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적층고무베어링을 사용한 면진구조물의 지진해석방법

Seismic Analysis Method for the Seismically Isolated Structures Using LRBs

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ABSTRACT

To substantiate the application of LRB(Laminated Rubber Bearing) to the seismic isolation system, it is necessary to develop a seismic analysis method considering the non-linear behavior of LRBs, which may significantly affect the seismic responses. In this paper, seismic analyses and shaking table tests are carried out for a seismically isolated structure using four LRBs. The parameter equations of seismic isolation frequency are obtained from the shaking table tests and the quasi-static tests of LRB itself to investigate the effects of the LRB characteristics in the prediction of maximum peak acceleration responses by analysis. From the comparison of the maximum peak acceleration responses obtained from numerical analyses and experiments, it is verified that the horizontal stiffness variations of LRB should be carefully considered in seismic analysis to obtain more accurate results.

1. Introduction

Recently, seismic isolation design using laminated rubber bearing (LRB) has received considerable attention due to its wide application to nuclear power plants, buildings, industrial structures, and so forth. In general, LRB is a composite structure laminated with thin rubber plates and steel plates. Due to the structural rigidity in the vertical direction, LRB can support heavy weights. However, it is horizontally very flexible to give superstructures almost rigid body motion when earthquake occur.

However, when applying LBR to seismic isolation design, there are many difficulties in overcoming the severe nonlinear behavior of LBR in actual seismic analysis[1,2,3]. Actually, LRB has complicated horizontal stiffness characteristics such as wind load control stiffness, earthquake control stiffness, and ultimate strain control stiffness in the range of cyclic shear strains[4]. And the characteristics of horizontal stiffness are also affected by the loading rates, i.e. excitation frequencies[5]. Therefore, the seismic isolation frequency may be changed as the earthquake level

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increases due to the nonlinear behavior of LRB. In this paper, two types of the seismic isolation frequency functions are developed to consider the horizontal stiffness changes of LRB by the quasi-static tests of LRB itself and the shaking table tests using a seismically isolated structure(SIS) of about 23 tons. The seismic time history analysis for a seismically isolated test structure is carried out with consideration of the developed seismic isolation frequency functions to investigate the effects of the nonlinear behavior of LRB on seismic responses. Comparisons of the maximum peak acceleration responses obtained from analyses and experiments are performed to verify the importance of horizontal stiffness changes of LRB in seismic analysis.

2. Seismic Isolation Frequency Functions

LRBs used in seismic isolation are the reduced 1/8 scale models. The outer and inner diameter of the LRB is 144 *mm* and 19 *mm*, respectively. The rubber and steel plate thicknesses are 1.2 *mm* and 1.7 *mm*, respectively, and the number of rubber plates is 29. Fig. 1 shows the hysteretic characteristics of LRB obtained from quasi-static experiments of LRB itself with a vertical load 4.5 tons and loading rate of 0.05*Hz* for shear strains of 25%, 50%, 100% and 150%. Table 1 gives the equivalent stiffness and damping of the LRB evaluated for Figure 1. As shown in the table, the LRB used in experiments has high damping characteristics from 12% to 16%.

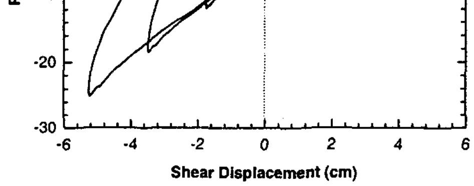


Fig. 1 Hysteretic Characteristic of LRB(Quasi-Static Tests)

Table 1. Characteristic of LRB (Quasi-Static Tests)

Strain γ(%)	Stiffness K_{eq} (*ton/mm*)	Damping Ratio,ξ_{eq}	Max. Disp. (*mm*)
25	0.09034	0.16	8.75
50	0.06679	0.15	17.5
100	0.05185	0.13	35.0
150	0.04717	0.12	52.5

In general, the hysteretic behavior of LRB shows that the horizontal stiffness decreases as the maximum shear displacements for each cyclic load increase. Therefore, the seismic isolation frequency is changed according to the input seismic level.

Fig. 2 shows the parameter curves of seismic isolation frequency variation obtained from experimental results. The solid curve in Fig. 2 is produced from the data of the transfer response functions obtained from the shaking table tests of SIS using random excitations and the dotted curve is obtained from a simple equation, $f_{iso} = (1/2\pi)\sqrt{(K_{eq}/M)}$, using the quasi-static test data of LRB itself shown in Table 1. The results of Fig. 2 are in good agreement with general characteristics of the loading rate effects for the high damping LRB[5].

The developed seismic isolation frequency functions to be used in the seismic time history response for the SIS are as follow :

from shaking table tests :

$$f_{iso} = 2.673 - (2.492\text{x}10^{-2})x - (4.067\text{x}10^{-4})x^2 + (8.682\text{x}10^{-6})x^3, \quad (1)$$

from LRB tests :

$$f_{iso} = 2.802 - (7.873\text{x}10^{-2})x + (1.891\text{x}10^{-3})x^2 - (1.567\text{x}10^{-5})x^3, \quad (2)$$

where x is a shear displacement of LRB with a unit of mm.

The horizontal stiffness and damping of LRB used in seismic time history analyses are calculated using a simple equation, $K_H = M(2\pi f_{iso})^2$, where f_{iso} is obtained using the shear displacement data corresponding to the shaking table acceleration level measured in the experiments.

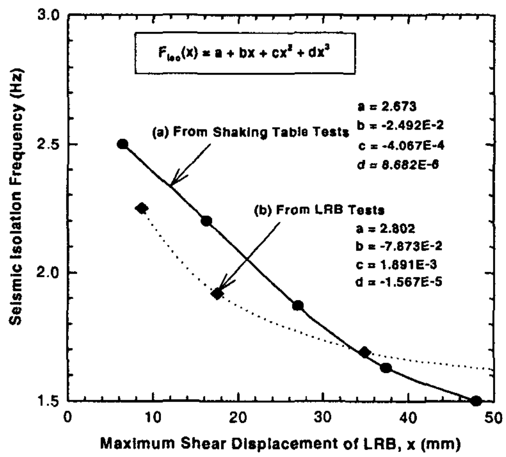


Fig. 2 Seismic Isolation Frequency Curves Obtained by Tests

3. Seismic Analysis for the Seismically Isolated Structure

3.1 Analysis Model and Input Motion

To investigate the isolation characteristics of a seismically isolated structure, the shaking table tests for the reduced model using four LRBs, which support 4 corners of the basemat as shown in Fig. 3, are carried out. In the schematic drawing of Fig. 3, the slab(6.0 tons) is supported by four columns which are anchored at the basemat (16.0 tons). The total weight of the superstructure is about 23 tons. To perform the numerical simulation for this structure, two types of analysis modeling methods are used, one of which is the rigid body model and the other the multi-d.o.f. model as shown in Fig. 4. Detail formulations for these models are presented in Ref[6].

The input table motion used in the experiments is 1940 El-Centro NS. The time interval of the input table motion is determined as 7.071*ms* considering the scale factor, 1/8 for original data of 0.02 seconds.

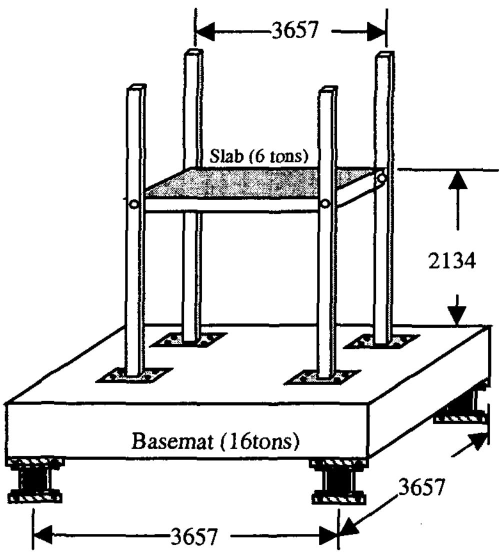


Fig. 3 Dimensions of Seismically Isolated Test Structure (23 tons)

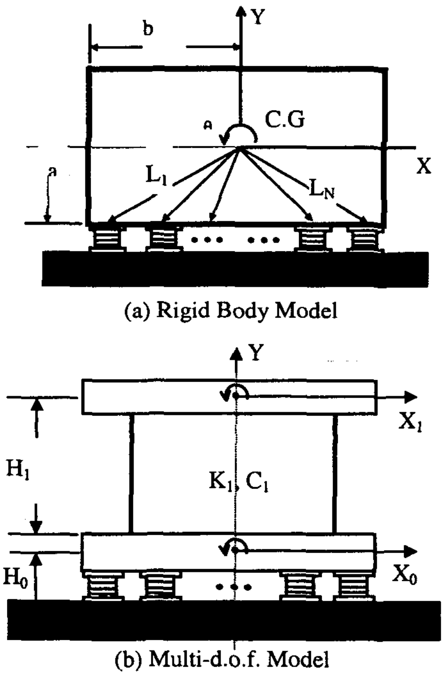


Fig. 4 Mathematical Models for Analysis

3.2 Seismic Responses

Fig. 5 shows the comparison results between the isolation case and the non-isolation case for the maximum peak acceleration responses at the slab obtained by the shaking tests. In these test results, the maximum peak acceleration responses at the slab for the seismic isolation case are significantly reduced compared with those of the non-isolation case. For example, the reduction ratio of 0.3g table motion is about 7.5. This will greatly increase as the table acceleration levels increase.

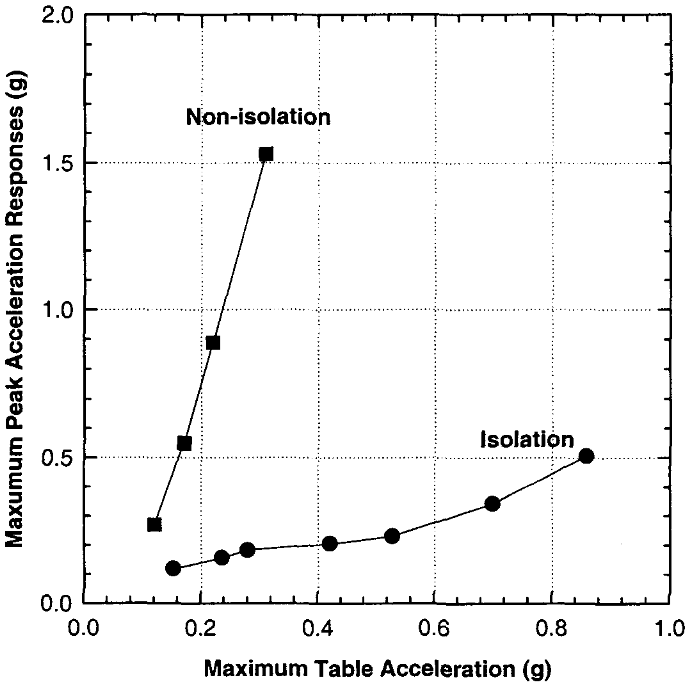


Fig. 5 Maximum Peak Acceleration Responses at Slab (Test Results))

Fig. 6 and Fig. 7 show the maximum peak acceleration responses at basemat and slab, respectively. In the figures, the numerical analysis results are obtained using the multi-d.o.f. model with and without considering the isolation frequency variations. In the figures, we can see that the seismic isolation frequency variations significantly affect the maximum peak acceleration responses Therefore, it is recommended that the variation of the mechanical characteristics of LRB corresponding to the cyclic shear displacements should be considered in seismic isolation design by analysis.

Fig. 8 and Fig. 9 show the acceleration time history responses at the basemat and slab for 0.28g input table motion. In the figures, the overall waveforms of acceleration responses obtained from numerical analyses are in good agreement with those of the experiments.

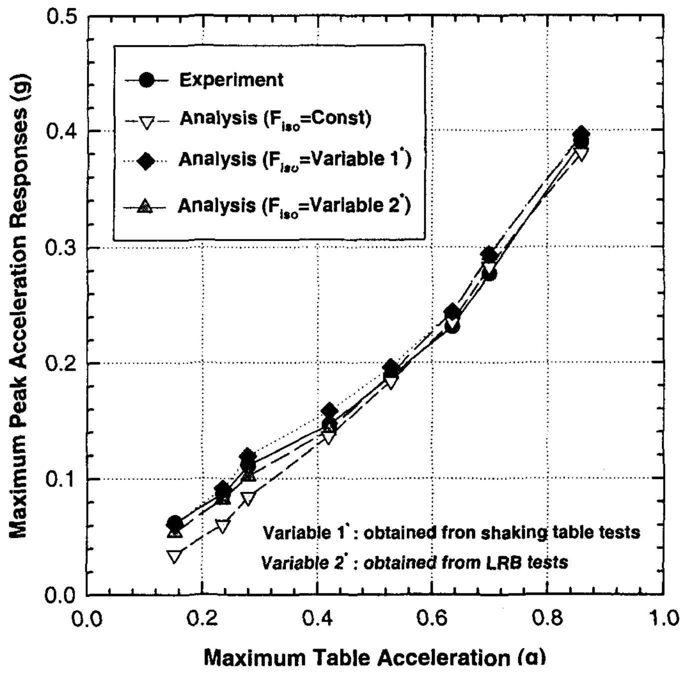
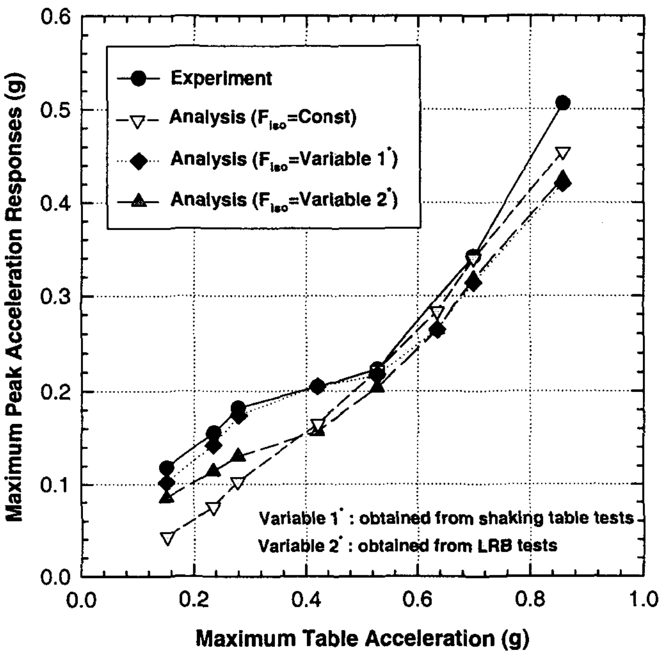


Fig. 6 Maximum Peak Acceleration Responses at Basemat



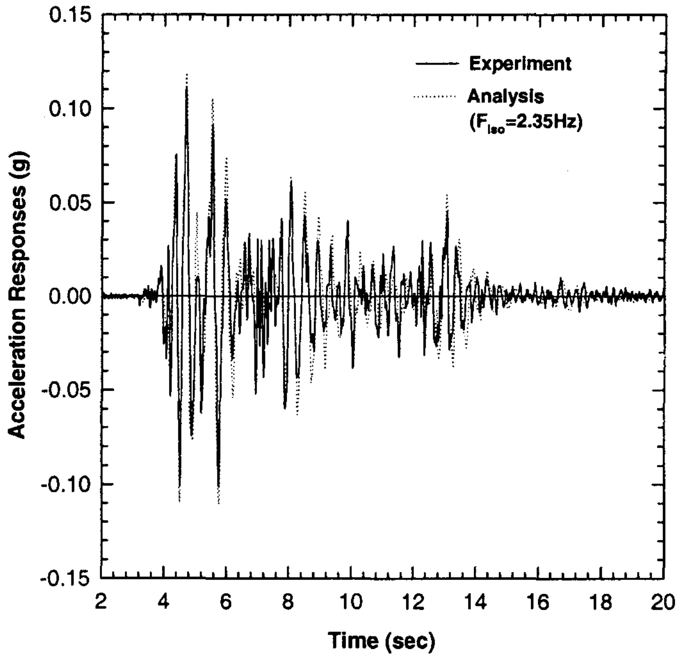


Fig. 8 Acceleration Time History Responses at Basemat (0.28g)

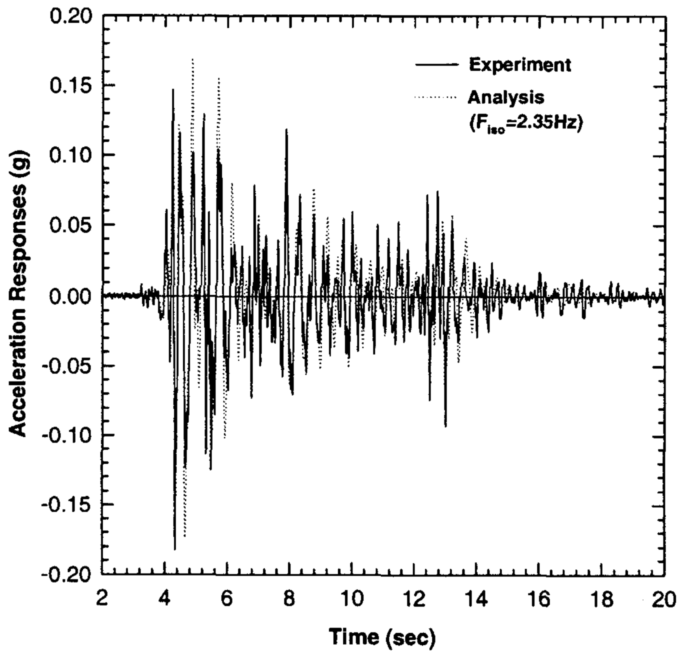


Fig. 9 Acceleration Time History Responses at Slab (0.28g)

4. Conclusions

Seismic responses can be significantly reduced when introducing the seismic isolation design using LRB. From the comparison of the maximum peak acceleration responses obtained from numerical analyses and experiments, it is verified that the developed seismic isolation frequency functions by tests are very important factors affecting the seismic acceleration responses. Therefore, it should be carefully considered when performing the seismic analysis for the seismically isolated structures to obtain more accurate results.

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