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APPLICABILITY OF LEAD RUBBER BEARINGS WITH LARGE BEARING LOAD TO BASE ISOLATED REACTOR BUILDING

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SUMMARY

It is to be desired to reduce the number of laminated rubber bearings from the viewpoint of economical efficiency of base isolated reactor buildings by increasing the vertical stress acting on it. When decreasing the number of lead rubber bearings (LRB) by increasing their vertical stress, the section area of a lead plug needs to be expanded in order to raise the damping efficiency of a single unit of laminated rubber bearings. In this study, the applicability of LRBs with large vertical stress to base isolated reactor building was investigated by carrying out element tests on LRBs and shaking table tests using a reactor building model. Furthermore, analyses for simulating the results of shaking table tests were carried out. As a result, the element tests showed that the LRB secures the damping characteristics which were aimed for in the design stage even in the case of the ratio of diameter to height for lead plugs being less than 1.25. The shaking table tests confirmed that even when the number of LRBs is reduced to 1/2 of that in the case of the period being 2sec, the safety of base isolated reactor buildings can be secured if the section area of lead plugs is doubled. The seismic response characteristics of a superstructure and LRB can be simulated by making bi-linear type models for the hysteresis curve of the LRB.

1. INTRODUCTION

In order to reduce the construction costs of base isolated reactor buildings, it is to be desired that the number of laminated rubber bearings should be reduced with an increase in the vertical stress acting on it. For this, the effects exerted both by elongation of the period and by enlargement of the section area of lead plugs in order to equalize the damping characteristics were investigated. In this study, the application of LRBs to base isolated reactor buildings was examined by carrying out loading tests on LRB and shaking table tests using a base isolated reactor building model.

2. ELEMENT TESTS FOR LRB

2.1 Outline of Model

There are two different types of the LRB to be used for base isolated reactor building as shown in Fig.1. The LRB shown in Fig.1(b) is to be used in sites with large design seismic force. These two LRBs are designed with 2.0sec for the natural period. Vertical stress is 50kg/cm^2 for the LRB shown in Fig.1(a) and 25kg/cm^2 for the LRB shown in Fig.1(b). When using the LRB shown in Fig.1(b) with initial vertical stress of 50kg/cm^2, the section area of a lead plug must be doubled in order to equalize response displacement. The ratio of height to diameter (H/D) for the lead plug in Fig.1(b) is 1.46. In Japan, the ratio of diameter to height for a lead plug is recommended as 1.25<H/D<4.5. Since there is little test data of LRBs with less than 1.25 for H/D, element tests were carried out on LRB with H/D<1.25. Models for the element tests are scaled down to 1/3 of LRBs shown in Fig.1(b). When the section area of the lead plug for the 1/3 scale model shown in Fig.1(b) is set at 2A, the following four LRB models shown in Fig.2 are used in the tests. The value of H/D is 1.03 ~ 2.06. The results

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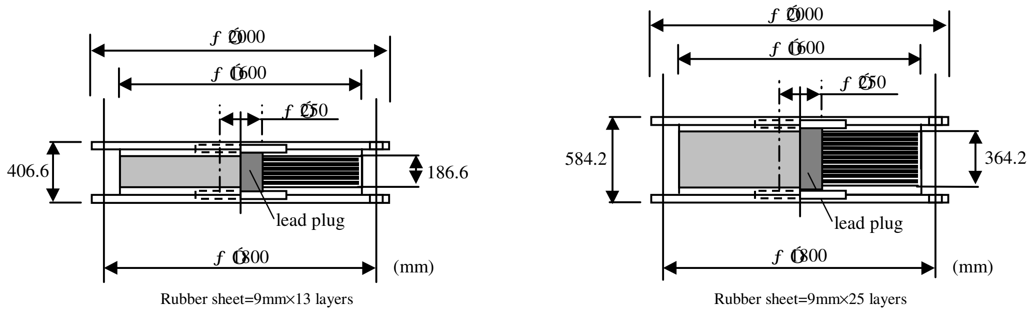
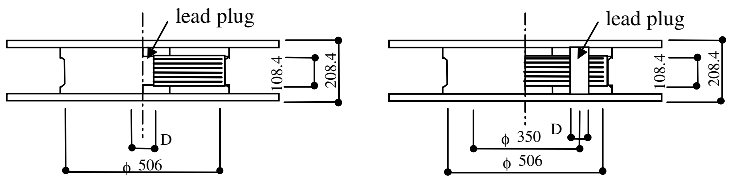
obtained from the tests of model 1A are reported in literature 1.



(a) Bearing Load 1000tonf (b) Bearing Load 500tonf

Figure 1: LRB for demonstrated Fast Breeder Reactor building



Test model	Vertical stress (kg/cm^2)	Diameter of lead plug	H/D	Natural period
1A	25.0	ϕ57	2.06	2.0sec
2A	25.0	ϕ81	1.45	2.0sec
3A	37.5	ϕ99	1.18	2.45sec
4A	50.0	ϕ114	1.03	2.82sec
4×A	50.0	ϕ57×4	2.06	2.82sec

H: Effective hight of lead plug =118.4mm
Rubber sheet=2.8mm×25layers
Inserted steel plate=1.6mm×24layers

(a) 2A,3A,4A model (b) 4×A model

Figure 2: LRB for element tests

2.2 Testing Items

Table 1 shows the testing items and parameters. Shearing deformation was added to the laminated rubber in a horizontal direction using sinusoidal waves under the state of imposing a constant axial force.

Table 1: Testing items

Testing Item	Axial force	Excitation frequency
Dependency on Axial force	0,25,50kg/cm^2 (2A,4A, 4×A) 37.5,50kg/cm^2 (3A)	0.35Hz
Dependency on Excitation frequency	25kg/cm^2(2A),37.5kg/cm^2(3A),50kg/cm^2(4A,4×A)	0.35Hz, 0.5Hz

2.3 Test Results

(1) Horizontal stiffness K_H, yielding force characteristic value Q_d and equivalent viscous damping h_{eq}

The relationship between the shear force Q and the horizontal shear strain γ for the models 2A, 3A and 4A is shown in Fig.3. Tests were carried out with 0.35Hz for the excitation frequency and 25kg/cm^2, 37.5kg/cm^2 and 50kg/cm^2 for the axial stress intensity. The hysteresis area and the Q_d value (shearing force at γ=0%) when the horizontal shear strain is changed from 50% through 200% increase with a rise in the diameter of the lead plug.

The hysteresis loop of the LRB can be illustrated with a bi-linear type as simply shown in Fig.4. The characteristics of a bi-linear model can be indicated with K_H, Q_d and h_{eq}. Fig.5 shows the results obtained by dividing K_H, Q_d and h_{eq} for the bi-linear type hysteresis loop modeled by Fig.4 (initial period: 1sec, period after yield: 2sec (2A), 2.45sec (3A), 2.82sec (4A) and 2.82sec (4×A), ratio of yield force Q_y to bearing load W : $\beta=Q_y/W=$ 0.1) which was aimed at in the design stage for the LRB's shape by K_H, Q_d and h_{eq} all of which can be computed from Fig.3. When comparing the results of the tests of models 3A and 4A both of which have H/D<1.25 and model 4×A with four lead plugs to those of model 2A with H/D=1.45, the following can be made clear.

i) The values of shear stiffness K_H for models 3A, 4A and 4×A are almost equivalent to the value for model 2A. In the case of the shear strain exceeding 50%, the shear stiffness K_H is hardly influenced by the size of a lead plug and is determined by the shape and dimension of the laminated rubber.

ii) The values of Q_d/Q_d(bi-linear) for models 3A, 4A and 4×A are slightly lower than the value for model 2A. With an increase in the section area of a lead plug, the value of Q_d obtained from tests tends to approximate that at the design stage for the shape of the laminated rubber.

iii) The values of h_{eq}/h_{eq}(bi-linear) for models 3A, 4A and 4×A is also slightly lower than that for 2A when the shear strain exceeds 50%. With regard to model 2A, a h_{eq} value in the case of the shear strain being 50% is considerably smaller than that in the case of 100%.

(2) Dependency of Qd on Axial Force

Tests in which the vertical stress was changed from 0 through 50kg/cm^2 setting the excitation frequency at 0.35Hz were carried out. Fig.6 shows the results obtained by normalizing the yielding load characteristic values using numerical values in the case of the vertical stress being 50kg/cm^2 for each of the models. When the shear strain is 50%, the Qd value in the case of the vertical stress being 0 tends to become smaller than the Qd value in cases in which it acts on the model. However, when the shear strain is 100% or more, conspicuous dependency of the Qd value upon axial force is not discernible.

(3) Dependency of Qd on Excitation Frequency

Confirmation tests for the excitation frequency dependency were carried out on model 2A. The vertical stress is 25kg/cm^2. Two cases of 0.35Hz and 0.5Hz for the excitation frequency are subject to the tests. As shown in Fig.7 in the range of 50% ~ 200% for the shear strain, a differences hardly discernible in the Qd value between 0.35Hz and 0.5Hz for the excitation frequency.

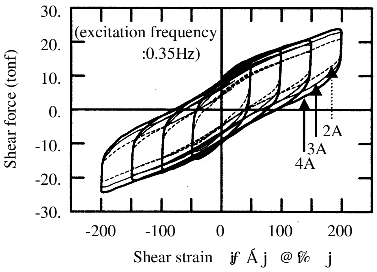


Figure 3: Hysteresis behavior

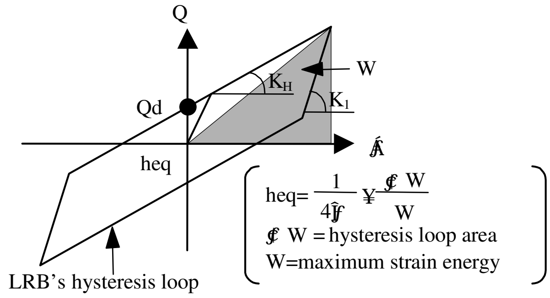
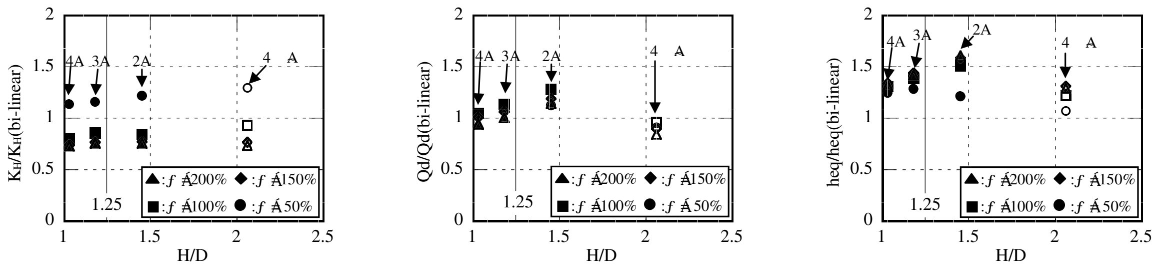
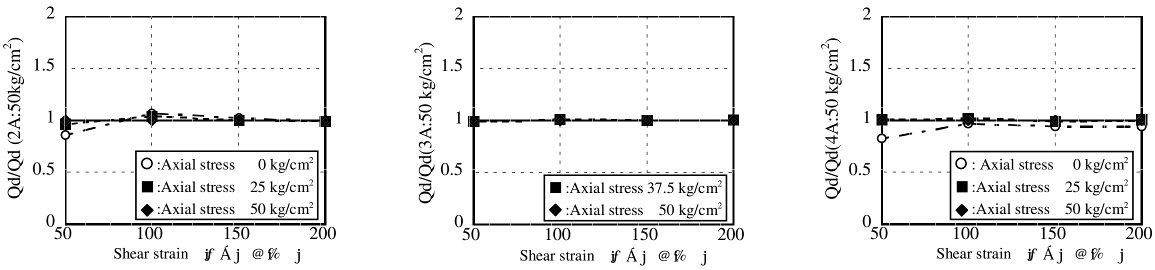


Figure 4: Simplified LRB's hysteresis



(a) KH(test) /KH(bi-linear) (b) Qd(test) /Qd (bi-linear) (c) heq(test) /heq(bi-linear)

Figure 5: Ratio of test results to values estimated by simplified LRB's hysteresis



(a) Model 2A (b) Model 3A (c) Model 4A

Figure 6: Dependency of Qd on axial force

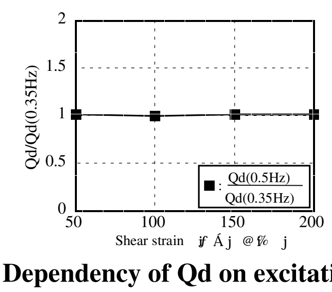


Figure 7: Dependency of Qd on excitation frequency

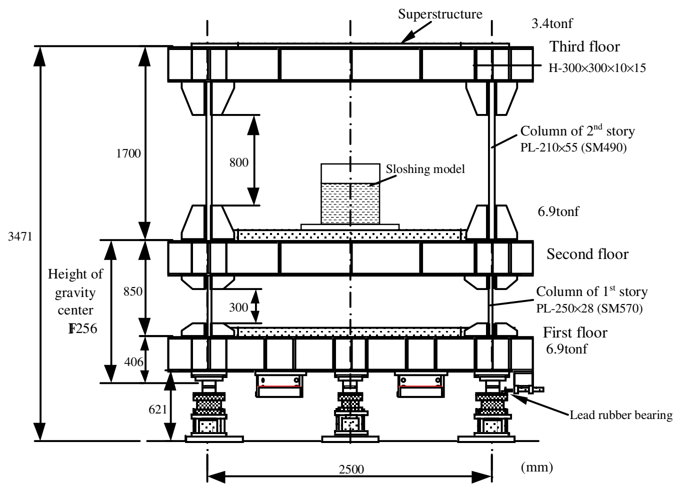
3. SHAKING TABLE TESTS

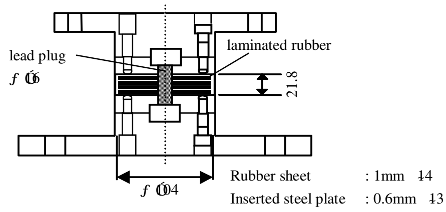
3.1 Testing Procedure

(1) Model

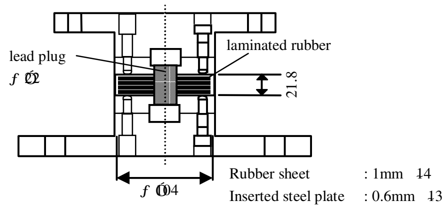
The superstructure was made of three-storied steel frames simulating the period characteristics of a FBR reactor building. The second story supports the model of a reactor vessel. Fig.8 shows the model outline. LRBs were used as seismic isolated devices. The isolation period was 2.0sec and 2.83sec for actual devices. In the case of the isolation period being 2.0sec, the superstructure was supported by eight units of LRB. In the case of 2.83sec, the same superstructure was supported by four units of LRB. The LRB with 2.83sec for the period has the same shape as that of the LRB with 2.0sec. The section area of a lead plug for the former is twice that for the latter. Vertical initial stress intensity is 25kg/cm^2 for the LRB with 2.0sec period and 50kg/cm^2 for the LRB with 2.83sec period. Fig.9 indicates the dimensions for the shape of the LRB used in the tests.

Regarding to similarity law, the vertical stress of LRB was set at the same value as that for the actual devices. The similitude ratios both for length and for time were set at about 1/15.3 and 1/4 respectively taking into account the capacity of the shaking table.





(a) LRB for vertical stress 25kgf/cm^2 (T=2.0sec)

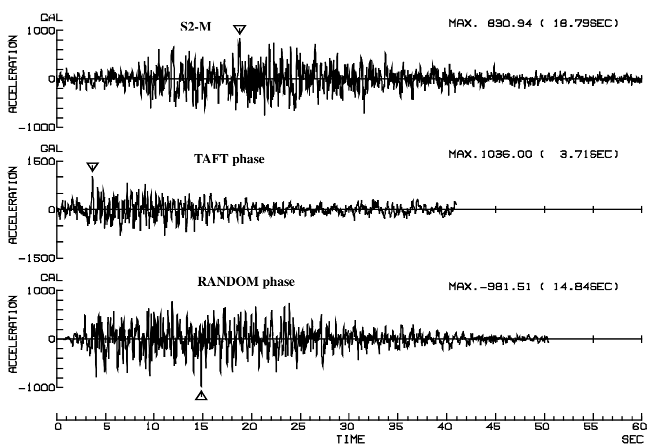


(b) LRB for vertical stress 50kgf/cm^2 (T=2.83sec)

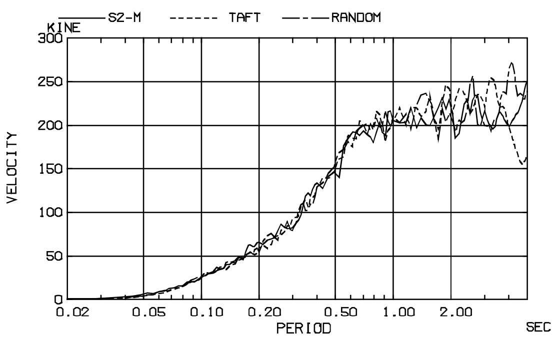
Figure 8: Model outline **Figure 9: LRB for specimen**

(2) Input Seismic Motion

Design seismic motion of the highest level (S2-M) for investigations was used as input seismic motion for excitation loading. Velocity response spectrum for the damping ratio of 5% is 200 kine in the range of 1 to 10 seconds in period. The phase is a LA-UNION phase. Moreover, in order to investigate the effects of phase difference upon responses, the following two artificial waves were used: artificial wave with Taft EW phase which was made to have the same spectral shape as that of S2-M wave and artificial wave with random phase. Fig.-10 shows the acceleration time history wave of input wave as well as the response spectra.



(a) Acceleration waveform



(b) Velocity response spectra (h=5%)

Figure 10: Input seismic motion
(Time axis is reduced by 1/4 when inputting to the shaking table)

3.3 Test Results

(1) Hysteresis Curve of Shear Force and Horizontal Displacement for LRB

Fig.11 shows the relationship between the shear force Q and the horizontal displacement. The shear force Q in the figure indicates the sum of the shear forces occurring in the LRBs which support the superstructure.

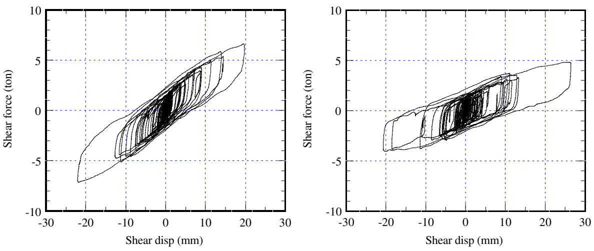
The stiffness K1 of the hysteresis curve for the LRB with the period of 2.83sec is larger than that for the LRB with 2.0sec. The stiffness K1 of the hysteresis curve has an influence upon floor response spectrum. Since the larger the stiffness K1 is, the larger the floor response spectrum becomes, it affects the design of equipments. However, in the element tests carried out by imposing 0.35Hz, any difference is not discernible in the restitution stiffness K1 of the hysteresis curve between model 2A and model 4A as shown in Fig.-3. It can be thought that it was one of the causes for the occurrence of difference in the stiffness K1 to have shortened the time to 1/4 of the actual time in the shaking table tests.

(2) The Maximum Response Acceleration

Fig.12 shows the maximum response acceleration of each floor as well as that of the shaking table. The maximum response acceleration of the superstructure is lowered by elongating the period from 2.0sec to 2.83sec. There is little difference in the maximum response acceleration caused by the variation of the phase characteristics of input seismic motions.

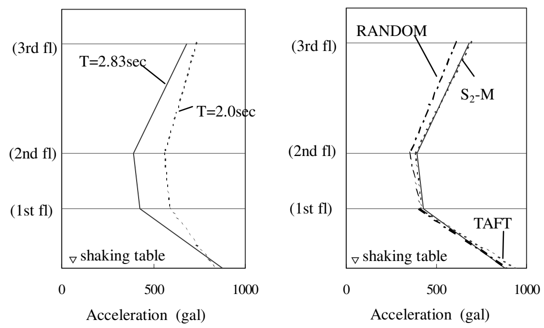
(3) Floor Response Spectrum of Superstructure

The floor response spectra (damping ratio h=1%) of the second floor in the superstructure which supports the reactor vessel is shown in Fig.13. With an elongation in the period from 2.0sec to 2.83sec, the floor response spectrum in a range of 0.1sec ~ 1.0sec falls. No difference can be seen in the floor response spectra in a short period domain for less than 0.07sec even when the period of the LRB is elongated. The peak value of spectra in this short period domain is high. It can not be said that seismic isolation effects are fully developed. This is thought to be caused by the fact that the stiffness K1 of the LRB is high and that the damping is slight due to the superstructure model being made of steel. As a result of the tests conducted using the LRB with a period of 2.83sec, it was found that the effects of the variation in the phase of input wave upon the floor response spectrum of the superstructure are slight.



(a) T2=2.0sec (b) T2=2.83sec

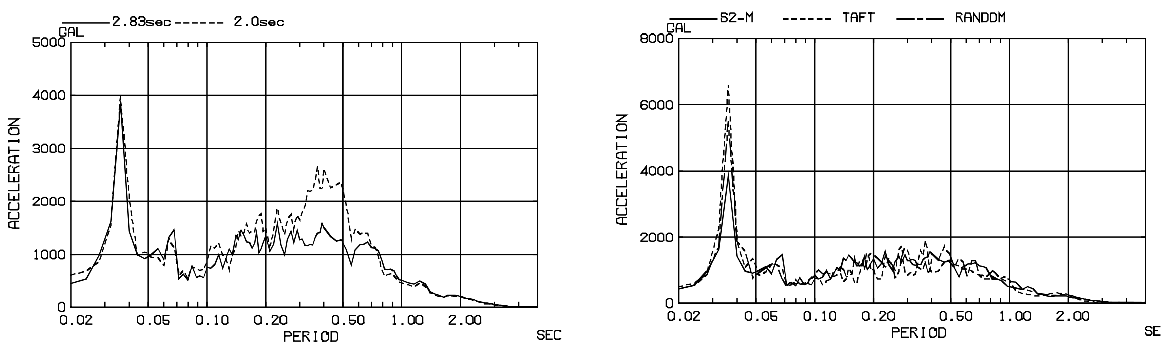
Figure 11: Hysteresis curve of LRB (S2-M)



(a) Effect of LRB's period (b) Effect of input motion

(Input motion: S2-M) (T=2.83sec)

Figure 12: Maximum response acceleration



(a) Effect of LRB's period (S2-M:h=1%) (b) Effect of input motion (T=2.83 sec:h=1%)

Figure 13: Floor response spectra on the second floor

4. SIMULATION ANALYSES OF SHAKING TABLE TEST RESULTS

4.1 Investigation Purpose

It is to be confirmed that the dynamic analysis method based on a bi-linear type model substituted for the restoring force characteristics of seismic isolated devices is applicable even under the condition of the elongation of LRB's period.

4.2 Analytical Conditions

(1) Input Condition

The acceleration time history wave observed on the shaking table is used as the input seismic wave for an analysis model.

(2) Analysis Model

a. Modeling of Superstructure

A lumped mass model each of whose stories is composed of shear springs and rocking springs is used for the superstructure. Fig.14 shows the analysis model outline.

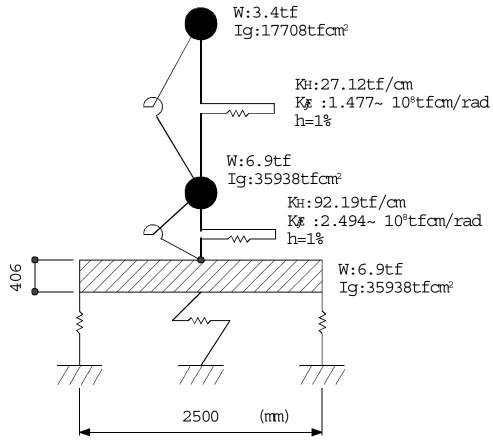


Figure 14 : Analytical model

b. Modeling of Hysteresis Curve of LRB

The horizontal hysteresis curve of the LRB is modeled using the following three methods.

1) Bi-linear Model-1

The second stiffness K2 is established based on the target period for design. The stiffness K1 is set at 6.5×K2. The yielding force is 0.1W (W: weight of the superstructure) which is a design target value.

2) Bi-linear Model-2

The second stiffness K2 as well as the Qd value is set based on the results of the element tests. Excitation amplitude is carried out under the conditions of the shear strain of 100% and the excitation frequency of 0.5Hz respectively. The stiffness K1 is established to fit the hysteresis loop for the element tests using the least square method. K1 is set at K1=11×K2 for the LRB with 2.0sec for the period and at K1=14×K2 for the LRB with 2.83sec.

3) Modified Bi-linear Model

The stiffness K2 and the Qd value depend on the shear strain. The estimating expressions of K2 and Qd were evaluated on the element test results used for bi-linear model-2. The stiffness K1 was established as K1=11×K2 for the LRB with a period of 2.0sec and K2=14×K2 for the LRB with 2.83sec in the same fashion as applied to bi-linear model-2.

A linear spring is substituted for the hysteresis model of the LRB in a vertical direction due to the response in a range where tensile stress does not occur in the LRB. The value of the vertical stiffness Kv of the LRB when using bi-linear model-1 needs to correspond to the natural period of 20Hz. As for bi-linear model-2 and the modified bi-linear model, the vertical stiffness Kv is established on the basis of the element test results.

Table 2 shows the conditions for setting the three hysteresis curves.

Table 2 : Modeling of hysteresis curve

<table>
<tr><th>Bi-linear Model-1</th><th>Bi-linear Model-2</th><th>Modified Bi-linear Model</th></tr>
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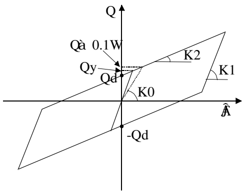
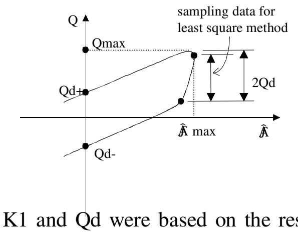
<td>

K1 = 6.5×K2
(K0: Correspond to period 1.0sec)

K2: Correspond to isolation period 2.0sec or 2.83sec
Q≅0.1W

Kv: Correspond to natural period 0.05sec (20Hz)</td>
<td>

K2, K1 and Qd were based on the results of the element tests (shear strain 100%,excitation frequency 0.5Hz)
• K1 = 11.0×K2 (T2=2.0sec)
• K1 = 14.0×K2 (T2=2.83sec)

Kv: Based on the results of the element tests (P0±0.5P0)
P0 : Vertical bearing load of LRB</td>
<td>K2(γ)=Kr(γ)+Gp(γ)*Ap/hr
Kr: shear stiffness of rubber
Kr(γ)=b*Gs(γ) (kg/cm)
Gs(γ)=α1+α2γ+α3γ²
<table>
<tr><td>shear strain</td><td>α1</td><td>α2</td><td>α3</td></tr>
<tr><td>25% ≤ γ ≤ 200%</td><td>6.067</td><td>-1.437</td><td>0.4653</td></tr>
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b=465.7 (T2=2.0sec)
=220.8 (T2=2.83sec)
Gp: shear modulas of lead plug

Qd(γ)=a*τq(γ)
τq (γ)=β1+β2γ+β3γ²+β4γ³ (kgf/cm²)
<table>
<tr><td>shear strain</td><td>β1</td><td>β2</td><td>β3</td><td>β4</td></tr>
<tr><td>25% ≤ γ ≤ 200%</td><td>38</td><td>102</td><td>-68</td><td>15</td></tr>
</table>
a=22.36 (T2=2.0sec)
=20.68 (T2=2.83sec)

Kv: simillar to Bi-linear Model-2</td>
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4.3 Analysis Results

(1) Maximum Response Acceleration

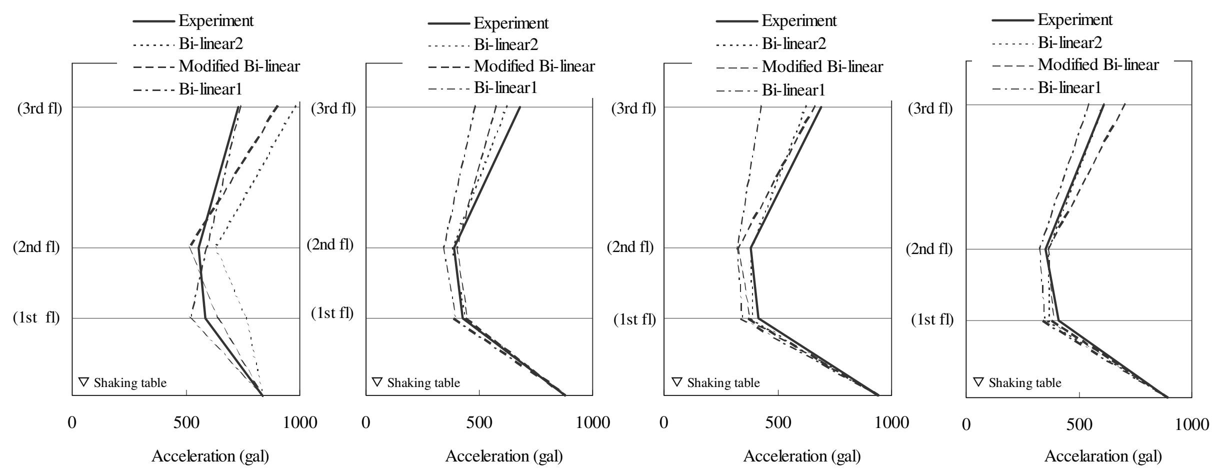
Fig.15 shows the maximum response acceleration profile at the mass point of the analysis model. When using the LRB with a period of 2.83sec, it is found that the analysis results of both bi-linear model-2 whose hysteresis curve was set based on the element test results and the modified bi-linear model have a good agreement with the test results.

(2) Hysteresis Loops of LRB

The hyseresis loops of the LRB are shown in Fig.16. The hysteresis loops shown by bi-linear model-2 and the modified bi-linear model accurately simulate the test results.

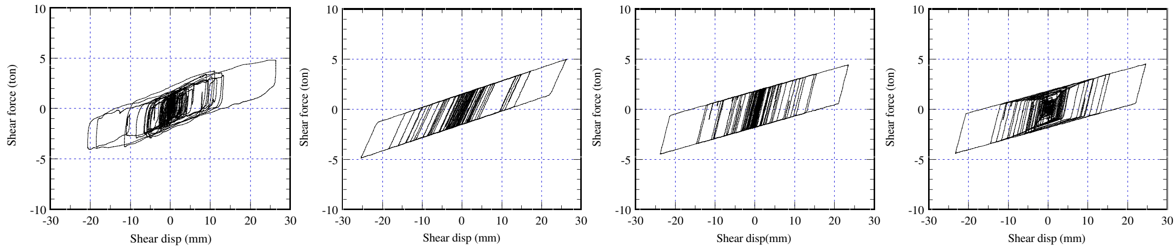
(3) Floor Response Spectrum

Fig.17 shows the floor response spectrum (h=1%) of the second floor of the superstructure. When simulating a peak value of floor response spectrum, the use of a modified bi-linear model is desired. Since the stiffness K1 has an influence upon the floor response spectrum in the short period domain, it is of importance to estimate the restitution stiffness accurately based on the results of element tests.



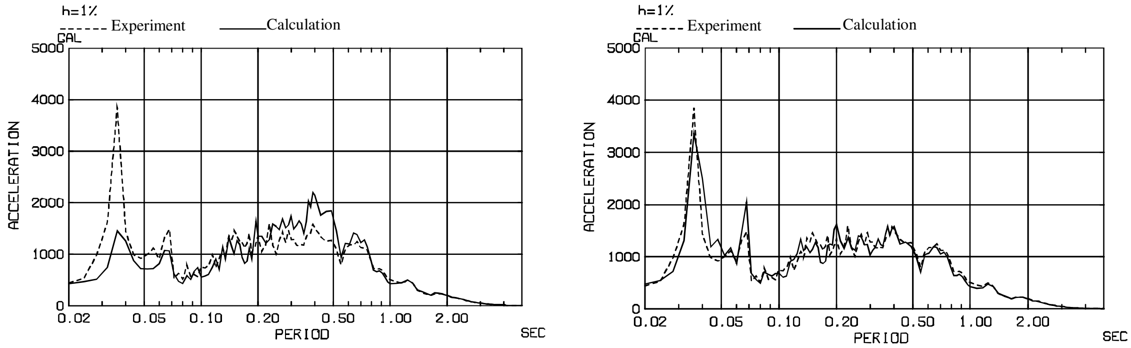
(a) S2-M (T=2.0sec) (b) S2-M (T=2.83sec) (c) TAFT (T=2.83sec) (d) Random (T=2.83sec)

Figure 15 : Maximum response acceleration profile



(a) Experiment (b) Bi-linear Model-1 (c) Bi-linear Model-2 (d) Modified Bi-linear

Figure 16 : Hysteresis loop of LRB (LRB's period 2.83 sec : S2-M input)



(a) Bi-linear Model-1 (b) Modified Bi-linear Model

Figure 17 : Floor response spectra on the second floor (LRB's Period 2.83 sec : S2-M input)

5. CONCLUSION

Applicability of LRB with a large initial vertical stress to base isolated reactor buildings was investigated by carrying out the element tests for LRBs and the shaking table test of a base isolated reactor building model. Furthermore, through the simulation analyses of the shaking table test results, the validity of a method for modeling a hysteresis of the LRB in seismic response analyses was firmed. As a result, the following have been made clear.

i) The element tests for the LRB show that the LRB secures the damping characteristics which were aimed for in the design stage even in the case of the ratio of diameter to height (H/D) for lead plugs being less than 1.25.

ii) The shaking table tests confirmed that even when the number of the installed LRBs in a base isolated reactor building is reduced to 1/2 of that in the case of the period being 2.0sec, the safety of base isolated reactor buildings can be secured if the section area of lead plugs is doubled.

iii) The seismic response characteristics of a superstructure and LRB can be simulated by making bi-linear type models for the hysteresis curve of the LRB. When simulating peak values of floor response spectra, the use of a modified bi-linear model which simulates the hysteresis of LRB in more detail is desired.

6. Acknowledgements

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