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Probabilistic Stability Assessment of Small LRBs for Seismic Isolation of Equipment

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Abstract

Recent earthquakes occurred in south-east region of Korea have increased concerns about seismic safety of nuclear power plant (NPP) near the epicenter. And some researches are being conducted for the enhancement of operating plant seismic performance. In the study, probabilistic stability assessment is performed for the vertical loads of small laminated rubber bearings (LRBs) designed for equipment seismic isolation against beyond design basis earthquakes (BDBE). The first-order reliability method (FORM) is chosen for reliability evaluation among the reliability analysis options. The limit state function g(x) is defined for reliability analysis, which determines the limit state. And a parameter x of the function is the probability variable.

In the study, a limit state function is defined by using the formula to predict the limit of buckling load in lateral displacement presented in NUREG/CR-7255[1]. It defines the critical buckling load variable with lateral displacement. The function can be used to determine whether the small LRB is buckled or not when lateral shear deformation increases step by step while the vertical load is applied. If g(x) is greater than 0, it is considered stable in safety and vice versa.

$g(x) > 0$: Stable(safe), $g(x) = 0$: Limit state, $g(x) < 0$: Unstable(fail)

Distribution of probability variables corresponding to the critical buckling load is assumed to be in normal distribution, and each value is defined as the mean value. Allowable tolerances for the design and manufacturing of LRB and the load/displacement control errors of the test device are used to define the standard deviation of each probability variable. Using the defined limit state function, FORM analysis and sensitivity analysis with Finite Element Reliability Using MATLAB(FERUM) are performed.

As a result, the probability of LRB buckling can be checked at a certain range of vertical design load versus shear strain ratio. And the effects of mean and standard deviation of each probability variables on the stability of LRB buckling can be verified quantitatively by the sensitivity analysis. To verify the analysis, it is compared with the result of static performance test for compression-shear of the small LRB. And from the visual inspection of LRB cross section it can be found a trend of local buckling. The reliability analysis enables to estimate the critical load that causes the local buckling. It is expected that the performance and stability of the small LRB can be improved through design changes near the future. Dynamic analysis and shaking table test are planned to evaluate the seismic isolation effect.

Keywords: LRB; Stability; FORM; Reliability; FERUM

1. Introduction

Seismic Isolation has become a widely known technology for structural design. And it has already been applied to the NPP structures. Recently, there occurred a considerable earthquake in South Korea, which is the most in a century. And that was enough to increase the public concerns about whether the seismic performance of operating NPPs are OK in BDBE. The Korean type NPP represented as APR1400 is designed to withstand 0.3g level of safety shutdown earthquake (SSE), and is known to have a seismic performance above 0.5g level. APR1400 contains a variety of structures, systems and components (SSCs), among which some may be vulnerable to earthquake. Upgrading the target seismic performance of APR1400 to more than 0.6g level may increase the number of vulnerable equipment. So, this research has been launched to improve the seismic performance of NPP for beyond design basis earthquakes.

There are several ways to increase the seismic performance of nuclear power plants. In this study, probabilistic stability assessment of LRBs designed and manufactured for equipment in NPP is performed. In particular, it may be required to check the stability of buckling when deformation occurs due to the BDBE. Equations for buckling stability evaluation have been proposed through prior researches for large scale LRBs of building or bridge structures. 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 properly. In this study, evaluation of the buckling limit of small LRB's deformation using the equations given for large structures is done. And the results are also compared with those of the static performance test.

2. Design of Small LRBs

A design strategy is like that some preferred percentages of shear displacement may be initially determined as design variables for the small LRB of SSCs. For the purpose, the target maximum shear displacement for the design basis earthquake like SSE is set to be 100% of the total rubber thickness in the isolator bearing, and 200% is set to be a maximum to withstand seismic loading beyond design basis earthquake of 0.6g level.

In large LRB design in general, the long-term compressive deformation of rubber layer thickness has been mainly taken into account for large loading. And satisfying the requirement for shape factors, which assures the stability of isolators and structures, has not been any problem. In general, the primary shape factor for large-scale isolator 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, it is different for small LRBs. In case of small LRB design for equipment isolation, both of the shape factors are very limited by the fabrication constraints of thin laminated rubber sheet. Difficulties to make relatively thin rubber layer 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.

For the reason, in this study, the objective primary shape factor is adjusted to be 6 or higher and the secondary shape factor to be 2.5 or higher when designing small LRBs for NPP equipment. And the tentative prototype design is checked through the static performance test. The deformation of the rubber layer for the vertical design loading is turned out to be very small as expected, which is based on the Poisson ratio of 0.5 by volumetric immovable characteristic of rubber.

2.1 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 load.

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

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

H_B is a total height of LRB, P is a design vertical load, respectively. S_b and S_s are 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, t_s, I and A_s represent the number of rubber layer, the thickness of the rubber layer, the thickness of the steel layer, area moment of inertia and shear area of the rubber layer, respectively. And $\overline{E_b}$ is the apparent compressive modulus of rubber considering volumetric compression by bending of the laminated rubber. It 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 characteristics of rubber, which 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 in case of a circular cross section, expressed as follows[2, 3] where D_o and D_i are outer and inner diameter of the rubber layer..

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

2.2 Vertical Stiffness

For design vertical loads of 1-ton, the design vertical stiffness K_v is determined by the following equation.

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

Where $\overline{E_c}$ is apparent Young's modulus corrected for bulk compressibility depending on the primary shape factor. And it is determined by following equation [2, 3] where E_c and E_∞ are the apparent Young's modulus corrected by allowing for compressibility and rubber bulk modulus, respectively.

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

2.3 Specification of the Prototype Design

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

Table 1 – Specification of LRB

Design Loading (ton)	**Diameter (mm)**	**Total Rubber Height (mm)**
1	65	24

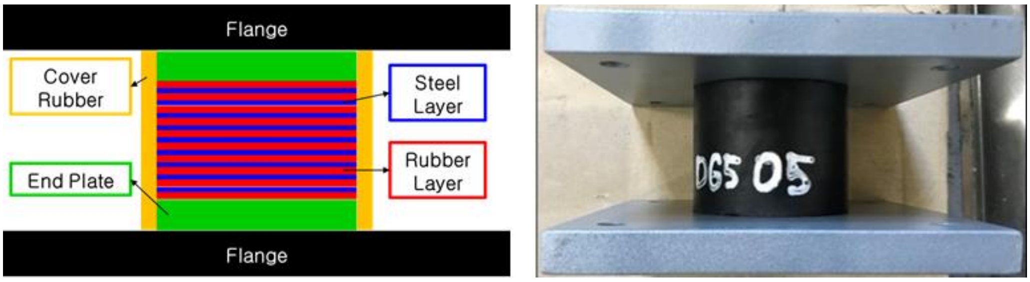


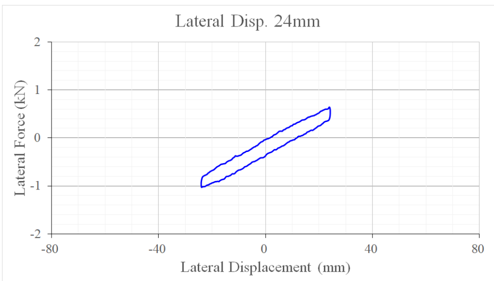
Fig. 1 – Shape of LRB

The design horizontal displacement of the LRB is defined as the total rubber height, which is 24mm to be 100% of shear strain in DBE, and 48mm in BDBE.

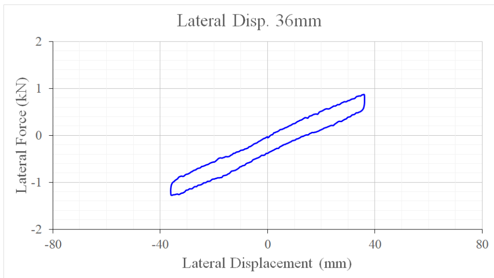
2.4 Static Performance Test

Static tests are carried out to check the performance of the LRBs. The test method and sequence are based on the ISO 22762-1 [4]. The t

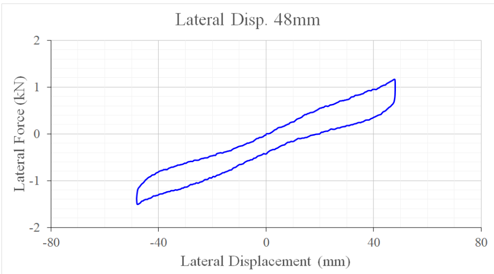
ests are performed with 50, 100 and 200% of the vertical design load and 50, 100, 150, 200, 250 and 300% of the design horizontal shear displacement. The test processes and results are described in detail in the preceding study [5]. The figures below show the shape of the hysteresis curves from the tests by varying the shear strain at 100% of vertical loading.



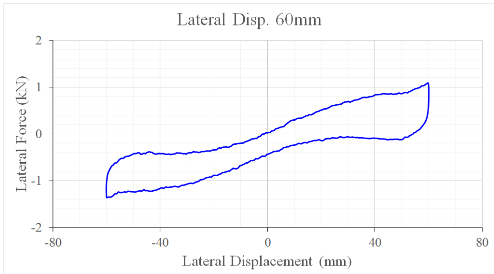
(a) 100% Shear Disp. Test



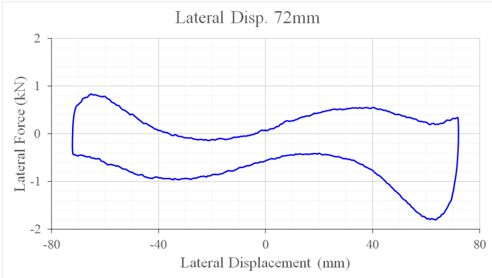
(b) 150% Shear Disp. Test



(c) 200% Shear Disp. Test



(d) 250% Shear Disp. Test



(e) 300% Shear Disp. Test

Fig. 2 – The Shape of Hysteresis Curves by Varying the Shear Displacement

Fig. 2 shows similar shape trend of hysteresis curve from the 4 tests of shear strain less equal to 200%. However, at the test of 250% and 300% shear strain, the shape is somewhat different. The tangent of hysteresis curve end changes from plus to minus for some region, which is estimated to occur buckling as described in ISO 22762-1[4]. In this study, the point at which tilt reversal is observed in the hysteresis curve of static test results can be considered as starting of buckling. Even if the shape of the hysteresis curve shows a tilt reversal, the actual test results indicate that structural stability has been sufficiently secured in the static performance tests.

3. Reliability Analysis

In this study, the probabilistic vertical stability of small LRB for nuclear power plant equipment is evaluated. FORM and sensitivity analysis, one of the reliability analysis methods, is performed for probabilistic stability assessment. This requires defining a limit state function, which is defined using an expression that calculates the critical buckling load under the various lateral displacement conditions presented in NUREG/CR-7255. Details for reliability analysis are as follows.

3.1 Limit-States Function

The limit state function is a function that defines the limit state. The limit state is the boundary between stable and unstable, and the limit state function g(x) is defined by the concept of Capacity – Demand. Stable state when the g(x) is greater than 0, unstable state when g(x) is less than 0 and limit state when g(x) is 0. To summarize this in this way, the equation is as following.

$$g(x) = \text{Capacity} - \text{Demand} \tag{9}$$

NUREG/CR-7255 proposes an expression to calculate the critical buckling load using the variation in the ratio of the upper and lower overlab area of the LRB depending on the shear strain. In this study, the difference between the critical buckling load(P_{cr}) and the design load(W) defines the limit state function. The limit state function is as follows.

$$g(x) = P_{cr} - W \tag{10}$$

The critical buckling load in compression is given by the expression derived from the two-spring model [6]:

$$P_{cr0} = \sqrt{P_S P_E} \tag{11}$$

where P_E is the Euler buckling load and is given by:

$$P_E = \frac{\pi^2 E I_S}{h^2} \tag{12}$$

$$P_S = G A_S \tag{13}$$

where A_S and I_S are the shear area and moment of inertia after accounting for the rigidity of steel shims, and are given as:

$$A_S = A\frac{h}{T_r} \tag{14}$$

$$I_S = I\frac{h}{T_r} \tag{15}$$

where A is the bonded rubber area, I is the area moment of inertia, T_r is total rubber thickness, and h is the total height including the rubber and steel shims but excluding the end plates. The modulus of elasticity here is the rotation modulus:

$$E = E_r \tag{16}$$

A list of rotation moduli for different shapes and obtained using different solutions is provided in Constantinou et al. [7]. For circular bearings rotation modulus is

$$E_r = 2GS_1^2 \tag{17}$$

The critical buckling load in equation varies with lateral displacement. The area reduction method has been shown to provide conservative results [8, 9, 10, 11]. The reduced critical buckling load is:

$$P_{cr} = P_{cr0}\frac{A_r}{A} \tag{18}$$

For circular bearings of bonded area of diameter D

$$A_r = \frac{D^2}{4}(\delta - sin\delta) \tag{19}$$

$$\delta = 2cos^{-1}({}^{\Delta}/_{D}) \tag{20}$$

Where, Δ is the lateral displacement of the bearing. Substituting the value of δ in equation, the reduced area can be written as

$$A_r = \frac{D^2}{4}\left[2cos^{-1}({}^{\Delta}/_{D}) - 2\frac{\Delta\sqrt{D^2 - \Delta^2}}{D^2}\right] \tag{21}$$

The area reduction method suggests zero capacity for a bearing at a horizontal displacement equal to the diameter of bearing. However, experiments have shown that a bearing does not lose all of its capacity at Δ = D but rather retains a residual capacity. The model proposed by Warn and Whittaker (2006) is considered here, which uses a linear approximation of area reduction method and takes into account the finite buckling capacity of a bearing at zero overlap area. The piecewise linear approximation of reduced area model is illustrated in Fig. 3. The mathematical formulation of model is given by set of equations:

$$P_{cr} = \begin{cases} P_{cr0}\frac{A_r}{A} & \frac{A_r}{A} \geq 0.2 \\ 0.2P_{cr0} & \frac{A_r}{A} < 0.2 \end{cases} \quad (22)$$

where P_{cr0} is the buckling load at zero displacement, and P_{cr} is the buckling load at overlapping area A_r of a bearing with an initial bonded rubber area of A[1]. Fig. 3 shows the reduced overlap area of an elastomeric bearing.

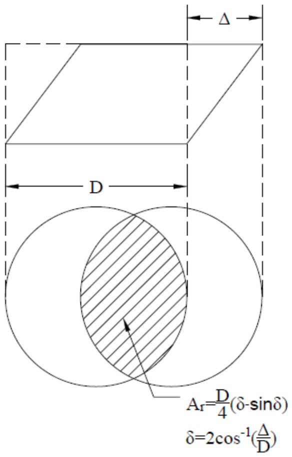


Fig. 3 – Reduced overlap area of an elastomeric bearing (US NRC, 2019)

If A_r /A is less than 0.2 in the above expression, the threshold buckling load value will have the same value even if the shear strain rate is increased. The purpose of this study is to verify probabilistic vertical stability of the change of critical buckling load with the change of shear strain, so do not use such equation. Also, the moment the A_r/A reaches zero is about 267% of the shear strain and if beyond the shear strain ratio, the critical buckling load cannot be calculated using the equation. So, the results of the analysis up to 250% of the shear strain will be compared with the results of the static performance test presented earlier. Reliability analysis is performed using the corresponding equation which A_r /A is greater than 0.2 and the results are compared with the results of static performance test.

3.2 Probability Variables

In the study, the lateral displacement, diameter, and design vertical load expected to affect the vertical stability of the LRB among the components that make up the limit state function are selected as probability variables. And assume that the various terms that make up the limit state function have distributions, not one fixed value. It is assumed that all variables follow normal distribution, and the distribution is as follows. The mean and standard deviation of each probability variable are assumed using manufacturing tolerances of design values and calibration certificate of the test device as follows.

Table 2 – Distribution of the Probabilistic Variables

Symbol	Variables	Unit	Distribution
Δ	Lateral Displacement	mm	f_{Δ} ~ N(Varying*, 0.2^2)
D	Diameter	mm	f_D ~ N(65, 5^2)
W	Design Load	N	f_W ~ N(9800, 19.6^2)

Varying*: Mean value of the lateral displacement changes as the amount of shear displacement changes(24, 36, 48, 60 mm).

3.3 FORM

FORM converts the limit state function expressed as a probability variable into the limit state function of the standard regular variable, and then applies the repetition method using the Lagrange multiplier technique to obtain the minimum distance from the origin expressed by the generalized safety index beta[12]. In FORM, the probability of failure is approximated using the correlation between the reliability index and the probability of failure.

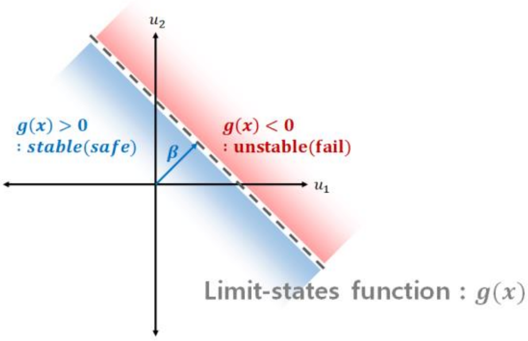


Fig. 4 – The FORM approximation concept

3.4 Sensitivity Analysis

Estimating how the results change with the change in probability variables is called Sensitivity analysis. If the randomness of the variables is relatively small, the deterministic analysis results can be used as they are. However, if a specific variable is highly random, it is necessary to identify the effect of the probability variable on the result. The probabilistic method analyzes the effect of probability variables with just one interpretation, considering the variability of probability variables other than parametric studies that perform multiple analyses if there are probability variables in the existing deterministic methods.

4. Results

Using the limit state function and reliability analysis method, probabilistic vertical stability assessment was performed according to the variation of shear strain of small LRB for equipment, and the results are as follows. Reliability analysis was performed at 50% intervals from 100% to 250% of shear strain.

Table 3 shows the value of the critical buckling load(P_{cr}) using the critical buckling load calculation equation presented in NUREG/CR-7255 and the failure probability among the results of the reliability analysis. And as the shear strain increases, it can be seen that the change in failure probability is not significant compared to the rapid reduction of critical buckling loads. In the case of a shear strain of 250% and 300%, as shown in Fig. 2, the shape of the hysteresis curve is shown to be buckling. However, looking at the failure probability as a result of the reliability analysis, we can see that the failure probability is relatively small.

From the results of the sensitivity analysis, we can quantitatively check the effect of the unit variation in the parameters (mean, standard deviation) of each probability variable on the failure probability. The failure probability tends to increase (+) as the mean value of the lateral displacement, design load increases, and the failure probability decreases (-) as the mean value of the diameter of the LRB increases. This is consistent with intuitively predictable trends. And the mean of the lateral displacement have a relatively large effect on the failure probability compared to the parameters of other probability variables. However, it is confirmed that the quantitative value did not represent a relatively significant value.

Table 3 – Vertical Stability with Changes in Shear Strain (Failure Probability)

Lateral Disp. (mm)	24	36	48	60
Shear Strain Rate (%)	100	150	200	250
Design Load, W^* (N)	9800			
Critical Buckling Load, $P_{cr}{}^*$(N)	10965	6747	4055	4055
Safety Rate (P_{cr}/W)	1.12	0.69	0.41	0.41
Failure Probability (%)	53.6	53.7	53.7	53.8

W^*: Design vertical load per LRB

$P_{cr}{}^*$: Values calculated using critical buckling load calculation equation presented in NUREG/CR-7255

5. Conclusion

In this study, probabilistic vertical stability assessment was performed according to the variation of shear strain of small LRB for equipment using the critical buckling load calculation equation according to the shear strain rate of large scale Isolator presented in NUREG/CR-7255[1].

In comparison to the critical buckling load calculation equation in NUREG/CR-7255, a 150% shear strain can also be identified that the safety rate is less than 1 in Table 3. However, it was possible to verify that up to 250% of shear strain had sufficient structural stability during the actual static performance test.

Comparison of static performance test results and reliability analysis results confirmed that the critical buckling load calculation equation given in NUREG/CR-7255 is sufficiently conservative. This result is the use of equation corresponding to large scale isolator, and the suitability for use in evaluating the vertical stability of the small LRBs for equipment under R&D in this study needs to be demonstrated by further studies in the future.

6. Acknowledgement

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