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# Vertical Seismic Responses Using Test Data of Integral 3D Laminated Rubber Bearings and Comparison of Seismic Responses among Fixed Base, 2D, and 3D Seismic Isolation Systems for A Nuclear Facility

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## 1. Introduction

It has been issued that vertical seismic responses of nuclear facilities seismically isolated by 2D horizontal seismic isolation (SI) system are larger than those of fixed base structures [1-2]. There are several studies on developing 3D SI systems composed of integral 3D LRBs [3] to reduce the amplified vertical seismic responses in 2D SI nuclear facilities; proposing vertical isolation frequency of 1~2Hz requiring the vertical acceleration responses of superstructure be less than zero period acceleration (ZPA) of the design input motion [4].

Some studies on application of 3D SI in nuclear structures have shown that a vertical isolation frequency of 3 Hz can effectively reduce the vertical responses, whereas further to reduce vertical isolation frequency to 1 Hz causing rocking effect obviously [5-6].

This paper presents the seismic responses of a Nuclear Facility, as an example, KALIMER (Korean Advanced Liquid Metal, Sodium coolant Fast Reactor, 150MWe) Reactor Building, equipped with 3D-LRBs using their static and dynamic shear-compression test results [7] subjected to artificial time histories (ATH) compatible to zero period acceleration (ZPA) of 0.3g as Design Basis Earthquake (DBE) in USNRC 1.60 Design Response Spectra (DRS) [8].

The comparison of the seismic responses among Fixed Base, 2D SI, and 3D SI systems also presents the effectiveness of 3D SI system vertically reducing the amplified acceleration responses in 2D SI systems while keeping horizontal seismic responses equally reduced.

## 2. Design Targets and Test Data for 3D-LRBs

The key design targets for the integral 3D-LRBs are horizontal and vertical stiffness, damping coefficients, the maximum shear strain and vertical free movements under design and beyond design loads, aiming that;

- Seismic isolation frequencies of 3D and 2D isolators to be 0.5Hz in horizontal directions, and 1.0~1.5Hz for 3D SI, whereas 21Hz for 2D SI, in vertical direction, respectively.
- damping coefficients of 3D and 2D isolators to be 12% in horizontal directions, and 10% or more for 3D SI, whereas 5% for 2D SI in vertical direction, respectively.
- design shear strain of 3D and 2D isolators to be 100% at design vertical load at DBE, and maximum shear strain of 300% at Beyond Design Basis Earthquake (BDBE) in horizontal directions.
- Additionally the integral 3D isolators to be required to move freely up and down proposing up to 10~15 cm displacements in vertical direction to restrict the rotational effects.

The five 1/8 scale integral 3D-LRBs composed of 2D horizontal rubber bearing with series of disc springs on top of the 2D LRB connected by rigid surrounding cylindrical container were tested as shown in Figure 1.

Fig. 1 Shear-Compression Test for 3D-LRB

Five 3D-LRBs show a good horizontal and vertical performance during shear-compression tests with 2 different speeds of 0.05Hz as static test, and 0.5Hz as dynamic one, and the vertical hysteretic curves at 0.5Hz (dynamic test) for 3D-LRB-01 are typically shown in Figure 2.

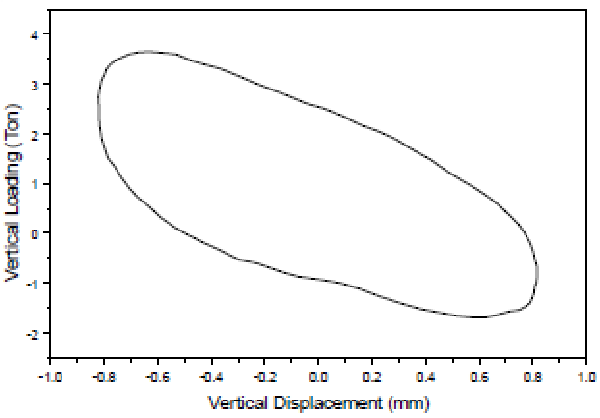
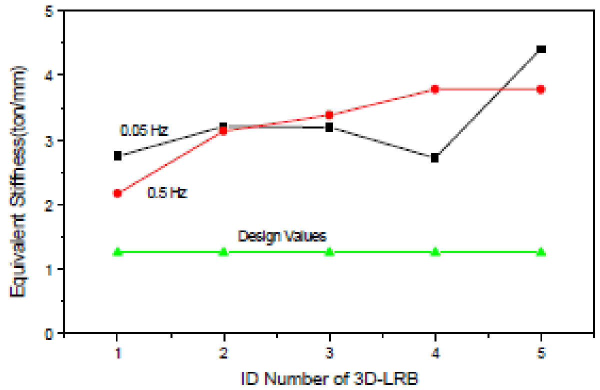
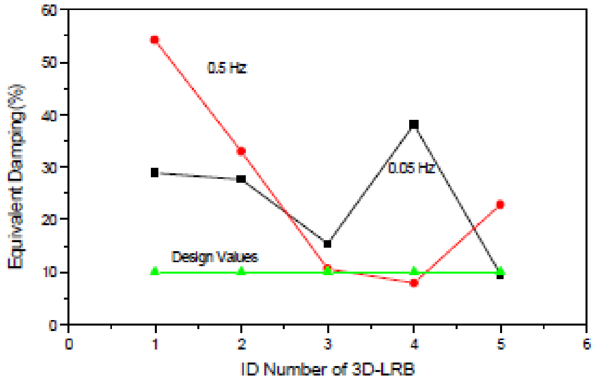



Fig. 2 Vertical Hysteretic Curve of 3D-LRB-01 Isolator (Third cycle (0.5Hz), 2.17 ton/mm, 54.26% Damping)

The vertical equivalent stiffness and damping values of five 3D-LRBs obtained by the shear compression tests are shown in Figure 3, and summarize in Table 1.




a) Vertical Equivalent Stiffness of 3D-LRBs




b) Vertical Equivalent Damping of 3D-LRBs

Fig. 3 Vertical Equivalent Stiffness and Damping of Five 3D-LRBs
(green: design value, black: 0.05Hz, red: 0.5Hz)

Table 1 Vertical Equivalent Stiffness and Damping of 3D-LRBs

| | Test Speed | 3D LRB-01 | 3D LRB-02 | 3D LRB-03 | 3D LRB-04 | 3D LRB-05 |
|---|---|---|---|---|---|---|
| Equivalent Stiffness (Ton/mm) | 0.05Hz | 2.746 | 3.210 | 3.196 | 2.719 | 4.415 |
| | 0.5Hz | 2.170 | 3.136 | 3.387 | 3.786 | 3.784 |
| Equivalent Damping (%) | 0.05Hz | 28.88 | 27.65 | 15.40 | 38.10 | 9.54 |
| | 0.5Hz | 54.26 | 33.00 | 10.60 | 7.88 | 22.82 |

The vertical equivalent stiffness values for five 3D-LRBs made of serial disc springs vary from 2.17 to 4.4ton/mm, which are larger than the design target of 1.25ton/mm. The larger vertical stiffness would cause to increase the vertical isolation frequency.

The vertical equivalent damping values for five 3D-LRBs made of serial disc springs vary 7.88~54.26%, and average vertical equivalent damping values are 23.9% in static tests, and 25.7% in dynamic tests, which are larger than the design target of 10%.

**3. Modeling of 3D-LRB SI and Reactor Building**

The Reactor Building (W 61m x D 40m x H 51m) of KALIMER (Liquid Metal coolant Fast Reactor, 150MWe) made of concrete shear walls and slabs weighs about 63000 tons, and is seismically isolated using 210 integral 3D–LRBs as shown in Figure 4.

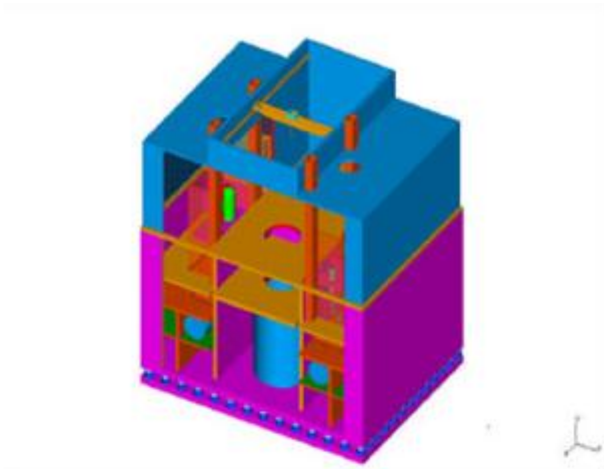


Fig. 4 Schematics of Isolated Reactor Building of KALIMER

The simplified Lumped Mass Beam Model of isolated Reactor Building is developed using beam elements, lumped mass, spring and dashpot in ANSYS [9] as shown in Figure 5.

It is noted that the equivalent stiffness and damping values for the 3D Isolator in Model of 3D SI system in Lumped Mass Beam of Isolated Reactor Building are linearly amplified from those test data obtained by dynamic shear-compression tests.

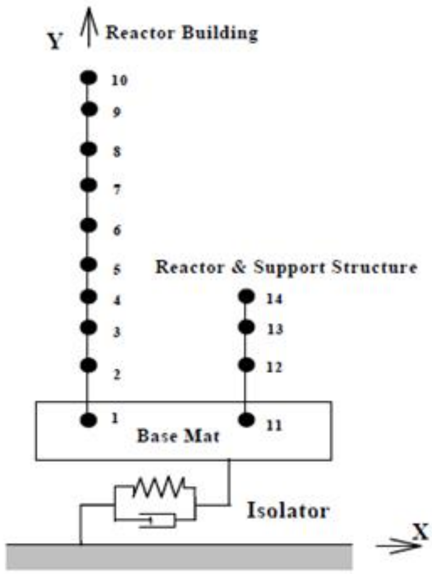



Fig. 5 Lumped Mass Beam Model of Isolated Reactor Building

### 4. Seismic Responses of Nuclear Facility equipped with Fixed Base, 2D and 3D-LRBs

The modal analyses and the linear transient time history analyses for 3 cases of Fixed Base, 2D SI, and 3D SI of the Reactor Building are performed by ANSYS using the simplified lumped mass beam model when subjected to 3 components of Artificial Time Histories compatible to ZPA of 0.3 g in the USNRC RG 1.60 DRS.

The calculated natural frequencies are 6.18 Hz in x direction, 6.26 Hz in y, and 14.85 Hz in vertical direction for the Fixed Base, 0.5 Hz, in x and y directions for 2D and 3D SI systems, while 12.64 Hz for 2D SI system, but 0.9 Hz for 3D SI system in vertical direction, respectively. The calculated modal properties are summarized as in Table 2.

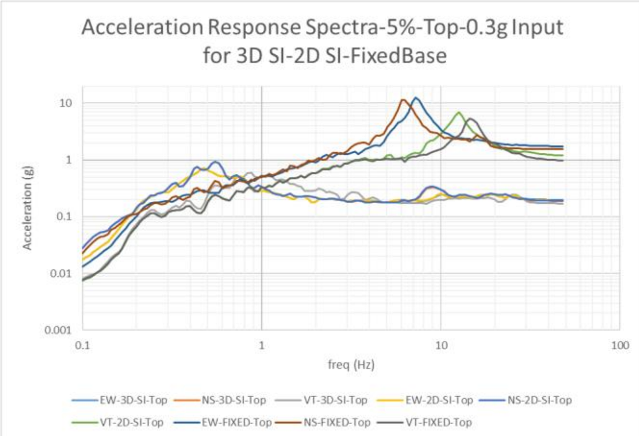
Table 2 Natural frequencies and modal properties for 3D SI, 2D SI, and Fixed Base of Reactor Building

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 3D isolation | | | | | | | |
| mode | frequen | Effective Mass | | | | | |
| | | x, kg | y, kg | z, kg | rx, kg·m2 | ry, kg·m2 | rz, kg·m2 |
| 1 | 0.5025 | 0 | 6E+07 | 0 | 3E+10 | 0 | 0 |
| 2 | 0.5027 | 6E+07 | 0 | 0 | 0 | 2.9E+10 | 0 |
| 3 | 0.9046 | 0 | 0 | 6E+07 | 0 | 0 | 0 |
| 4 | 6.1877 | 0 | 0 | 0 | 0 | 0 | 2E+10 |
| 5 | 8.5451 | 0 | 557.31 | 0 | 2E+10 | 0 | 0 |
| 6 | 9.8412 | 290.97 | 0 | 0 | 0 | 2.9E+10 | 0 |
| 7 | 18.058 | 0 | 0 | 0 | 0 | 0 | 2E+09 |
| 8 | 21.456 | 20.42 | 0 | 0 | 0 | 2.7E+07 | 0 |
| 9 | 22.684 | 0 | 19.664 | 0 | 2E+08 | 0 | 0 |
| 10 | 24.146 | 0 | 0 | 164.54 | 0 | 0 | 0 |
| | | | | | | | |
| 2D isolation | | | | | | | |
| mode | frequen | Effective Mass | | | | | |
| | | x, kg | y, kg | z, kg | rx, kg·m2 | ry, kg·m2 | rz, kg·m2 |
| 1 | 0.5025 | 0 | 6E+07 | 0 | 3E+10 | 0 | 0 |
| 2 | 0.5027 | 6E+07 | 0 | 0 | 0 | 2.9E+10 | 0 |
| 3 | 6.1877 | 0 | 0 | 0 | 0 | 0 | 2E+10 |
| 4 | 8.5451 | 0 | 557.31 | 0 | 2E+10 | 0 | 0 |
| 5 | 9.8412 | 290.97 | 0 | 0 | 0 | 2.9E+10 | 0 |
| 6 | 12.646 | 0 | 0 | 5E+07 | 0 | 0 | 0 |
| 7 | 18.058 | 0 | 0 | 0 | 0 | 0 | 2E+09 |
| 8 | 21.456 | 20.42 | 0 | 0 | 0 | 2.7E+07 | 0 |
| 9 | 22.684 | 0 | 19.664 | 0 | 2E+08 | 0 | 0 |
| 10 | 29.318 | 0 | 0 | 0 | 0 | 0 | 8E+08 |
| | | | | | | | |
| without isolation | | | | | | | |
| mode | frequen | Effective Mass | | | | | |
| | | x, kg | y, kg | z, kg | rx, kg·m2 | ry, kg·m2 | rz, kg·m2 |
| 1 | 6.1877 | 0 | 0 | 0 | 0 | 0 | 2E+10 |
| 2 | 6.2619 | 0 | 3E+07 | 0 | 5E+10 | 0 | 0 |
| 3 | 7.2206 | 3E+07 | 0 | 0 | 0 | 5.7E+10 | 0 |
| 4 | 14.853 | 0 | 0 | 4E+07 | 0 | 0 | 0 |
| 5 | 16.509 | 1E+07 | 0 | 0 | 0 | 3.7E+08 | 0 |
| 6 | 16.935 | 0 | 1E+07 | 0 | 2E+08 | 0 | 0 |
| 7 | 18.058 | 0 | 0 | 0 | 0 | 0 | 2E+09 |
| 8 | 27.697 | 2E+06 | 0 | 0 | 0 | 1.1E+09 | 0 |
| 9 | 29.318 | 0 | 0 | 0 | 0 | 0 | 8E+08 |
| 10 | 30.505 | 0 | 1E+06 | 0 | 5E+08 | 0 | 0 |

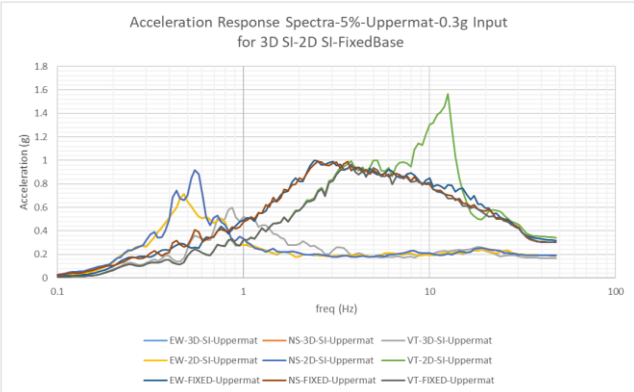
The calculated acceleration response spectra with 5% damping values at two different locations; one at Base Uppermat supported by SI systems (or at Fixed Basemat), and the other at Top of the Reactor Building isolated by 2D SI and 3D SI (or Top at Fixed Base) are as shown in Figure 6 and Table 3.

It shows that at Base Uppermat, horizontal peak spectral acceleration (PSA) responses in 2D and 3D SI systems are much reduced to 0.3~0.2g flat in 1.5~50 Hz from 1.0~0.8g of the Fixed Base in 2~10 Hz frequency ranges, and ZPA in 2D and 3D SI systems are also reduced to 0.19g from 0.3g of the Fixed Base. However vertical PSA responses in 2D SI system are highly increased to 1.6g from 0.67g in 9~14 Hz ranges, while that in 3D SI reduced to 0.2g flat in 1.8~50 Hz.

And at Top, PSA, much further reduced to 0.3~0.2g, keeping flat with little amplification in 1.5~50 Hz from 12.7~11.4g in 6.3~7.2 Hz, and ZPA to 0.19g from 1.54g, respectively. However vertical PSA in 2D SI system are highly increased to 6.9g from 5.4g in 12~15 Hz ranges in Fixed Base, while that in 3D SI reduced to 0.3~0.2g flat in 1.8~50 Hz.




a) FRS 5% at Top of Reactor Building




b) FRS 5% at Base Uppermat of Reactor Building

Fig.6 Acceleration Response Spectra at Top and Base Uppermat for 3D SI, 2D SI, and Fixed Base of Reactor Building subject to 0.3g ZPA of ATH

Table 3 Peak Accelerations and maximum Relative Displacements in 3 directions for Fixed Base, 2D SI and 3D SI Reactor Building subjected to 0.3g

| | x-direction (EW) | | | y-direction (NS) | | | z-direction (VT) | | |
|---|---|---|---|---|---|---|---|---|---|
| location | fixed | 2D SI | 3D SI | fixed | 2D SI | 3D SI | fixed | 2D SI | 3D SI |
| Uppermat accel. g | 0.30 | 0.19 | 0.19 | 0.30 | 0.19 | 0.19 | 0.30 | 0.33 | 0.17 |
| Top accel. g | 1.70 | 0.19 | 0.19 | 1.53 | 0.19 | 0.19 | 0.91 | 1.13 | 0.17 |
| base rel disp. mm | 0.00 | 161.14 | 161.03 | 0.00 | 157.63 | 157.45 | 0.00 | 0.62 | 41.63 |
| Top rel disp. mm | 8.33 | 162.15 | 162.03 | 10.43 | 158.96 | 158.76 | 1.07 | 1.90 | 41.83 |

The maximum relative displacements for the Fixed Base and 2 different SI systems are summarized in Table 3, and the relative displacement response time histories for 3D SI, for example, are shown in Figure 7.

The calculated maximum relative displacements in horizontal directions are small as 8.3~10.4 mm at Top for Fixed Base, increased to 157.6~161.1 mm at Uppermat for 2D SI and 3D SI, respectively. Those in vertical direction are very small as 1.1 mm at Top for Fixed Base, and 1.9 mm at Uppermat for 2D SI, whereas increased to 41.6 mm at Uppermat for 3D SI. The maximum relative displacement of 161.1 mm in horizontal directions for 2D and 3D LRBs equivalent to the shear strain of 57.9% (for total rubber thickness of 278 mm) is well within the design shear strain requirement of 100%. The vertical maximum relative displacement of 41.6 mm for 3D LRBs is also within tentative displacement requirement of 100 mm.

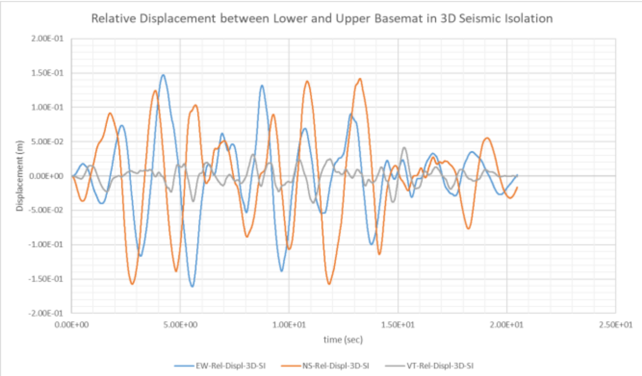



Fig.7 Relative Displacements in 3 Directions between Lower Mat and Superstructure for 3D SI of Reactor Building subject to 3 component ATHs of 0.3g ZPA

## 4. Conclusion

This paper evaluates the seismic responses of a Reactor Building using 3D SI system having equivalent stiffness and damping values of prototype 3D LRBs assuming linear amplification of average test data of 1/8 scaled down 3D-LRB shear compression tests

The dynamic time history analyses of the Nuclear Facility have been performed using the lumped mass beam model of the Reactor Building equipped with 2D SI and 3D-SI subjected to ATH compatible to the DRS of 0.3g ZPA, and their seismic responses are compared in acceleration responses and relative displacements.

The conclusions of the evaluation of the 3D LRB tests and seismic responses of 3D and 2D SI system are as follows;

All five 3D-LRB shows a good mechanical performance in horizontal and vertical directions. Average horizontal equivalent damping values of 10% for five 3D-LRBs are less than the design target of 12% due to NRB are used for 3D-LRBs, but for the analyses horizontal equivalent stiffness and damping values of 3D LRBs are modeled as same as those of 2D isolators. Average vertical equivalent damping values of 25.7% for five 3D-LRBs made of serial dish springs are larger than the design target of 10% and average vertical equivalent stiffness are stiffer than the design target.

The comparison of the seismic responses between 2D and 3D SI systems also presents the effectiveness of 3D SI systems vertically reducing the amplified acceleration responses in 2D SI systems while keeping horizontal seismic responses equally reduced much more than those of the Fixedbase.

The relative displacements in horizontal directions between Lower Basemat and Superstructure in 2D and 3D SI systems are equally amplified up to 16.2 cm, while those in 3D SI are vertically amplified to 4.2 cm, but those in 2D SI system and Fixed Base very little.

Following further studies to verify the effectiveness of the 3D SI system applied for any Nuclear Facilities are recommended;

1) The design optimization and characterization tests of prototype 3D isolators, especially design of disc springs with in parallel and series combinations, and damping values due to friction between disc springs
2) 3D SI system dynamic tests for various types of reactor buildings including reactors, and its reactor internal structures, such as Control Rod Driving Mechanism, Shutdown Rod Driving Mechanism, and fuel assemblies.

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