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Effect of Nonlinear Hardening of Lead Rubber Bearing on Long Term Behavior of Base Isolated Containment Building

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1. Introduction

The rubber material used in laminated rubber bearings is the hyper elastic material whose stress-strain relationship can be defined as nonlinearly elastic. Therefore it is important that the proper model such as bilinear and hardening was used for evaluating the seismic response of base isolated structure directly affected by the mechanical properties of base isolators. Generally the bilinear model has been used for design of base isolated structure. Although the behavior of lead rubber bearing (LRB) under design load and low to moderate earthquake can be demonstrated by the bilinear model to provide an accurate prediction of the isolator, the bilinear model unable to capture the nonlinear hardening behavior of LRB at high shear strain induced by near field earthquake and beyond design earthquake.

From the previous research [1], it was presented that the rubber hardness and stiffness was increased by the aging of LRB. The mechanical properties of LRB changed by aging can directly affect a nonlinear hardening behavior. Therefore it is needed to consider the nonlinear hardening effect for exactly evaluating the seismic safety of base isolated structure during the life time.

In this study, the seismic response analysis of base isolated containment building was performed by using the bilinear model and the hardening model to identify the effect of structural response on the nonlinear hardening behavior of isolator. Moreover the floor response spectrum of base isolated structure considering the aging was analyzed by according to the analysis model of LRB.

2. Nonlinear behavior of LRB

The hysteresis curve of LRB depends on the lead and rubber material properties. The lead material defined a damping and a yield force of hysteresis curve. The post yield stiffness of LRB was defined by a hardness and thickness of rubber material. From the several test results [2], when the shear strain of LRB exceeds a certain shear strain, the nonlinear hardening is significantly occurred by a geometric effect of the rubber material.

When the seismic analysis of base isolated structures was performed by using OpenSEES[3], the LRB can be modeled by Bouc-Wen model, KikuchiAiken model, LeadrubberX model. In this study, the Elastomeric bearing element based on Bouc-Wen model was used for considering the nonlinear hardening behavior of LRB.

3. Example model

3.1 Design of LRB

The total weight of containment building was to be 1,157,185 kN considering the mat foundation and target frequency of base isolated containment building was 0.5 Hz and design displacement was to be 21 cm. The LRBs were modeled using the bilinear model and nonlinear hardening model. The total effective stiffness was to 11,646 kN/cm.

3.2 Modeling of LRB and containment building

As shown in figure 1, the post yield stiffness of ElastomericBearing model was changed by variables. Where α_1 was the post yield stiffness ratio of linear hardening, α_2 was the post yield stiffness ratio of nonlinear hardening and μ was the exponent of nonlinear hardening, respectively. These variables were usually defined from the test results. In this study, the variables related to the nonlinear hardening behavior of isolators was defined from the shear test results of LRB-D250 and finite element analysis results of LRB-D1500.

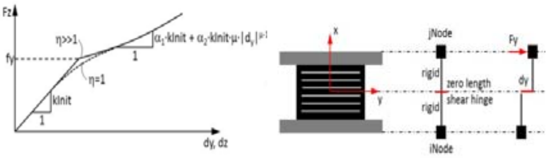

Fig. 1. Analytical model of LRB using elastomeric bearing model [3]

From the aging test, the α_1 was changed with the age of LRB. Figure 2 showed the force-displacement curve of LRB according to the nonlinear model of LRB. It was represented that the post yield stiffness of LRB was increased with time because of aging effect. In this study, the nonlinear hardening variables were defined considering the aging depth of LRB.

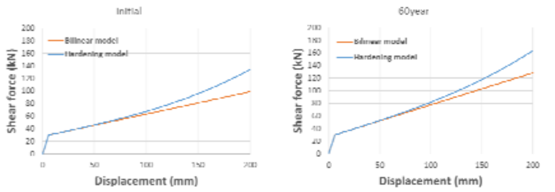

Fig. 2. Force-displacement curve of LRB-D250

The containment building of SHIN-KORI 3&4 were chosen as an analytical model. The structure model was represented by lumped-mass stick models for the seismic analysis. The mass of each floor includes the mass of walls, slabs, columns, and heavy equipment. The shear wall, dome and mat foundation were modeled by using elastic beam element.

4. Seismic response analysis of base isolated containment

For performing the finite element analysis of LRB-D1500 considering the aging depth which was calculated from the aging test of LRB-D250, it was assumed that the limit shear strain of LRB was equal regardless of the diameter and the aging depth has no effect on the diameter of LRB.

Nonlinear time history analysis for the containment building was performed by using the design spectrum of NRC Reg. guide 1.60[4] with 1.2g of peak ground acceleration considering the ultimate strain of LRB.

The effect of hardening of LRB on maximum acceleration responses of containment building was shown in Figure 3. It was represented that the maximum acceleration was increased with hardening of LRB. It was also observed that the maximum acceleration was increased with time.

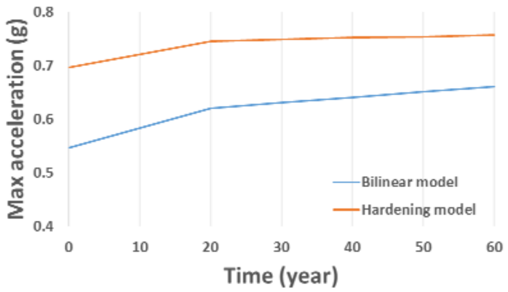

Fig. 3. Maximum acceleration response of containment by nonlinear model

Figure 4 showed the floor response spectrum (FRS) ratio of hardening model to bilinear model. The difference of FRS for hardening model and bilinear model was increased with time. Because the hardness of rubber material by aging was increased the FRS was increased between 0.5Hz and 0.6Hz.

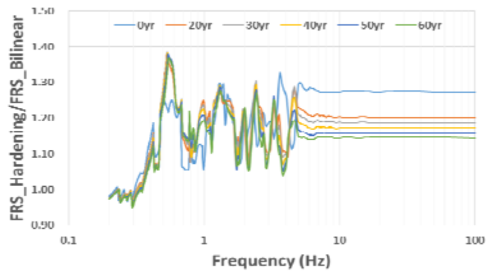

Fig. 4. Ratio of FRS by hardening effect

5. Conclusion

The hardening behavior of lead rubber bearing occurs at high strain. Therefore it is reasonable to assume that the hysteretic model of LRB is the nonlinear hardening model for exactly evaluating the seismic response of base isolated structure.

The nonlinear analysis of base isolated containment was performed by using the nonlinear hardening variables which was resulted from the test results and finite element analysis.

From the analysis results, it was represented that the FRS was higher about 40% with nonlinear hardening model than with the bilinear model. Therefore the seismic response of base isolated structure with bilinear model can be underestimated than the real response. It is desired that the nonlinear hardening model of LRB is applied for the seismic risk evaluation requiring the ultimate state of LRB. Especially when the seismic response analysis of equipment located in the base isolated NPPs is performed, the hardening effect of LRB should be considered.

Acknowledgement

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