

## MECHANICAL PROPERTIES OF LAMINATED RUBBER BEARINGS FOR THREE-DIMENSIONAL SEISMIC ISOLATION

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## SUMMARY

Rubber bearings with thick rubber layers to be used for three-dimensional (3-D) base isolation system are developed. Design parameters of the rubber bearings are determined to effectively reduce both horizontal and vertical seismic loads especially for equipment in the system; horizontal and vertical natural frequencies of the system supported by the rubber bearings are 0.3 Hz and 3 Hz, respectively. Furthermore, primary and secondary shape factors and design vertical pressure of the rubber bearings are determined to give stable mechanical properties. Using scale models of the rubber bearings, static, dynamic and failure tests were carried out to evaluate the mechanical characteristics and the performance of the rubber bearings. From these tests, it is shown that the developed rubber bearings are efficient as 3-D base isolation devices.

## INTRODUCTION

Seismic isolation systems to reduce horizontal seismic loads for nuclear power plants, especially for fast breeder reactors (FBRs), have been developed and confirmed the effect [e.g. Sawada et al., 1989]. On the other hand, reduction of vertical seismic loads can be expected to simplify some equipment in FBR further. However, conventional (2-Dimensional) seismic isolation systems are not effective for vertical seismic load. Thus, 3-D base isolation system to reduce vertical seismic load for internal equipment, of which vertical natural frequency is about 10 Hz, has been proposed by Central Research Institute of Electric Power Industry (CRIEPI). In the 3-D base isolation system, whole reactor building is three-dimensionally isolated with 3-D isolators installed between an upper structure and a base mat. The 3-D seismic isolation system has a merit not to need to change the design of upper structures. It has been suggested that vertical natural frequency of a structure introduced the 3-D base isolation system is required to reduce horizontal seismic loads and to provide good performance on failure as well as conventional seismic isolation system. The effectiveness of the 3-D seismic isolation to the equipment and piping system was confirmed from response analyses [Yashiro et al., 1998] and shaking table tests [Kanazawa et al, 1999].

Several 3-D isolators such as combinations of horizontal and vertical isolators [e.g. Fujita et al., 1995] are proposed. However, it is considered that a laminated rubber bearing with thick rubber layers is appropriate as 3-D isolators to realize the above system by the following reasons. First, it has simple structure, or it consists of steel plates and thicker rubber sheets than those of conventional rubber bearings. Secondary, it individually works as 3-D isolators, so that the 3-D isolation system is also simple. Moreover, as characteristics of rubber bearings in horizontal and vertical directions are not strongly non-linear except for the ultimate state, it might be easy to design 3-D isolators. On the other hand, they say that mechanical properties of rubber bearings with thick rubber layers are generally inferior to those of rubber bearings with thin rubber layers. In particular, when shape of the rubber bearing is inappropriate, unstable phenomena such as a buckling may occur.

Therefore, we designed and developed rubber bearings with thick rubber layers as 3-D isolators to satisfy the

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above requirement for the proposed 3-D seismic isolation system. Furthermore, rubber bearing tests for reduced scale models of the 3-D isolators were conducted to confirm the required mechanical properties and evaluate the performances.

## **3-D SEISMIC ISOLATOR TESTING**

#### Development of rubber bearings for 3-D base isolation

It needs to develop the rubber bearing with thick rubber layers to reduce vertical seismic load around 10 Hz and to provide horizontal performance which conventional rubber bearings have. The design parameters of rubber bearing were determined to achieve the above design targets. First, considering the reduction of seismic loads, it was determined that horizontal and vertical natural frequencies were about 0.3 Hz and 3 Hz, respectively.

As mentioned above, it is important to avoid unstable behavior such as buckling in development of the rubber bearings with thick rubber layers. Thus, we appropriately determined shape of the rubber bearing, rubber material and design vertical pressure. The factors to define the shape of the rubber bearing are as follows.

$$S_1 = \frac{D_R - D_I}{4t_R} \tag{1}$$
$$S_2 = \frac{D_R}{nt_R} \tag{2}$$

where

 $S_1$ : primary shape factor  $S_2$ : secondary shape factor  $D_R$ : diameter of rubber bearing  $D_I$ : diameter of center hole  $t_R$ : rubber thickness n: number of rubber layers.

 $S_1$  is a parameter to control the vertical natural frequency.  $S_2$  is related to the buckling of rubber bearings; the buckling might occur with decreasing  $S_2$ . Considering vertical natural frequency and stabilization of mechanical properties, we determined each shape factor;  $S_1$  and  $S_2$  are 4.2 and 6.4, respectively.

Creep of a thick rubber sheet is generally larger than that of a thin rubber sheet, so that we selected natural rubber as material of rubber sheets, which has better performance for the creep to compare with the other rubber. Further, the rubber material was compounded to provide shear modulus of  $4.0 \text{ kgf/cm}^2$  (0.39 MPa).

As a result, we determined that compressive stress in design, diameter of a full-scale rubber bearing, thickness of a rubber layer and number of rubber layers were 50 kgf/cm<sup>2</sup> (4.9 MPa), 1600 mm, 83 mm and 3, respectively.

## **Test specimens**

1/6.3-scale models to the full-scale rubber bearing with thick rubber layers were used as test specimens from capacity of a test apparatus. The test specimen is shown in Fig.1 and specification of the rubber bearing is shown in Table 1. The diameter of the test specimen is 253 mm. It consists of three rubber sheets and two insert steel plates, and thickness of the rubber sheet and the steel plate are 13.1



Fig.1 Test specimen (scale factor: 1/6.3)

## Table 1 Specification of test specimen

Design sustained weight (kgf) 1/6 2)	25000
Design vertical pressure (kgf/cm <sup>2</sup> )	50.5
Horizontal stiffness K <sub>H</sub> (kgf/cm)	503.5
Vertical stiffness K <sub>V</sub> (kgf/cm)	56463.1
Diameter of rubber bearing $D_R(cm)$	25.30
Diameter of Center hole D <sub>I</sub> (cm)	3.20
Cross section area A $(@m^2)$	494.7
Number of rubber layer n	3
Thickness of a rubber sheet t <sub>R</sub> (cm)	1.31
Total thickness of rubber layers $h_R$ (cm)	3.93
Primary shape factor S <sub>1</sub>	4.2
Secondary shape factor S <sub>2</sub>	6.4
Shear modulus G (kgf/cm <sup>2</sup> )	4.0
Number of steel plates	2
Thickness of a steel plate (cm)	0.9
Young's modulus of rubber $E_0$ (kgf/cm <sup>2</sup> )	15
Bulk modulus of rubber E $\frac{1}{4}$ (kgf/cm <sup>2</sup> )	10500
Modification factor of rubber hardness $f$	0.85

mm and 9 mm, respectively. Three test specimens were used for evaluation of the mechanical properties of rubber bearings with thick rubber layers.

### **Test apparatus**

Dynamic two-dimensional test apparatus for the rubber bearings in CRIEPI was used for this study as shown in Fig.2. Specification of the apparatus is shown in Table 2. It can comfortably perform dynamic loading tests over the range of interest for 3-D seismic isolator response, which is from 0 Hz to 30 Hz.

## **Test description**

#### Horizontal and vertical tests

Horizontal loading tests were carried out for a shear strain of 25%, 50%, 100% and 200% with vertical pressure,  $\sigma$ , varying from 0 to 100 kgf/cm<sup>2</sup> (0 MPa to 9.8 MPa).

Vertical loading tests were performed for amplitude of vertical pressure of 6.25 kgf/cm<sup>2</sup>, 12.5 kgf/cm<sup>2</sup>, 25 kgf/cm<sup>2</sup> and 50 kgf/cm<sup>2</sup> (0.61, 1.23, 2.45 and 4.9 MPa) under constant vertical pressure of 50 kgf/cm<sup>2</sup> (4.9 MPa). Furthermore, an offset shear strain varying from 0% to 200% was given in vertical loading tests. Each sequence was 4 cycles of sinusoidal loading under constant vertical pressure or shear strain.

Loading frequency was changed from 0.01 Hz to 2.0 Hz in horizontal direction, and from 0.01 Hz to 14 Hz in vertical direction.

#### Failure tests

The methods of failure tests were both cyclic loading and monotonic loading. In cyclic loading tests, shear strain increased by 50% each cycle under constant pressure of 50 kgf/cm<sup>2</sup> (4.9 MPa) or 100 kgf/cm<sup>2</sup> (9.8 MPa). Frequency of cyclic loading was 0.01 Hz. On the other hand, in monotonic loading test, shear strain monotonically increased at a strain rate of 24% per second under constant pressure of 50 kgf/cm<sup>2</sup> (4.9 MPa).

#### Definition of mechanical properties

Horizontal and vertical properties can be characterized by stiffness and damping; horizontal and vertical stiffness determines the fundamental frequency in each direction, and damping primarily controls deformation of isolators. Horizontal stiffness,  $K_H$ , and vertical stiffness,  $K_V$ , are given by

$$K_{H} = \frac{\Delta F}{\Delta d} = \frac{Q_{\text{max}} - Q_{\text{min}}}{d_{\text{max}} - d_{\text{min}}}$$
(3)

$$K_{V} = \frac{\Delta F}{\Delta d} = \frac{P_{\max} - P_{\min}}{d_{\max} - d_{\min}}$$
(4)

where  $Q_{\text{max}}$ ,  $Q_{\text{min}}$ ,  $P_{\text{max}}$  and  $P_{\text{min}}$  are the maximum shear force, the minimum shear force, maximum vertical force and minimum vertical force, and  $d_{\text{max}}$  and  $d_{\text{min}}$  are maximum and minimum displacement in each direction. Equivalent damping factors,  $h_{\text{eq}}$ , in horizontal and vertical directions are defined as follows;

$2\Delta W$	
$h_{eq} = \frac{1}{1 - \lambda \Gamma + \lambda I}$	(5)
$\pi \cdot \Delta F \cdot \Delta d$	



FIG.2 OUTLINE OF TEST APPARATUS

Table 2 Specification of test apparatus

Loading direction	Horizontal	Vertical
Load	50t onf	}100t onf
Stroke	}0cm	30cm
Velocity	}70cm∕sec	₿5cm∕sec
Frequency range	0 30Hz	

2452

where  $\Delta W$  is the energy dissipated per cycle. In the evaluation of the above parameters, the third cycle of the hysteresis loops is used.

#### **RESULTS AND DISCUSSION**

As variation of horizontal and vertical characteristics of the test specimens until a shear strain of 200% was small, the results of a test specimen are shown in section 3.1 and 3.2.

## Horizontal characteristics

The hysteresis loop of the rubber bearing with thick rubber layers under vertical pressure of 50 kgf/cm<sup>2</sup> is shown in Fig.3. The relationship between shear stress and shear strain was almost linear and stable less than a shear strain of 200%. The vertical strain for the pressure was about 12%. However, the vertical strain at a shear strain of 200% was 1.5%, or the vertical displacement was 0.6 mm in the relationship between the vertical strain and the shear strain, so that the vertical deformation caused by the shear deformation is rather small.





The relationships between shear strain and horizontal characteristics in varying vertical pressure are shown in Fig.4. Horizontal stiffness is normalized by design value. The horizontal stiffness decreases with increasing shear strain and vertical pressure by design value of -20%. The increase in the horizontal stiffness would raise the system period by 4.5%; thus, the effect is insignificant. Variation of the horizontal damping factors under constant pressure is small.



Fig.4 Normalized horizontal stiffness and equivalent damping factor in varying shear strain and vertical pressure (loading frequency: 0.01Hz)





Effects of loading frequency on horizontal characteristics are shown in Fig.5. Both horizontal stiffness and equivalent damping factor slightly increase with increasing loading frequency; however, the effect is appreciably small.

#### Vertical characteristics

#### Test results

The relationship between vertical stress and strain is shown in Fig.6. Varying an offset shear strain from 0% to 200%, the change of the relationship was little, especially less than an offset shear strain of 100%. Furthermore, the decrease of the vertical stiffness caused by the offset shear strain, which often occurs in conventional rubber bearings, could not be found.

Fig.7 shows vertical natural frequency of the full-scale rubber bearing, into which the test results were converted by a similarity law, and equivalent damping factor under design vertical pressure. The conversion of the vertical frequency is shown as follows;

$$f_{VP} = \frac{1}{2\pi} \sqrt{\frac{K_V g}{P_D}} \sqrt{\lambda}$$
(6)

5

Δ

3

2

0

10 20 30 40

Amp. of vertical pressure (kgf/cm<sup>2</sup>)

50

where

 $f_{VP}$ : vertical natural frequency of the full-scale rubber bearing  $K_V$ : vertical stiffness of the test specimen  $P_D$ : design sustained weight per a rubber bearing  $\lambda$ : scale factor (=1/6.3) g: gravity acceleration, respectively.

From the result, it was found that  $f_{VP}$  decreased from 4 Hz to 3 Hz with increasing the amplitude of the vertical pressure. As the design vertical frequency was 3 Hz, the test results were slightly higher. However, since the rubber bearing provided less than 4 Hz of vertical frequency, it is considered that the rubber bearing can sufficiently reduce vertical seismic loads for internal equipment from the mentioned study [Yashiro et al., 1998]. The vertical damping factor was about 3.5 % and almost constant against the amplitude of the vertical pressure.



damping factor (%)

Equivalent

6

4

2

0

0

10 20 30

Amp. of vertical pressure

 $(kgf/cm^2)$ 

40 50

The relationships between loading frequency and both vertical characteristics are shown in Fig.8.  $f_{VP}$  gradually raises according to an increase of loading frequency; it was 3.7 Hz in 3.0 Hz of loading frequency. On the other hand, the vertical damping factor was almost constant less than 3Hz of loading frequency; however, more than 3 Hz, it decreased by 2%.





Fig.8 Relationships between loading frequency and both vertical frequency,  $f_{VP}$ , and damping factor (vertical pressure:  $50\pm25 \text{ kgf/cm}^2$ )

## Modification of design evaluation of vertical stiffness

As before, vertical stiffness of the rubber bearing with thick rubber layers changed against the amplitude of vertical pressure. A conventional design evaluation of vertical stiffness,  $K_V$ , neglects vertical pressure as follows;

$$K_V = \frac{A}{nt_R} E'_C \tag{7}$$

$$E'_{C} = \frac{E_{C}E_{\infty}}{E_{C} + E_{\infty}} \tag{8}$$

$$E_{C} = (1 + 2\kappa S_{1}^{2})E_{0}$$
(9)

where

*A* : cross section area of the rubber bearing  $E_{\infty}$ : bulk modulus of rubber  $E_0$ : Young's modulus of rubber  $\kappa$ : modification factor of rubber hardness  $S_1$ : primary shape factor (see eq. (1)).

Using thick rubber layers in rubber bearings, the vertical deformation caused by vertical pressure is considerably larger than that of conventional rubber bearings with thin rubber layers, so that it can not be neglected. Therefore, we modified the evaluation of the vertical stiffness with the vertical displacement of the test specimen; in eq. (1) and (7),  $t_R$  is substituted for an apparent rubber thickness,  $t_R$ ', as follows and modified vertical stiffness is calculated.

$$t_{R}' = t_{R} - z(\sigma)$$

where  $z(\sigma)$  is tested vertical displacement caused by vertical pressure,  $\sigma$ .

Fig.9 shows a comparison between tangential vertical stiffness of the test specimen and modified vertical stiffness by the apparent vertical displacement. Modified vertical stiffness can qualitatively explain the tendency of the increase of the vertical stiffness cause by the vertical pressure; it is considered that the apparent decrease of the rubber thickness is a major factor of change of the vertical stiffness. However, as the modification method is insufficient, it should be improved.

## **Failure tests**

Deformations of the rubber bearing with thick rubber layers in cyclic loading test under vertical pressure of 100 kgf/cm<sup>2</sup>, which is two times as high as design pressure, is shown in Fig.10. As rubber layers are thick, sides of



Fig.9 Comparison between tangential vertical stiffness of the test specimen the vertical loading test (loading freq.: 0.01Hz) and vertical stiffness calculated by modified evaluation method considering apparent decrease of rubber thickness

(10)



Fig.10 Deformation of rubber bearing with thick rubber layers in cyclic loading test (vertical pressure: 100kgf/cm<sup>2</sup>)

rubber layers swelled like bellows at a shear strain of 0%. Further, it was not found that unstable phenomena such as a buckling or a failure occured at shear strains of 200% and 300%.

The stress-strain curves of failure tests are shown in Fig.11. Fig.11 (a) and (b) show cyclic loading tests under vertical pressure of 50 kgf/cm<sup>2</sup> (4.9 MPa) and 100 kgf/cm<sup>2</sup> (9.8 MPa). The result of monotonic loading tests under vertical pressure of 50 kgf/cm<sup>2</sup> (4.9 MPa) is shown in Fig.11(c). Although increases of the horizontal stiffness began at a shear strain of about 300% with increasing horizontal deformation, the curves were stable and buckling did not occur until the failure of the rubber bearing.

Moreover, the stress-strain curve of a conventional rubber bearing with thin rubber layers (primary shape factor  $S_1 = 31$ ) is shown in Fig.12 to compare those of the rubber bearings with thick rubber layers. The conventional rubber bearing is nearly equal to the rubber bearing with thick rubber layers except for primary shape factor. Although failure stresses of the rubber bearings with thick rubber layers were slightly smaller than that of the conventional rubber bearing, failure strains of the rubber bearings with thick rubber layers were about 500% from Fig.11; they almost agreed with that of the conventional rubber bearing shown in Fig.12. Therefore, it is considered that the rubber bearing with thick rubber layers has good performance on failure as well as conventional rubber bearings.



# Fig.11 Stress-strain curves of failure tests of rubber bearings with thick rubber layers



# Fig.12 Cyclic loading test of conventional rubber bearing with thin rubber layers

## CONCLUSIONS

We designed and developed rubber bearings with thick rubber layers for the 3-D base isolation system to reduce vertical seismic loads for internal equipment of which vertical natural frequency is about 10 Hz.

When we developed the rubber bearing as 3-D isolators, design targets were reduction of horizontal and vertical seismic loads and good horizontal performances as well as conventional (2-D) rubber bearings. It was determined that horizontal natural frequency and vertical natural frequency of the 3-D base isolation system were about 0.3 Hz and 3 Hz in design to reduce seismic loads. Considering creep of a thick rubber layers, we selected natural rubber and the rubber material was compounded to provide shear modulus of 4.0 kgf/cm<sup>2</sup> (0.39 MPa). Further, we appropriately determined that design parameters of the rubber bearing to avoid unstable behavior such as a buckling. As a result, we determined that design vertical pressure, diameter of a full-scale rubber bearing, thickness of a rubber layer and number of rubber layers were 50 kgf/cm<sup>2</sup> (4.9 MPa), 1600 mm, 83 mm and 3, respectively.

We carried out rubber bearing tests with specimens, which was 1/6.3 of full scale, to evaluate characteristics and performances of the developed rubber bearings. From the horizontal tests, it was found that the hysteresis loop was stable and horizontal stiffness relatively agreed with the design value.

On other hand, the vertical frequency converted to that of the full-scale rubber bearing decreases from 4 Hz to 3 Hz with increasing the amplitude of the vertical pressure; it was slight higher than the design value. However, as it was less than 4 Hz, it is considered that the rubber bearing can sufficiently reduce vertical seismic loads for internal equipment. Moreover, we confirmed that the apparent decrease of the rubber thickness caused by the vertical pressure was a major factor of change of the vertical stiffness.

From the failure tests, failure strains of the rubber bearings with thick rubber layers were about 500%. Therefore, it is considered that the rubber bearing with thick rubber layers has good performance on the failure as well as conventional rubber bearings.

From the above results, we could confirm the feasibility of the rubber bearings with thick rubber layers for the 3-D base isolation system

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