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Development of a lead rubber bearing with a stepped plug

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ABSTRACT: The purpose of this study is to develop an improved lead rubber bearing realizing superior seismic isolation device which offers sufficient seismic response control for small to large earthquakes as well. The study examines the characteristics of an improved seismic isolation device by loading tests, simulating the hysteresis curve, and analyzing the efficiency of the seismic response control. Through this study, the improved seismic response control device (the LRB-SP) was confirmed to have seismic isolation capability superior to that of the conventional lead rubber bearing (LRB) for small to medium earthquakes and to have performance equivalent to the conventional LRB for large earthquakes, and a design method is proposed for the LRB-SP.

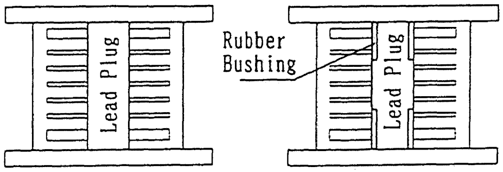
1. INTRODUCTION

The lead plug of conventional Lead Rubber Bearing (LRB) has shape of a straight column (see Fig. 1). The lead plug completely enclosed by the laminated rubber receives the lateral pressure from the sides of the laminated rubber during shearing deformation. The lead plug is deformed under pure shear and absorbs the energy by its plasticity. The stress-strain curves of the lead plug are closely affected by the shear speed, and in a range of large strain they are non-linear. Modulus of elasticity due to plastic resistance of the lead plug is useful as a trigger function and is desired in a earthquake isolation device and is expected for damping during small displacement magnitudes.

However, the existence of plastic resistance to small and medium deformation increases the equivalent spring constant, as a result, can not achieve a sufficient long period of the earthquake isolation system for small and medium earthquake compared with that for large earthquake, which is not a desired result for excellent seismic response control.

Lowering the elastic-plastic resistance of the lead plug can be proposed of as one means for improving the performance of the LRB as an earthquake isolation device for small earthquakes. A method for realizing these dynamical characteristics is to make an alteration to the straight lead plug of conventional LRB which occurs uniform shear strain in the vertical direction.

The improved isolation device LRB-SP was designed to control a combination of shear strain and bending strain in the range of small displacement amplitudes, and shear strain for large displacement amplitudes. The construction of the LRB-SP, as shown in Fig. 1, uses the identical laminated rubber as was used for conventional LRB, however, only the central partion of the lead plug comes in direct contact with laminated rubber and the upper and lower portions of the lead plug have a smaller diameter and form a stepped shape.



LRB LRB-SP

Figure 1. LRB and LRB-SP

In the space between the laminated rubber and the lead plug in the section with small diameter it is inserted a rubber bushing which encloses the lead. This lead plug has to forms one body.

By making a stepped lead plug, pure shear deformation occurs in the large diameter section of the lead plug and bending deformation appears in the small diameter section. As a result, a low initial rigidity is obtained during small displacement and the elastic-plastic resistance force which is the shear resistance of the large diameter section of the lead plug occurs creating damping factor equal to that of LRB at large displacement. The performance as a earthquake isolation devices was confirmed by performing loading tests to check the characteristics for small to medium amplitude displacements and for large displacements, and to check fatigue. This paper reports the design theory of the LRB-SP and the prediction method for the hysteresis curves, and verifies them based on experiment results. In order to gain a quantitative understanding in the response to the earthquakes, the parametric earthquake response analysises ware carried out and given here.

2. LOADING TEST OF THE LRB-SP

In the loading test, two size of test specimens (350 mm diameter and 1100 mm diameter) shown in Fig. 2 were used. A test specimen with a diameter of 350 mm is that the diameter of the small section of the lead is 50 mm with a height of 66 mm, and the large section is 60 mm and a height of 64 mm. A 1100 mm test specimen is that the diameter of the small section of the lead plug is 160 mm with a height of 123 mm, and the diameter of the large section is 180 mm and a height of 124 mm.

The vertical load on the test specimen had a pressure of 60 kgf/cm^2 with 56 tf and 550 tf applied respectively. The incremental loading test was performed for amplitude of shear strain range of ±1% to ±200%.

In order to investigate fatigue, a test was performed with a displacement of amplitude ± 200 mm, being acted continuously for 10 cycles for a total of 100 cycles. For comparison, a conventional LRB with the same dimensions as the 1100 mm test specimen was prepared, and the same tests were performed. The hysteresis curves for various displacement amplitudes obtained by loading tests are shown in Fig. 3. For both of the test specimens, somewhat constricted hysteresis shape was observed. The range for the constricted field of both was within ±10 cm.

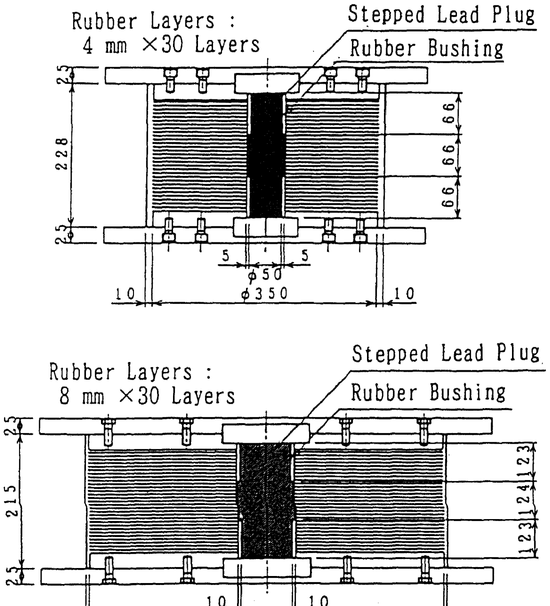


Figure 2. Test specimens

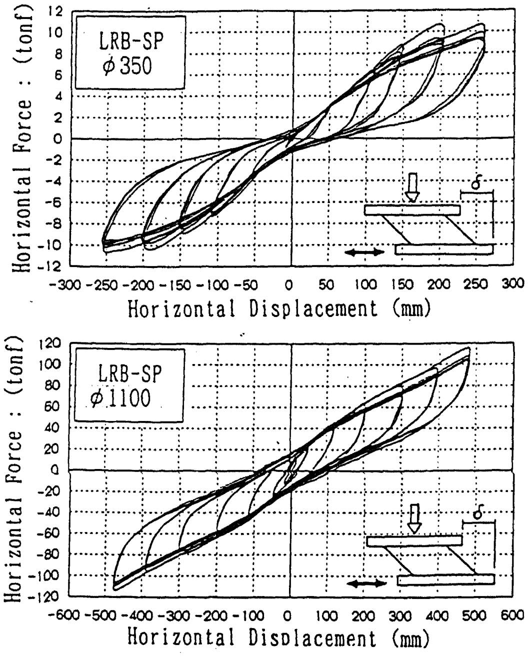


Figure 3. Hysteresis curves

Fig. 4 shows equivalent rigidity and damping factor evaluated from test results at each shearing strain amplitude. As the shearing strain becomes smaller, the equivalent rigidity and damping increases rapidly for the conventional LRB and these behavior for the LRB-SP becomes less than the LRB, and when the shearing strain is 1%, it is less than half that of the LRB. As the shearing strain becomes larger, the difference from the conventional type LRB becomes small and the rigidity of LRB-SP coincides with that of LRB at shearing strain of 50% or more. The equivalent damping becomes a maximum of 16% at a shearing strain of 50%. At a shearing strain of 1%, the equivalent damping factor is less than that of LRB, but it is 8%. The equivalent damping becomes the same as the conventional type LRB at a shearing strain of 130% or more.

The results of the fatigue test are shown in Fig. 5. The equivalent rigidity was seen to be 15% less after the test of the continuous 10 cycles, however, it recovered during a 1 hour rest. There was very little change in the equivalent damping factor.

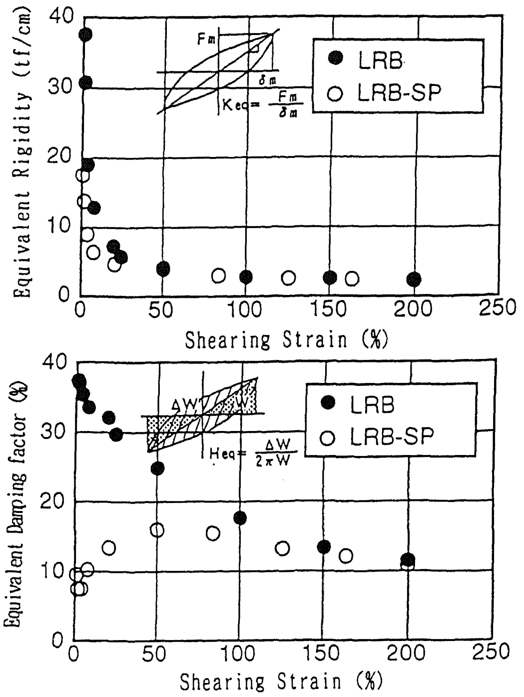


Figure 4. Strain dependency of hysteresis characteristics

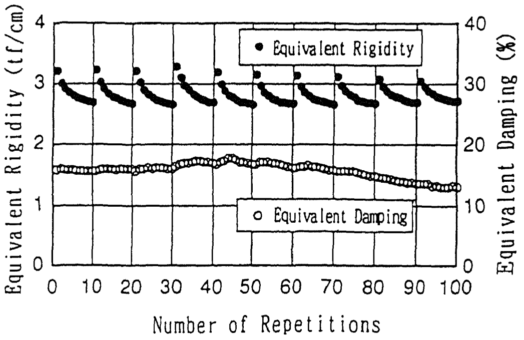


Figure 5. Changes the hysteresis characteristics due to repetitions

3. FORMULATION OF THE HYSTERESIS CURVES

The central large diameter portion of the lead plug of the LRB-SP contact directly to laminated rubber but the top and bottom portion having a smaller diameter is wrapped by a rubber busing, therefore the strain on the lead plug of the section with the smaller diameter can be considered as occurring both shearing deformation and bending deformation, while same pure shear deformation as the lead plug in conventional LRB occurs in the large diameter portion. The characteristic features of the LRB-SP for small to medium displacement amplitudes are due to the behavior of the bending deformation. As a result, one of the characteristics of the LRB-SP hysteresis curves is that there is constriction shape at the center of the amplitude. The design of the LRB-SP and estimation of the hysteresis curves can be idealized by formulating a displacement width of the constricted shape and characteristic value of the yield load based on the design of the conventional LRB.

3.1 Deformation and rigidity of the stepped plug

The stepped plug can schematically be drawn as shown in Fig. 6. It was assumed that the uniform load act on the small section of the lead plug through the rubber bushing and the bending deformation on the cantilever fixed end is at the border of the large section (Stepped Part) occurs. The bending and shear rigidity of the small portion, K_b and $K_{\tau 1}$ are found the bending strain and shear strain and defined by equations ① and ②.

$$K_b = \frac{8EI}{\ell_1^{3}} \qquad ①$$

Here, ℓ_1 : Height of the small diameter section
I : Moment of inertia
E : Young's modulus of lead

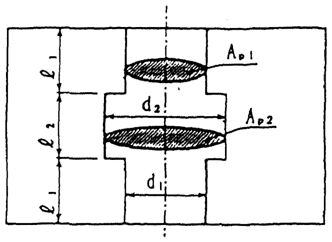


Figure 6. Schematic drawing of the stepped lead plug

$$K_{\tau 1} = \frac{G_P \; A_{P1}}{\ell_1} \qquad ②$$

Here, A_{P1} : Cross-sectional area of the small diameter section
G_P : Apparent Shear modulus of lead

For the deformations of the large diameter section, bending is neglected and attention is placed only on the shearing strain, with the shear rigidity being given by :

$$K_{\tau 2} = \frac{G_P \; A_{P2}}{\ell_2} \qquad ③$$

Here, A_{P2} : Cross-sectional area of the large diameter section of the lead plug
ℓ_2 : Height of the large diameter section

The total rigidity K_P of the lead plug inside the laminated rubber is obtained from equation ④.

$$K_P = \left(\frac{2}{K_P} + \frac{2}{K_{\tau 1}} + \frac{1}{K_{\tau 2}} \right)^{-1} \quad \text{——} \ ④$$

The displacement range of the constricted field X_a , is defined by equation ⑤ for conditions that the horizontal load according to the rigidity K_p obtained does not exceed the yield load of the lead plug.

$$\therefore X_a = \frac{\delta_{pb} \cdot A_{P2}}{K_P} \quad \text{————} \ ⑤$$

δ_{pb} : Shear yield stress for lead

3.2 Yield load characteristics

The characteristic value of the yield load is assumed to be proportional to the equivalent rigidity of lead plug, and is defined by equation ⑥, where μ is the rigidity ratio of the total rigidity to pure shear rigidity (equation⑦).

$$Q_{d1} = \mu \cdot Q'_{d1} \quad \text{————} \ ⑥$$

Q'_{d1} : Shearing yield load value of the small diameter section

$$\mu = \frac{1}{\frac{G_P}{E} \cdot \left(\frac{\ell_1}{d_1} \right)^2 + 1} \quad \text{——} \ ⑦$$

3.3 Rigidity for releasing load

Equation ⑧ provides good approximation of the rigidity during releasing load K_u , which is evaluated using the relationship found by test results.

$$K_u \fallingdotseq 6.5 \frac{Q_{d2}}{\delta_{max}} \quad \text{————} \ ⑧$$

Q_{d2} : The yield load value of the large diameter section of the lead plug.

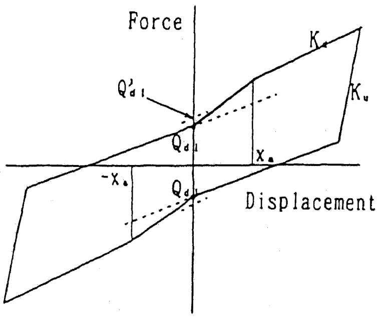


Figure 7. Idealized hysteresis curve of the LRB-SP

Besides this, the skeleton curves were examined and the conformity with the hysteresis curves of conventional LRB was examined. Then it becomes possible to predict the hysteresis curves at each displacement amplitude. The idealized hysteresis curves are shown in Fig. 7

4. COMPARISON OF THE CALCULATED VALUES OF THE HYSTERESIS CURVES AND EXPERIMENT RESULTS

Fig. 8 shows the calculated hysteresis curves of a test specimen with a diameter of 350 mm, Fig. 9 shows the calculated hysteresis curves of the test specimen with a diameter of 1100 mm. In Figs. 10 and 11, equivalent rigidity and damping factor of calculated curves are compared with the test results for the 1100 mm diameter results. From these results, the idealized hysteresis curves and its strain dependency describes a characteristic of the LRB-SP well, and the equivalent rigidity and damping factor coincides with the results of experimentation, therefore the estimation method for the hysteresis curves is judged to be adequate.

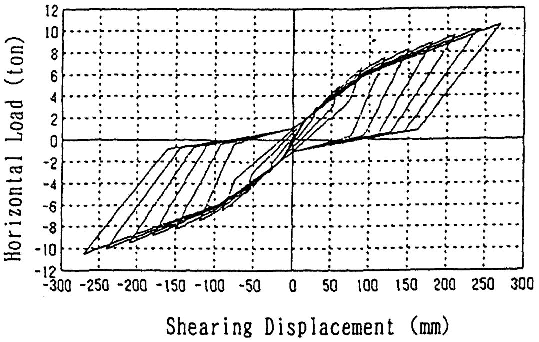


Figure 8. Hysteresis curve for a diameter of 350 mm (Calculated results)

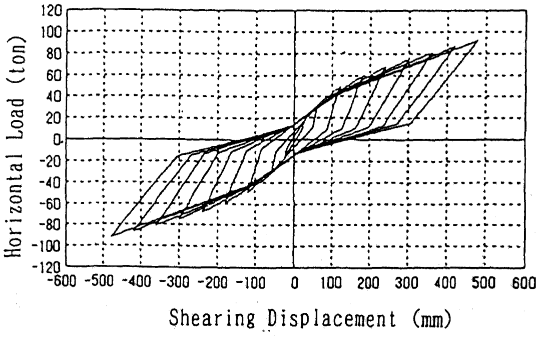


Figure 9. Hysteresis curve for a diameter of 1100 mm (Calculated results)

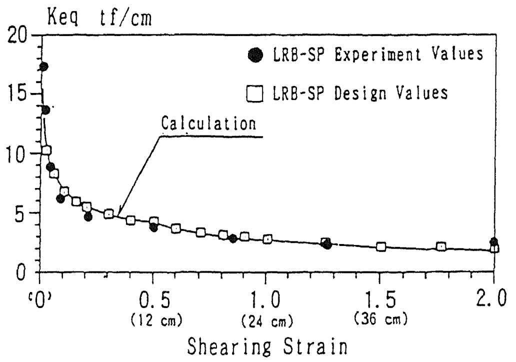


Figure 10. Comparison of the equivalent rigidity for ϕ1100 mm specimen

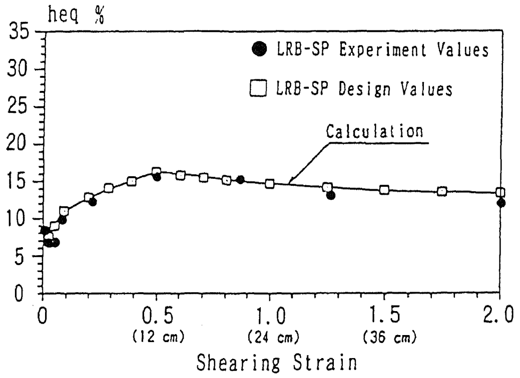


Figure 11. Comparison of the strain dependency of the equivalent damping factor for ϕ1100 mm specimen

5. EARTHQUAKE RESPONSE ANALYSIS

In order to gain various estimation of the results showing improvements in the response for small to medium earthquakes, a parametric earthquake response analysis was performed. The analysis model shown in Fig. 12 is three lumped mass building model and with a horizontal nonlinear spring representing the seismic isolation device. The analysis parameters are the earthquake isolation device (LRB-SP and LRB), the rigidity of the building, the input earthquake wave, and the maximum input acceleration.

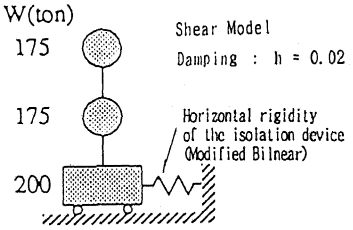


Figure 12. Analysis model

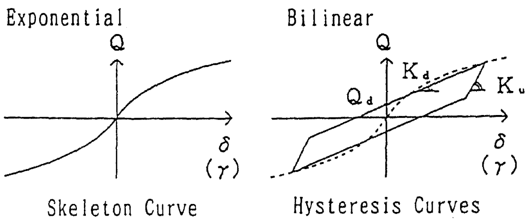


Figure 13. Modified bilinear model

5.1 Model for the earthquake isolation device

Both of the LRB-SP and LRB are modeled into modified bilinear model based on the test results of the large test specimen. The modified bilinear model used here has an exponential skeleton curve and bilinear hysteresis curves configuration varies depending on the maximum horizontal displacement is shown in Fig. 13. The equivalent rigidity of the device, K_{eq}, can be approximated by an exponential function as shown Fig. 14 (a). And skeleton curve $Q_s(\gamma)$ obtained by equation⑨.

$$Q_s(\gamma) = \gamma \, t \, K_{eq} \qquad ⑨$$

Where γ is the shearing strain of rubber, and t is the total thickness of the rubber. The characteristic values K_u, K_d and Q_s of the bilinear hysteresis curve are given by equation ⑩ to ⑫. On the other hand, the equivalent damping factor h_{eq} is approximates by piece-wise linear function (dashed line in Fig. 14 (b)). Then the modified bilinear model has equivalent rigidity and damping factor very close to these of test results.

$$K_u = \begin{cases} 3.0 \; K_{eq} \text{ (LRB-SP)} \\ 5.0 \; K_{eq} \text{ (LRB)} \end{cases} \qquad ⑩$$

$$K_d = K_{eq} \frac{(1-0.5\pi h_{eq}) K_u - K_{eq}}{K_u - (1+0.5\pi h_{eq}) K_{eq}} \qquad ⑪$$

$$Q_d = (K_{eq} - K_d) \, \gamma \, t \qquad ⑫$$

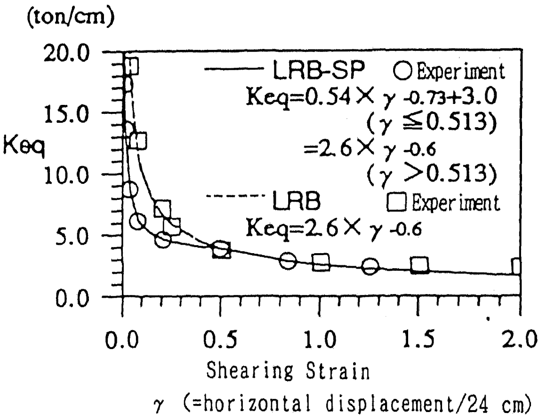


Figure 14. (a) Equivalent rigidity : K_{eq}

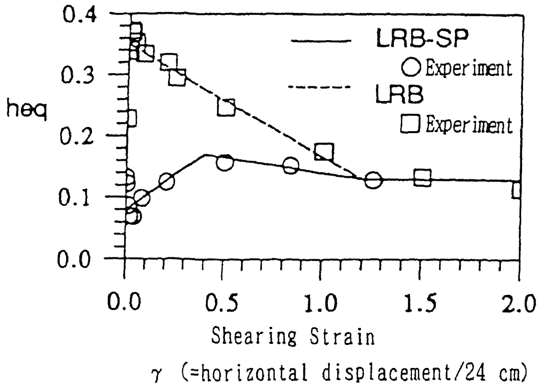


Figure 14. (b) Equivalent damping factor : h_{eq}

5.2 Results of the earthquake response analysis

Fig. 15 shows an example of the maximum acceleration response of the building (25 Gal input, 0.75 sec. of building period). According to this analysis results, the acceleration response for each wave is reduced by half when compared with the LRB. Fig. 16 summarizes the changes in input level for magnification of the acceleration response for a building period of 0.25 and so improvement can be seen for 10 to 100 Gal, and it appears that it is especially effective at 25 to 50 Gal. Also, changes in magnification of the acceleration response due to the building period (rigidity) for an input of 25 Gal is shown in Fig. 17. According to Fig. 17, the rigidity of the building, it is seen that the improvements of the acceleration response are most effective for a natural period of 0.25 to 0.75 seconds.

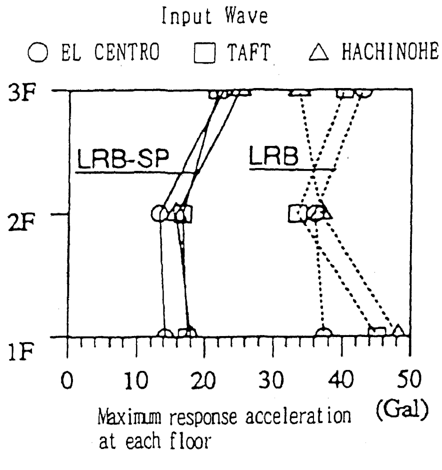


Figure 15. Example of the analysis results (Maximum input acceleration 25 Gal, building period of 0.75 sec.)

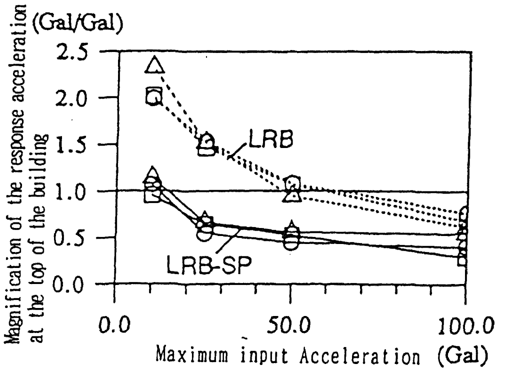


Figure 16. Comparison of the magnification of the response acceleration due to the maximum input acceleration

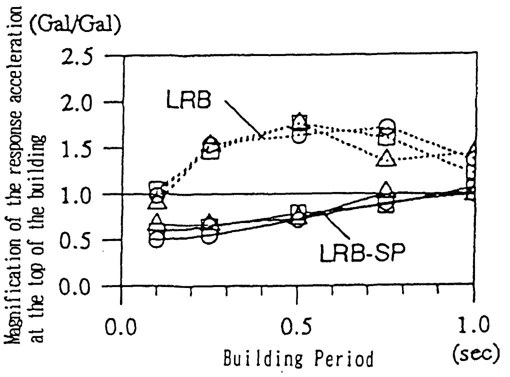


Figure 17. Comparison of the magnification of the response acceleration at the top of the building due to building period

6. CONCLUSION

The characteristics of the LRB-SP for small to large earthquakes wave found that the equivalent rigidity for small displacement amplitudes was less than half that of conventional types and the characteristics for large displacement amplitudes were the same as for conventional types. The bending deformation of the stepped plug was introduced into the deign methods and the idealized hysteresis curves with the constricted shape were formulated and found to be adequate through comparison with the results of experimentation.

From the parametric earthquake response analysis which reflects the hysteresis characteristics of the lead rubber bearing with a stepped plug for small to medium earthquakes, it could be seen that for a wide range of earthquake levels and building rigidity, there was a large reduction in the acceleration response, more than for the conventional type LRB, and that the LRB-SP isolation system can be used for not only large earthquakes but for small earthquakes as well.