 4S2 input, and the failure mode of the bearing which broke first of the four elements was tension-shear mode.

These results demonstrate that the safety requirement of each type of laminated rubber bearing was satisfied.

## **6. Acknowledgements**

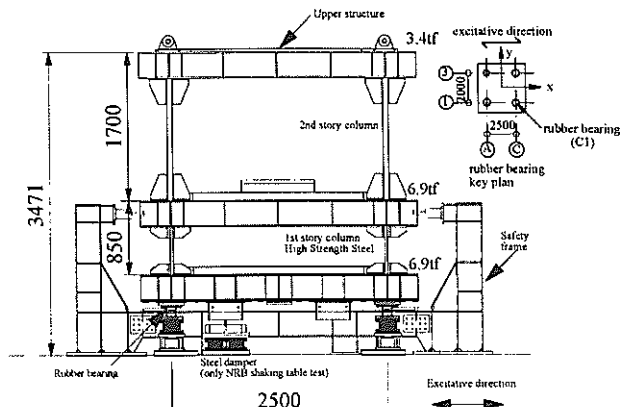
This study was carried out as a part of the FBR common research of the electronic power companies in Japan, entitled "Conceptual Design of DFBR". And this study was based on the support of Professor T.Fujita of Institute of Industrial Science, University of Tokyo, Japan, which the authors gratefully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

## **7. References**

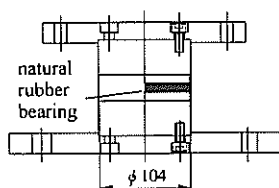
- [1] S.YABANA, Y.OHTORI, K.HIRATA, K.YASUI and T.MAZDA, "Study on Linear Limits of Rubber Bearings", AIJ annual report (1996) in Japanese
- [2] K.ISHIDA, H.SHIOJIRI, M.IIZUKA, K.MIZUKOSHI and K.TAKABAYASHI, "Failure Tests of Laminated Rubber Bearings " 11th SMiRT (1991) K25/5
- [3] M.KATO, Y.WATANABE, A.KATO, H.KOSHIDA, K.MIZUKOSHI, Y.FUKUSHIMA, O.NOJIMA, G.YONEDA and S.ONIMARU " Dynamic Breaking Tests on Base-Isolated FBR Plant" 12th SMiRT (1993) K22/1

**table.1 Input condition**

TEST NAME	INPUT LEVEL	MAX. ACC. (gal)
DESIGN	1S2	380
HARDENING	2S2	760
DESIGN LIMIT	3S2	1140
BREAKING	4S2	1520
	5S2	1900



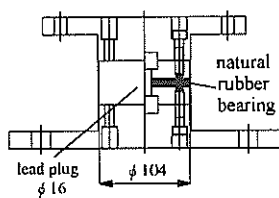
**fig.1 The test model**



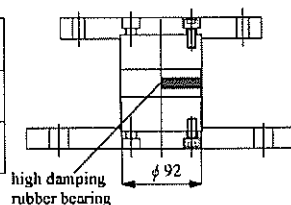
TOTAL THICKNESS OF RUBBER	7mm
A COEFFICIENT OF FIRST FORM	26
A COEFFICIENT OF SECOND FORM	15

ITEM	STEEL DAMPER
NUMBER	2
MATERIAL	STEEL
YEILD STRENGTH	235 N/mm <sup>2</sup>
DIAMATER	φ 17
HIGHT	86mm

**(a) NRB+SD**



TOTAL THCKNESS OF RUBBER	7mm
A COEFFICIENT OF FIRST FORM	26
A COEFFICIENT OF SECOND FORM	15

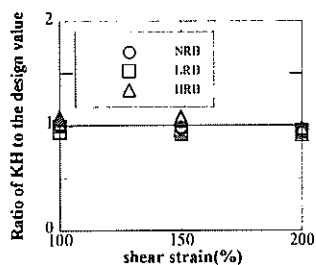


TOTAL THCKNESS OF RUBBER	8mm
A COEFFICIENT OF FIRST FORM	23
A COEFFICIENT OF SECOND FORM	12

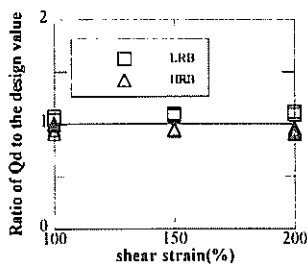
**(b) LRB**

**(c) HRB**

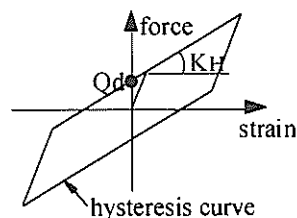
**fig. 2 The outline of the rubber bearing**



**(a) the shear stiffness (KH)**

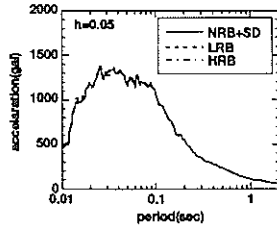


**(b) characteristic dissipator shear strength (Qd)**

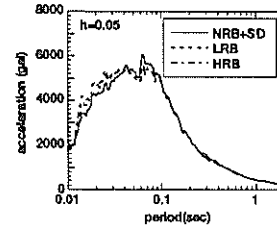


**characteristics of the isolation system**

**fig. 3 Results of static element tests**

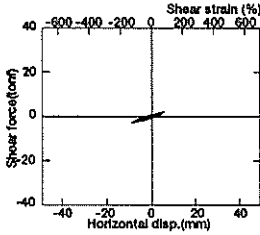


(a) 1S2 input

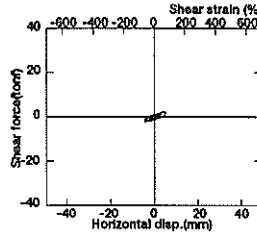


(b) 4S2 input

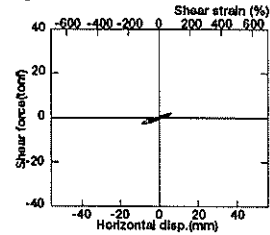
fig.4 The response spectra of the shaking input motion



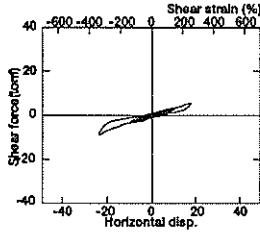
(a) 1S2 input



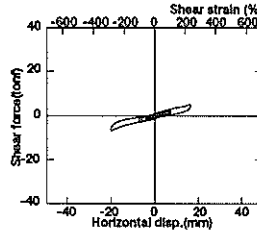
(a) 1S2 input



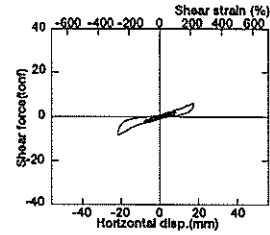
(a) 1S2 input



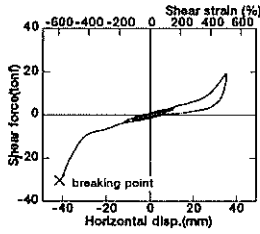
(b) 2S2 input



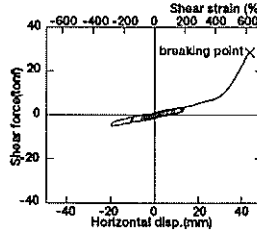
(b) 2S2 input



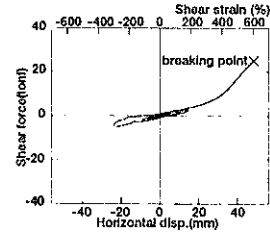
(b) 2S2 input



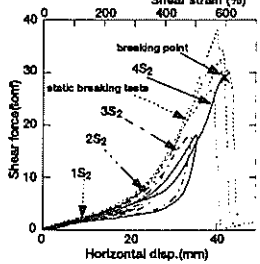
(c) 4S2 input



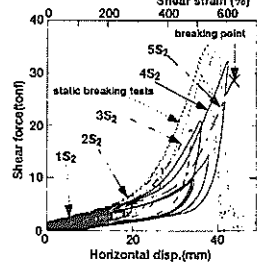
(c) 5S2 input



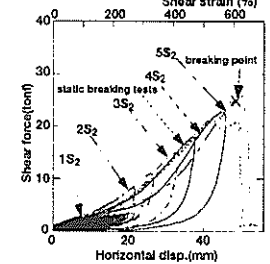
(c) 5S2 input



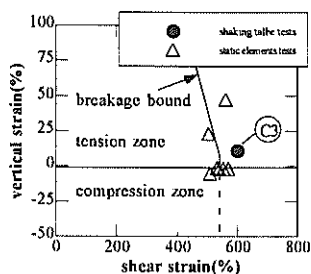
(d) static breakings test and shaking table test (NRB)  
fig.5(1) hysteresis behavior (NRB+SD)



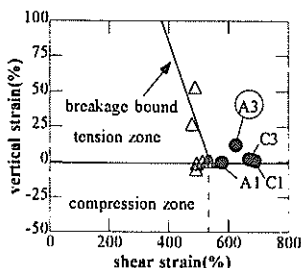
(d) static breakings test and shaking table test (LRB)  
fig.5(2) hysteresis behavior (LRB)



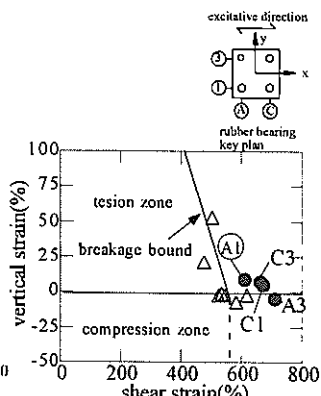
(d) static breakings test and shaking table test (HRB)  
fig.5(3) hysteresis behavior (HRB)



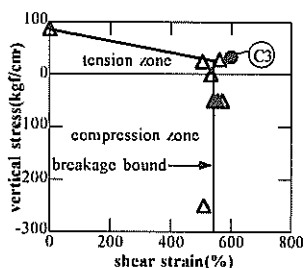
(a) vertical strain-shear strain relation



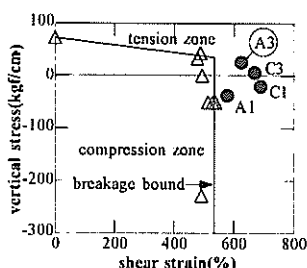
(a) vertical strain-shear strain relation



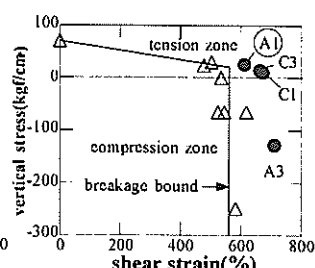
(a) vertical strain-shear strain relation



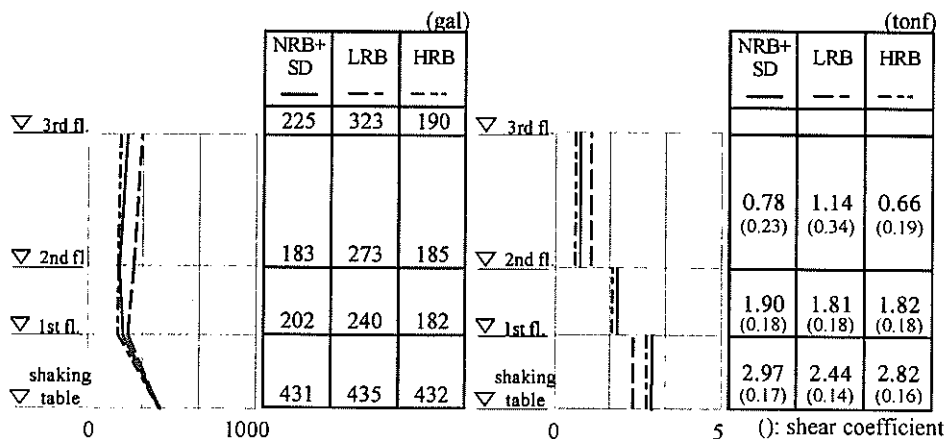
(b) vertical stress-shear strain relation  
fig.6(1) failure limits  
(NRB+SD)



(b) vertical stress-shear strain relation  
fig.6(2) failure limits  
(LRB)



(b) vertical stress-shear strain relation  
fig.6(3) failure limits  
(HRB)



(a) maximum response acceleration

(b) maximum response shear force and shear coefficient

fig.7 maximum response of the test model