Design Verification of Lead-Laminated Rubber Bearing for Seismic Isolation of Nuclear Facility Components

Gyeong-Hoi Koo[a*], Jin-Young Jung[a], Jin-Hyeong Lee[b], Tae-Myung Shin[b]
[a] *Korea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon, 305-335, Korea*
[b] *Korea National University of Transportation, Daehak-ro 50, Chungju, 27469, Korea*
[*]*Corresponding author: ghkoo@kaeri.re.kr*

1. Introduction

The efforts to enhance the seismic capacity of a nuclear power (NPP) plant have been done for a long time in some plant levels in points of in-structures, containment building, and auxiliary building. However, it is well known that the seismic capacity of the NPP is actually governed by some seismic fragile components such as component nozzles, electric cabinets, battery packs, emergency diesel generator, etc. rather than building structures.

As one of methods to enhance the seismic capacity of facility components, the seismic isolation technologies using the small size lead-laminated rubber bearing are being developed through the national project. There has been an effort to verify the Laminated Rubber Bearing (LRB) design method [1]. In this paper, the developed design specifications of the lead-laminated rubber bearing (LLRB), which can be used for the facility components of the operating NPP are described and the results of design verification tests are discussed.

2. LLRB Design Specifications

In this paper, the small sized LLRB is developed to assure the plant safety during the event of beyond design basis earthquake (BDBE). Therefore, the LLRB is designed to produce a design specification mainly having performance against the BDBE of Safe Shutdown Earthquake (SSE).

The used design options of LLRB are for two types (OPT-1, OPT-2), which are both designed for 1ton weight for upper structure. OPT-1 and OPT-2 have 76mm and 100mm outer diameters, respectively.

The used rubber material of LLRB is kind of a natural rubber with shear modulus of 0.3MPa. Table 1 presents the performance specifications.

Table 1. LLRB Design Specifications

Design Type	OPT-1	OPT-2
VERTICAL LOAD (Tons)	1	1
HORIZONTAL STIFFNESS (kN/m)	158	208.6
VERTICAL STIFFNESS (MN/m)	22.5	53.8
HORIZONTAL FREQUENCY (Hz)	2.0	2.3
VERTICAL FREQUENCY (Hz)	23.9	36.9
DESIGN SHEAR STRAIN RATIO (%)	200	175
DESIGN HORIZONTAL DISP. (mm)	35	35
BDB SHEAR STRAIN RATIO (%)	400	350
BDB HORIZONTAL DISP. (mm)	70	70

Table 2 presents the expected characteristics of bi-linear stiffness, yield load, and damping values.

Table 2. LLRB Bi-Linear Specifications

Design Parameters	Design Type	
	OPT-1	OPT-2
K1 (kN/mm)	10	3
Kd (kN/mm)	0.0863	0.123
Qd (kN)	2.5	3.0
DAMPING(%)	28.6	25.4

3. Simulations of Seismic Isolation Performance

To investigate the design performance presented in Table 1 and Table 2, the seismic time history response analyses are performed for a safety-related console of APR1400.

Fig.1 reveals the results of the acceleration response spectrum for BDBE of 0.5g (SSE=0.3g). As shown in the figure, we can see that the acceleration response is significantly reduced by the seismic isolation design.

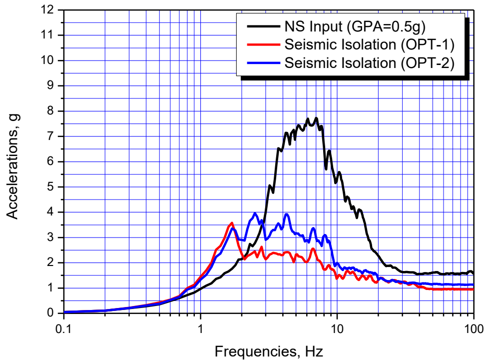
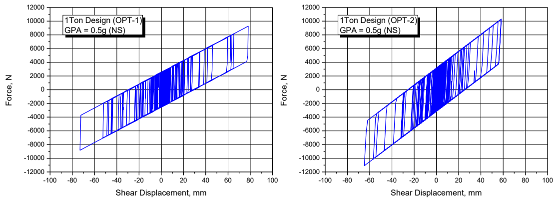


Fig. 1 Results of Seismic Isolation Performance (NS)

Fig. 2 shows the hysteresis responses for OPT-1 and OPT-2 corresponding to Fig. 1.



(OPT-1) (OPT-2)

Fig. 2 Hysteresis responses (NS, PGA=0.5g)

4. Design Verification of Dynamic Characteristics

For verification of the developed LLRB, the performance tests are carried out by the certificated organization of Korea Conformity Laboratories (KCL). The test matrix consists of three specimen for each OPT-1 and OPT-2 with tests of six types of a shear displacement range. Fig.3 presents an actual photo of a shear deflection shape of LLRB being tested. As shown in the figure, we can see that the shear deflections are so stable even for beyond design level.

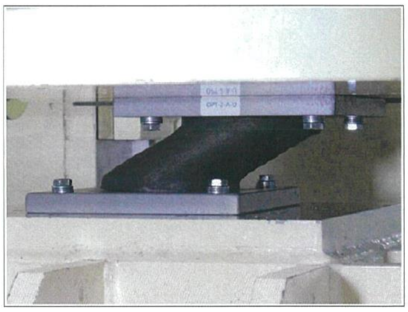


Fig. 3 Shear deflection shape being tested

As one of test results for OPT-1, Table 3 and 4 present the performance evaluation results. In the table, the calculations of the tangential stiffness Kd and the test damping are based on the draft standards being developed by the KEPIC [2]. For a design condition of d=35mm, the calculated equivalent viscous damping ratio for OPT-1A and OPT-2A are 30.7% and 23.9% respectively, which are in a good agreement with the design target damping of 28% and 25% respectively.

Table 3. Summary of OPT-1A Test

TEST ID	Kd (kN/mm)	D (mm)	Qd (kN)	Keff (kN/mm)	Damping (%)
OPT-1A-S1	0.268	1.8	0.224	0.545	19.9
OPT-1A-S2	0.193	7.0	0.613	0.281	19.7
OPT-1A-S3	0.121	17.5	2.000	0.235	30.6
OPT-1A-S4	0.080	35.0	2.633	0.155	30.7
OPT-1A-S5	0.055	52.5	2.635	0.105	30.4
OPT-1A-S6	0.037	70.0	2.172	0.068	29.1

Table 4. Summary of OPT-2A Test

TEST ID	Kd (kN/mm)	D (mm)	Qd (kN)	Keff (kN/mm)	Damping (%)
OPT-2A-S1	0.279	1.8	0.157	0.545	14.7
OPT-2A-S2	0.213	7.0	0.438	0.275	14.2
OPT-2A-S3	0.147	17.5	1.842	0.252	25.6
OPT-2A-S4	0.125	35.0	2.762	0.204	23.9
OPT-2A-S5	0.109	52.5	2.978	0.166	21.3
OPT-2A-S6	0.088	70.0	2.997	0.130	20.6

Fig.4 shows the hysteretic behavior corresponding to the design condition (OPT-2A-S4) in Table 4.

Table 5 represents the total summary design verification results of all test matrixes for the cases of design shear deflection of d=35mm by the ASCE method [3], ISO method [4], and the proposed draft KEPIC method [2].

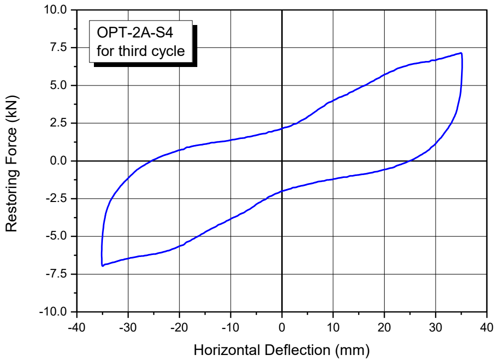


Fig.4 Hysteretic curve for OPT-2A-S4 test

As shown in Table 5, we can see that the performance characteristics from the overall test results are in a good agreement with the design. Especially, the proposed KEPIC approach, which considers the non-linear tangential stiffness (K_d) curve, gives more close results of the effective stiffness (K_{eff}) and the equivalent viscous damping ratio values than the ASCE [3] and the ISO methods [4], which are using much simpler approaches.

Table 5. Summary of Design Verifications

Test ID	Keff (kN/mm)				Damping (%)				Isolation Frquency (Hz)			
	ASCE	ISO	KEPIC	Design	ASCE	ISO	KEPIC	Design	ASCE	ISO	KEPIC	Design
OPT-1A-S4	0.130	0.160	0.155	0.158	36.557	29.7	30.7	28.6	1.8	2.0	2.0	2.0
OPT-1B-S4	0.139	0.167	0.165	0.158	37.511	31.1	31.6	28.6	1.9	2.1	2.0	2.0
OPT-1C-S4	0.130	0.166	0.163	0.158	38.699	30.2	30.8	28.6	1.8	2.1	2.0	2.0
OPT-2A-S4	0.180	0.208	0.204	0.209	27.138	23.5	23.9	25.4	2.1	2.3	2.3	2.3
OPT-2B-S4	0.185	0.209	0.199	0.209	25.851	22.9	24.0	25.4	2.2	2.3	2.2	2.3
OPT-2C-S4	0.185	0.202	0.195	0.209	25.787	23.6	24.4	25.4	2.2	2.3	2.2	2.3

5. Conclusions

In this paper, the results of the design verification through static performance test for the small size lead-laminated rubber bearing (LLRB) are described. The design purpose of the LLRB is to be used for the facility components of the NPPs. From the certified performance tests, it is verified that the design specification of the LLRB is in a good agreement with the result of verification test. The approach used for the small sized LLRB design is assured to make the intended the design performance. In the study, we are expecting that the small sized LLRB could be applied to the seismic isolation of fragile facility components in

NPPs so that it can enhance the overall seismic capacity in a plant level.

Acknowledgement

This study was supported by the Ministry of Trade, Industry and Energy through KETEP (Korea Institute of Energy Technology Evaluation Planning). (No. 20181510102380)

REFERENCES

[1] G.H. Koo, J.H. Lee, and B. Yoo, "Mechanical Characteristics of Laminated Rubber Bearings for Seismic Isolation," Journal of the Earthquake Engineering Society of Korea, Vol. 1, No. 2, pp.79-89, 1997.
[2] Seismic Isolation Guideline for Nuclear Facilities Using LRB, Draft-Rev.8, KEPIC-XXX-SIG, 2018.
[3] ASCE/SEI 4-16, Seismic Analysis of Safety-Related Nuclear Structures, ASCE Standard, 2017.
[4] 탄성 중합체 면진 장치 – 제 1 부: 시험방법, KS M ISO 22762-1, 2010