Design Approach of Laminated Rubber Bearings for Seismic Isolation of Plant Equipment

Jinhyeong Lee, Taemyung Shin and Gyeonghoi Koo

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J.H. Lee[1], T.M. Shin[2*], and G.H. Koo[3]

[1, 2]Korea National University of Transportation, 50 Daehak-ro, Chungju, 27469, Korea
[3]Korea Atomic Energy Research Institute, 989 Daedeok-daero, Daejeon, 34057, Korea
[1]leejinhyeong87@gmail.com, [2*]tmshin@ut.ac.kr, [3]ghkoo@kaeri.re.kr

Abstract. In this study, a small laminated rubber bearing(LRB) using near-natural rubber is designed as a representative model of equipment seismic isolator to improve the seismic performance of the nuclear power plant(NPP). Some equipment of high safety importance are chosen to apply the seismic isolation using LRBs, and its design variables in consideration are reviewed to reduce seismic response. In comparison with the large LRBs for building structures, the control of design parameters for small LRBs, such as natural frequencies and shape factor, is very limited by the difficulties of fabrication. The paper discusses how they are updated and changed through the performance testing process.

Keywords: Isolator, LRB, Natural Frequency, Hysteresis Curve

1 Introduction

Seismic Isolation is one of the widely used technologies. And it has already been applied to the NPP. Recently, there has been considerable earthquake in South Korea. Then concerns about the seismic performance of NPP increased during operation. The Korean type NPP represented as APR1400 is designed to withstand 0.3g of safety shutdown earthquake(SSE) and is known to have a performance of 0.5g. APR1400 contains a variety of structures and equipment, among which some may be vulnerable to earthquake. Upgrading the target seismic performance of APR1400 to more than 0.6g may increase the range of vulnerable equipment. So, this research has been launched to improve the seismic performance of NPP for beyond design basis earthquakes.

The standards and requirements related to seismic isolation is mainly concerned with large-scale seismic isolators for buildings or civil structures so far. It is confirmed that the relevant requirements for small-sized isolator for equipment subject to this study have not yet been established. For this reason, the design, fabrication, and test of small-sized isolators for equipment are carried out in reference to the existing standards and studies for the large-scale isolator design and applications. Besides of seismic enhancement of equipment in beyond design basis earthquakes, the objective of the study is to develop adequate requirements for the design, fabrication, testing of small-sized isolators with 10 tons or less as unit bearing weight. It is initiated by applying the existing codes requirements for large-scale isolators directly to the design of small-sized ones, and proceeded gradually by revising the design parameters thru seismic analysis and discussion with fabricators.

2 Characteristics of Equipment Isolation

The seismic technology using large LRBs for the structures, such as buildings or bridges, is already well known and increasingly used worldwide so far. Unlike large-scale structural seismic isolators, there are not many studies for the application or test of small LRBs for equipment, especially for the NPP equipment subject to this study. In addition, the relevant technical code and standards have not yet been established.

Design parameters of the small LRBs affecting the equipment seismic performance, for example, are weight and stiffness of the target equipment, and horizontal and vertical stiffness, the shear strain, natural frequencies, damping, shape factor of the isolator, the input earthquake and etc. In the study, to efficiently review and analyze the applicability of the seismic isolator to various types of equipment not yet selected, plant equipment are classified into some weight groups and assumed to be rigid. And most equipment is assumed to have their weights in range of about 4 ~ 100 tons and supported by approximately 4 ~ 10 isolators. Therefore, the design equipment weight per unit seismic isolator is assumed to have a representative value of four different kinds (1, 2, 5, 10 tons). In this paper, only the contents of the 1ton test specimen are covered.

3 Design of Small LRBs for NPP Equipment

A design strategy is tried so that the maximum shear strain and displacement may be initially picked up as the preferred design variables for the small LRB for equipment. For the design purpose, the target maximum shear strain for the design basis earthquake like SSE (Safe Shutdown Earthquake) is set to be 100% of the pure rubber portion in the isolator bearing, and 200% of shear strain is set to be a maximum to withstand seismic loading beyond design basis earthquake(0.6g).

In large LRB design in general, as the long-term compressive deformation of rubber layer thickness has been mainly taken into account for high loading. And the requirements for shape factors, which assure the stability of isolators and structures, has not been sensitive. In general, the primary shape factor for the large-scale isolators is designed to be at least 25 and the secondary shape factor at least 5, which meet the code requirements with no big difficulties.

However, this is different to small LRBs for equipment. In the case of small LRB design for equipment isolation, the shape factor of the bearing is very limited by the fabrication constraints of thin laminated rubber sheet. Difficulties to make relatively thin rubber layers satisfying the target performance of horizontal flexibility and vertical stiffness deteriorate the shape factors of the small LRBs for equipment, though they mitigate problem of long-term compressive deformation.

This shows in similar trend when designing small LRBs for NPP equipment. For the reason, in this study, the objective primary shape factor is designed to be 6 or higher and the secondary shape factor to be 2.5 or higher. And the tentative prototype design is reviewed by static performance test. The vertical deformation of the rubber layer for the design pressure is turned out to be very small as expected (Poisson ratio = 0.5: volumetric immovable characteristic).

3.1 Design of horizontal stiffness

The design horizontal stiffness K_H of the LRB is determined as follows by considering the shear and P-delta effects on the design vertical surface pressure.

$$K_H = \frac{1}{K_1 + K_2 \cdot K_3} \tag{1}$$

$$\mathrm{K_1 = H_B/S_s\,,\quad K_2 = H_B^3/12 \cdot S_b\,,\quad K_3 = (1 + P/S_s)^2}$$

H_B is a total height of LRB, P is a design vertical load and it is determined in the following equation.

$$S_b = \overline{E_b} I[nt_R + (n-1)t_s]/nt_R \tag{2}$$

$$S_s = GA_s[nt_R + (n-1)t_s]/nt_R \tag{3}$$

n, t_R and t_s represent the number of rubber layer, the thickness of the rubber layer and the thickness of the steel layer, respectively. And $\overline{E_b}$ is the apparent compressive modulus of rubber considering volumetric compression of the bending of the laminated rubber. This is determined by the following equation.

$$\overline{E_b} = E_b E_\infty/(E_b + E_\infty) \tag{4}$$

E_b is an apparent compression coefficient without considering the compressive properties of rubber and is determined as follows.

$$E_b = E_o\left(1 + \frac{2}{3}kS_1^2\right) \approx 3G\left(1 + \frac{2}{3}kS_1^2\right) \tag{5}$$

k and E_o represent the hardness modification factor and the elastic modulus of rubber, respectively. In addition S_1 is the primary shape factor, expressed as follows in the case of a circular seismic isolator[1, 2].

$$S_1 = (D_o - D_i)/4t_R \tag{6}$$

3.2 Design of vertical stiffness

For design vertical loads of 1ton, the design vertical stiffness is determined in the following equation.

$$K_V = (A_s \cdot \overline{E_c})/(n \cdot t_R) \tag{7}$$

$\overline{\mathrm{E_c}}$ is apparent Young's modulus corrected, if necessary, by allowing for compressibility. And it is determined in the following equation [1, 2]. E_c is apparent Young's modulus corrected for bulk compressibility depending on S_1.

$$\overline{E_c} = (E_\infty \cdot E_c)/(E_\infty + E_c) \tag{8}$$

3.3 Specification of the prototype design

The design specifications of the prototype small LRB, determined using the aforementioned design conditions and formulas, are shown in Table 1. And Fig. 1 shows the shape of the LRB for upper mass 1 ton.

Table 1. Specification of LRBs

Sort	Upper Mass 1ton
Outer Diameter (mm)	65
Total Rubber height (mm)	24
Horizontal Stiffness (kN/m)	31.4
Shape Factor S1	6.7
Shape Factor S2	2.7

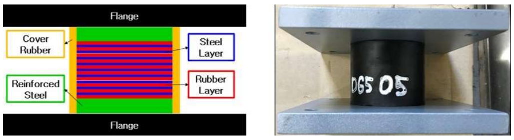

Fig. 1. Shape of LRB(Design vertical load 1ton)

According to the design, the maximum horizontal displacement of LRB should be within 24mm(100%) for design basis earthquake(0.3 g) and within 48mm (200%) for beyond design basis earthquake(0.6 g).

4 Static Performance Test and Analysis

In this chapter, it is reviewed for the static performance tests of small LRBs. Tests are carried out to check the performance of the LRBs designed and fabricated through the above process. The test method and sequence are based on the large LRBs according to the relevant criteria[3]. The static performance test was carried out with 50, 100 and 200% of the design load in vertical load and 50, 100, 150, 200 and 300% of the total rubber height in horizontal displacement. The static test was carried out for 11 cases. Test case 1 to 4 and 5 to 8 were same test case and repeated for verification of the repeatability of the design values. The vertical load of test case 1 to 4 (5 to 8) is the same as the design weight of 1 ton and the horizontal displacement is changed to 50, 100, 150 and 200% of the total rubber height. Test case 9 to 11 are subjected to extreme conditions, case 9, 10 are 1 ton vertical load, and horizontal displacement is

250% and 300% of the total rubber height, respectively. And case 11 has a vertical load 2 ton and a horizontal displacement of 300% of the total rubber height.

As a result, hysteresis curves and effective horizontal stiffness are obtained. From Fig. 2, we can see a slight decrease in effective horizontal stiffness, but this is estimated to be due to the effects of test case 4, and the repeatability problems for the design values are not significant. It should also be noted that test case 4 may have caused local damage inside the LRB.

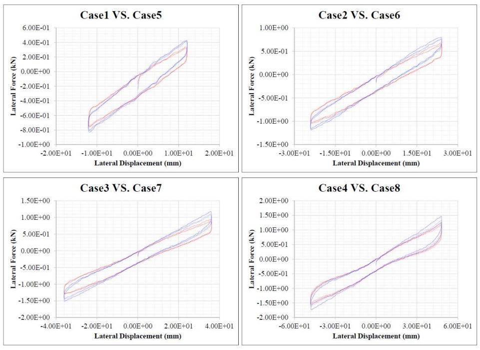

Fig. 2. Comparison of hysteresis curves for same tests

The effective horizontal stiffness at 100% horizontal displacement and 100% vertical load is 40kN/m, and at 200% horizontal displacement and 100% vertical load is 29kN/m. This has a error about 27%, 8% respectively compared to the design horizontal stiffness. In general, considering the 100% horizontal displacement and 100% vertical load conditions for the design values, it can be found that the conditions are beyond 20% of the tolerances of the design values specified in ASCE 4-16[4]. However, it can be seen that the performance of the beyond design basis earthquake(200% H-Disp.) is within the tolerances of the design value, and it is necessary to improve the design values later.

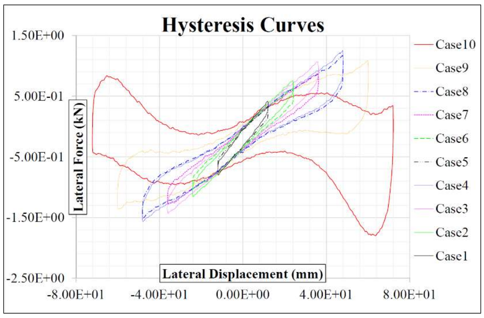

Fig. 3. Hysteresis curve with 100% vertical load cases

The Fig. 3 shows the shape of the hysteresis curve of 1ton specimen at 100% vertical load by varying horizontal displacement. The graph shows that the slope of the hysteresis curve gradually decreases and then reverses. This phenomenon is assumed to be due to poor shape factors. This can cause excessive bending motion on the edges of the LRB. The hysteresis curves for more than 200% horizontal displacement reveals a suspicion of local buckling, which can be observed by some deformation of steel plates after the test in Fig. 4. It is also possible to verify that the horizontal alignment of the laminated steel plate is not perfect and that there is a slight deviation in the thickness of the laminated rubber.

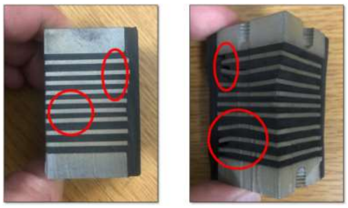

Fig. 4. Cross-section shape before(left) and after(right) the test(1ton)

5 Conclusion and future research

In conclusions, the effective horizontal stiffness obtained from hysteresis curve is quite close to the design value(allowable range ±20%). And the reversal in slope of the hysteresis curve obtained from the test is judged to have been caused by local buckling due to poor shape factor, which was caused by the limitation of thin rubber layer fabrication.

To improve the shape factor, a new test specimen is being fabricated by changing the design by raising the target horizontal frequency. And static performance test and shaking table test will be carried out soon using new test specimen.

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References

1. G.H. Koo, J.H. Lee, B. Yoo.: Mechanical Characteristics of Laminated Rubber Bearings for Seismic Isolation, Journal of EESK, Vol. 1, No. 2, pp. 79-89, (1997).
2. J.H. Lee, T.M. Shin, G.H. Koo.,: Feasibility Study for Seismic Performance Enhancement of NPP Based on Equipment Base Isolation, Trans. of KPVP, Vol.14, No.02, pp.88-95, (2018).
3. ISO 22762-1, Elastomeric seismic protection isolators Part1 Test methods, (2010).
4. ASCE 4, Seismic Analysis of Safety-Related Nuclear Sturctures, ASCE Standard, (2016).