

Seismic Performance Enhancement of a Reinforced Concrete Building Using an RB-HDRC Base Isolation System

Nur Khofifah^{1✉}, Ahmad Basshofi Habieb²

^{1,2} Civil Engineering Department, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia

✉ **Corresponding Author** : Nur Khofifah (e-mail: nkhofifah941@gmail.com)

Article Information	ABSTRACT
Article History Received : March 05, 2026 Revised : March 17, 2026 Published : April 04, 2026	This study investigates the seismic performance enhancement of a four-story reinforced concrete building retrofitted with a Rubber Bearing-High Damping Rubber Core (RB-HDRC) base isolation system. A three-dimensional numerical model was developed and subjected to nonlinear time-history analysis under two design earthquake levels (BSE 1-E and BSE 2-E). The results indicate that the base isolation system significantly reduces seismic demands compared to the fixed-base condition. Peak base shear was reduced by approximately 48% at the BSE-1E level and by 52% at the BSE-2E level. Roof acceleration decreased by about 76% and 79% at the BSE 1-E and BSE 2-E levels, respectively. The maximum interstory drift ratio was also reduced, demonstrating improved deformation control in the isolated system. Furthermore, the number of plastic hinges decreased significantly, while the energy dissipation capacity increased due to the hysteretic behavior of the RB-HDRC isolator. These findings demonstrate that RB-HDRC base isolation effectively enhances structural resilience and represents a promising strategy for improving the seismic performance of reinforced concrete buildings.
Keywords: <i>Base Isolation; RB-HDRC; Nonlinear Time History Analysis; Seismic Performance.</i>	

INTRODUCTION

In recent years, studies on seismic performance of buildings have undergone a paradigm shift from conventional design approaches that rely on the structural ductility of the system to the application of more sophisticated passive protection systems. Among the various technologies developed, base isolation systems have emerged as one of the most effective methods for improving structural stability when subjected to seismic excitations.

The fundamental principle of base isolation lies in its ability to modify the dynamic characteristics of a structure by lengthening the fundamental period and providing additional damping to minimize seismic forces acting on the structure (Apostolidi et al., 2021; Fujino et al., 2019; Makris, 2019; Sheikh et al., 2022). This period shift moves the natural frequency of the building away from the dominant frequency of the earthquake, which typically contains high energy at short periods. As a result, the seismic forces transferred to the superstructure are significantly reduced (Imran et al., 2024). In addition, this isolation system also incorporates a damping mechanism that dissipates energy, thereby minimizing dynamic responses such as interstory drift.

One commonly used type of isolator is an elastomeric isolator with a lead core, known as a Lead Rubber Bearing (LRB), which utilizes the plastic deformation of the lead core to dissipate earthquake energy through hysteretic energy dissipation (Choun et al., 2014; Kelly, 1999;

Robinson, 1982). However, the use of lead cores poses significant environmental and health risks due to their toxicity. Increasingly stringent global regulations, such as the European Union's Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH) directive which classifies lead as a Substance of Very High Concern (SVHC) are driving the search for more environmentally friendly and sustainable alternative materials for construction applications (Pianese et al., 2025; Pohl et al., 2017).

In response to these challenges, researchers have begun exploring safer alternatives to lead cores, one of which is the High Damping Rubber Core (HDRC). A numerical study by (Pianese et al., 2025), investigated the feasibility of using HDRC in elastomeric isolators, hereinafter referred to as Rubber Bearing-High Damping Rubber Core (RB-HDRC) isolators. Based on previous experimental studies on the characterization of high-damping rubber materials for seismic isolation (Pianese, Van Engelen, Tait, et al., 2024; Pianese, Van Engelen, Toopchi-Nezhad, et al., 2024a, 2024b), this study focuses not only on the geometry of the rubber core but also on the effect of High Damping Rubber (HDR) composition on the mechanical performance of the isolator.

Numerical findings regarding the potential of the RB-HDRC form the basis for its implementation in comprehensive structural analysis of buildings. By integrating its mechanical characteristics into a multi-story structural model, this study evaluates the effectiveness of RB-HDRC in reducing the dynamic response of buildings to earthquakes representative of seismic conditions in Indonesia. This approach provides a more comprehensive understanding of the behavior of RB-HDRC as an integrated component of the structural system while contributing to the development of more environmentally friendly and adaptive seismic isolation solutions for future earthquake-resistant infrastructure.

Therefore, the objectives of this study are: (1) to quantify the effectiveness of RB-HDRC base isolation on reducing seismic demands (base shear, roof acceleration, interstory drift ratio) for a typical four-story reinforced concrete building representative of construction practice in Indonesia; (2) to evaluate the effect of RB-HDRC on damage indicators (number of plastic hinges and hinge condition) under BSE-1E and BSE-2E ground motions; and (3) to compare the numerical findings with recent studies on elastomeric isolators to position RB-HDRC relative to established isolation devices. The principal contribution of this work is a comprehensive, quantitative assessment of RB-HDRC performance at the structural level, thus bridging the gap between component-level RB-HDRC investigations and whole-structure seismic evaluations under Indonesian seismic scenarios.

RESEARCH METHODS

This study evaluates the seismic performance of an existing building with a conventional fixed-base system and compares it with the structural response after the implementation of a base isolation retrofit. Nonlinear time-history analysis following the provisions of ASCE 41-17 is applied to investigate the structural response subjected to earthquake excitation. The evaluation considers several response parameters, including dynamic properties (natural period and mass participation), global structural responses (base shear and roof acceleration), deformation response (interstory drift ratio), and damage indicators such as the number of plastic hinges and the energy dissipation ratio.

Study Case

The case study focuses on an existing four-story reinforced concrete building located in Surabaya, Indonesia, with an overall height of 16.8 m. Each story has a uniform height of 4.2 m. The building serves as an educational facility and is categorized as Risk Category IV according to the applicable seismic design provisions. The site is located in an area with a medium soil classification (Site Class SD).

The structural system adopted in the existing building is a reinforced concrete special moment-resisting frame with fixed-base support conditions at the foundation. The building was designed and constructed in 2017 in accordance with SNI 1726-2012 for seismic resistance and

SNI 2847-2013 for reinforced concrete design. With the release of updated seismic design regulations, namely SNI 1726-2019 and SNI 2847-2019, a reassessment of the seismic performance of the existing building has become necessary to ensure its compliance with current standards.

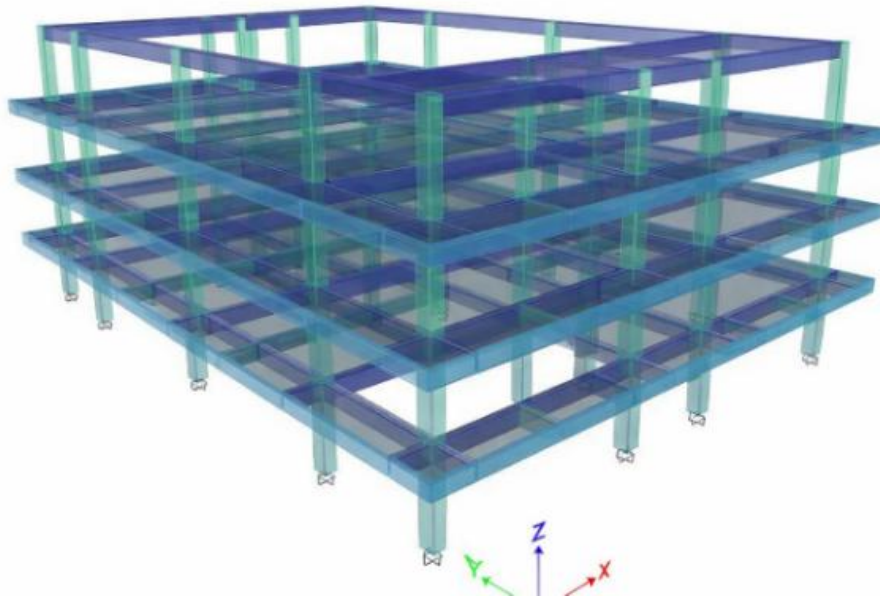


Figure 1. 3D view numerical modelling of existing building

The primary structural system utilizes concrete with a compressive strength of 25 MPa and reinforcing steel with a yield strength of 420 MPa. A three-dimensional numerical model of the existing building was developed using structural analysis software to comprehensively represent its dynamic response, as illustrated in Figure 1. To enhance the seismic performance of the structure, the model was subsequently modified by incorporating a base isolation system, with the modeling procedures and design parameters described in the following section.

Base Isolation Design and Modelling

To enhance the seismic performance of the existing structure, a Rubber Bearing–High Damping Rubber Core (RB-HDRC) base isolation system was incorporated into the numerical model. This system was selected due to its ability to lengthen the natural period, reduce inertial forces transmitted to the superstructure, and enhance energy dissipation capacity through the damping characteristics of high-damping rubber materials (Pianese et al., 2025).

RB-HDRC is a development of high-damping rubber isolators designed to provide adequate effective lateral stiffness and damping ratio without the use of a lead core, as employed in Lead Rubber Bearings (LRB). Its modeling is based on previous numerical studies that have validated its mechanical characteristics and dynamic behavior. Material parameters were adopted from relevant literature, while the geometric dimensions were determined based on the maximum vertical load and the target lateral deformation at the design earthquake level.

Table 1. Mechanical properties of the RB-HDRC

Parameters	Unit	RB-HDRC
K_{eff}	kN/m	940.27
k_v	kN/m	723677
ζ_{eff}	%	18.16
mass	kg	83849
weight	kN	822.56

The parameters used in the numerical modeling, including effective stiffness (K_{eff}), initial stiffness (k_v), effective damping ratio (ζ_{eff}), and the mass and weight of the isolator, are presented in Table 1. These parameters were directly input into the structural analysis software.

Meanwhile, the geometric dimensions of the isolator defining the physical configuration of the device including an outer diameter of 800 mm, a rubber core diameter of 400 mm, a rubber layer thickness of 8 mm, a steel plate thickness of 4 mm, and a total isolator height of 296 mm are presented in Figure 2. In the numerical model, the isolation system is installed at the base level by replacing the fixed-base condition with isolator elements that allow controlled lateral deformation. This configuration is intended to concentrate deformation within the isolator so that deformation responses and internal forces in the superstructure can be reduced. The dynamic response is evaluated using nonlinear time-history analysis, with the lateral behavior of the isolator represented by its effective stiffness and effective damping. This approach enables a more realistic assessment of the isolation system's performance in reducing seismic responses under the considered earthquake levels.

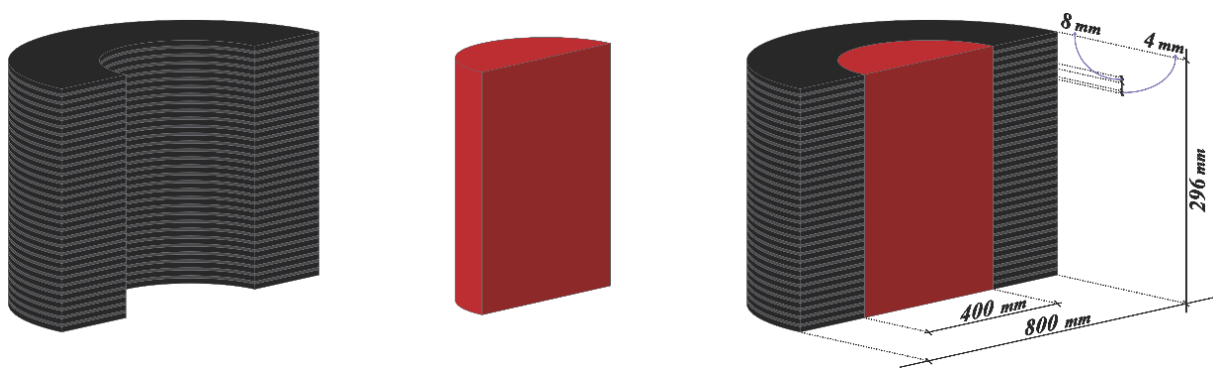


Figure 2. Schematic representation of the RB-HDRC

Performance Objectives

The structural performance assessment was carried out to confirm that the required safety targets specified in ASCE 41-17 Chapter 2 are achieved, considering both the building risk category and the level of seismic hazard. Since the case-study building falls under Risk Category IV, it is required to meet the Immediate Occupancy (IO) performance level for the 225-year return period earthquake (BSE-1E) and the Life Safety (LS) performance level for the 975-year return period earthquake (BSE-2E). The acceptance criteria are assessed through both global and local performance approaches, including the evaluation of plastic rotation ratios of structural elements.

Ground Motion Selection

Ground motion records were selected through seismic hazard deaggregation analysis to obtain the dominant source parameters, including magnitude (M), rupture distance (R_{rup}), and source mechanism.

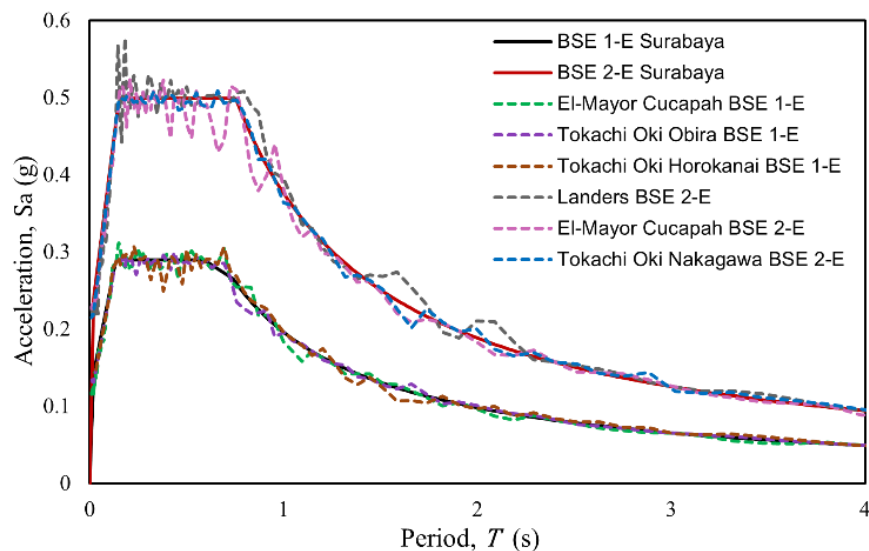
Table 2. Selection ground motion records BSE 1-E level

Mechanism	Direction	Earthquake Events	Year	Magnitude	Distance (R _{rup})	Vs30 (m/s)	Duration
Shallow Crustal	X	El-Mayor Cucapah (Rock Hill), Mexico	2010	7,2	58,47	309	85,7
	Y						
	X	Tokachi Oki (Obira), Japan	2003	8,29	25,01	218	88,86
	Y						
Megathrust	X	Tokachi Oki (Horokanai), Japan	2003	8,29	25,01	198	68,29
	Y						

Table 3. Selection ground motion records BSE 2-E level

Mechanism	Direction	Earthquake Events	Year	Magnitude	Distance (Rrup)	Vs30 (m/s)	Duration
Shallow Crustal	X	Landers (Indio-Coachella), California	1992	7,28	54,25	339,02	37,9
	Y						
	X	El-Mayor Cucapah (Westmoland), Mexico	2010	7,2	42,61	193,67	25,7
	Y						
Megathrust	X	Tokachi Oki (Nakagawa), Japan	2003	8,29	25,01	327,6	113,38
	Y						

Considering that the study area is influenced by the Beribis–Kendeng Fault, a reverse fault mechanism was adopted (Tim Pusat Studi Gempa Nasional, 2022). The deaggregation analysis was performed for two hazard levels corresponding to return periods of 225 years (BSE-1E) and 975 years (BSE-2E). Three pairs of selected ground motion records are presented in Tables 2 and 3 and were subsequently scaled to match the target response spectrum for Surabaya City with a damping ratio of 5% for each hazard level, as shown in Figure 3. In the structural analysis, the earthquake records were applied in two orthogonal directions, namely the X and Y directions, representing the principal orientations of the building

**Figure 3.** Acceleration response spectra of the three ground motions matched to BSE-1E and BSE-2E level

RESULTS AND DISCUSSION

The results of the nonlinear time-history analysis were obtained from two structural models: the fixed-base model and the base-isolated model, each subjected to three pairs of earthquake ground motion records. The response parameters compared in this study correspond to the maximum values obtained from the three pairs of ground motions.

Dynamic Characteristics

The dynamic characteristics of the structure were evaluated through the natural periods and mass participation factors. As shown in Table 4, the implementation of the base isolation system lengthened the natural periods by approximately three times in the first three modes, thereby shifting the structural frequencies away from the dominant earthquake frequencies and significantly reducing the seismic response. In addition, the cumulative mass participation approaches 90%, indicating that the structural response is primarily governed by the first three

modes, while the contribution of higher modes becomes negligible. This condition reflects a more controlled and stable dynamic behavior in the isolated structural system.

Table 4. Comparison of the dynamic characteristics

Dynamic Characteristics		Fixed Base	Base Isolated
Period	Mode 1	1,001	3,038
	Mode 2	0,97	3,025
	Mode 3	0,95	2,937
Mass Participation UX	Mode 1	76,43%	87,50%
	Mode 2	80,66%	87,53%
	Mode 3	80,66%	87,60%
Mass Participation UY	Mode 1	0,01%	0,03%
	Mode 2	0,02%	87,34%
	Mode 3	82,69%	87,61%

Base Shear

A comparison of the peak base shear between the two structural models under different earthquake hazard levels is presented in Figure 4. At the BSE-1E hazard level, the average base shear of the fixed-base structure was recorded as 3,422.23 kN, while the base-isolated structure decreased to 1,776.49 kN, representing a reduction of 48%, as shown in Figure 4(a). Meanwhile, at the BSE-2E hazard level, the average base shear of the fixed-base structure reached 5,933.52 kN, whereas the base-isolated structure experienced a reduction to 2,820.46 kN, corresponding to a 52% decrease, as illustrated in Figure 4(b).

The reduction in base shear occurs due to the lengthening of the natural period of the structure induced by the base isolation system, which results in lower earthquake acceleration being transmitted to the structure. Interestingly, the lower percentage of reduction at the higher earthquake hazard level indicates that the effectiveness of base isolation tends to decrease when the system experiences inelastic behavior under extreme seismic loading.

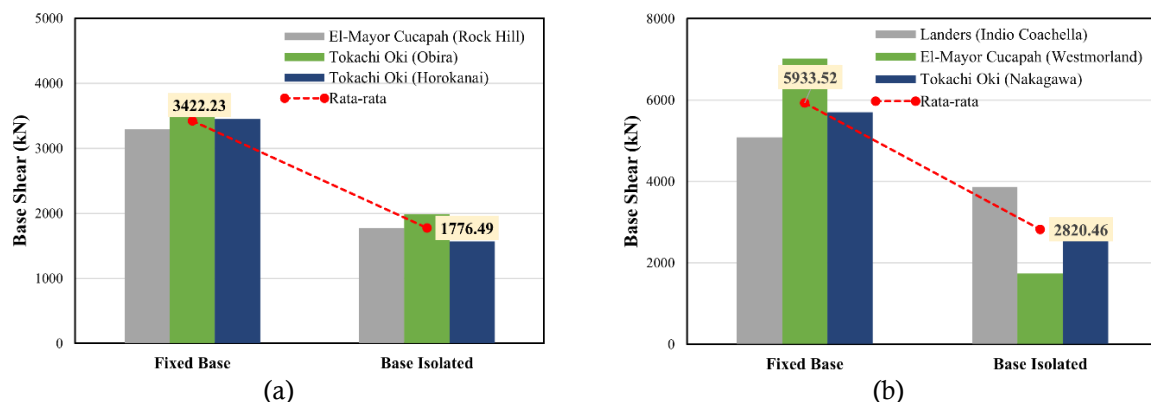


Figure 4. Comparison of base shear: (a) BSE 1-E level (b) BSE 2-E level

Roof Acceleration

Roof acceleration is an important parameter in ensuring the functional safety of buildings during earthquakes, as poorly designed non-structural components may pose hazards to occupants. At the BSE-1E hazard level, the average roof acceleration for the fixed-base structure was recorded at 2.45 g, whereas the base-isolated structure experienced a reduction to 0.59 g. This represents a 76% reduction, as shown in Figure 5(a). Meanwhile, at the BSE-2E hazard level, the fixed-base structure produced a roof acceleration of 4.21 g, while the base-isolated structure decreased to 0.88 g. As illustrated in Figure 5(b), the addition of base isolation resulted in a 79% reduction under this more extreme earthquake level.

The reduction in roof acceleration occurs because the base isolation system provides lower stiffness and higher damping at the base of the structure, thereby reducing the acceleration

transmitted to the upper floors (Fakih et al., 2021). However, the effectiveness of the isolator in reducing roof acceleration tends to decrease as earthquake intensity increases, which is reflected in the smaller percentage reduction at the BSE-2E level compared with BSE-1E.

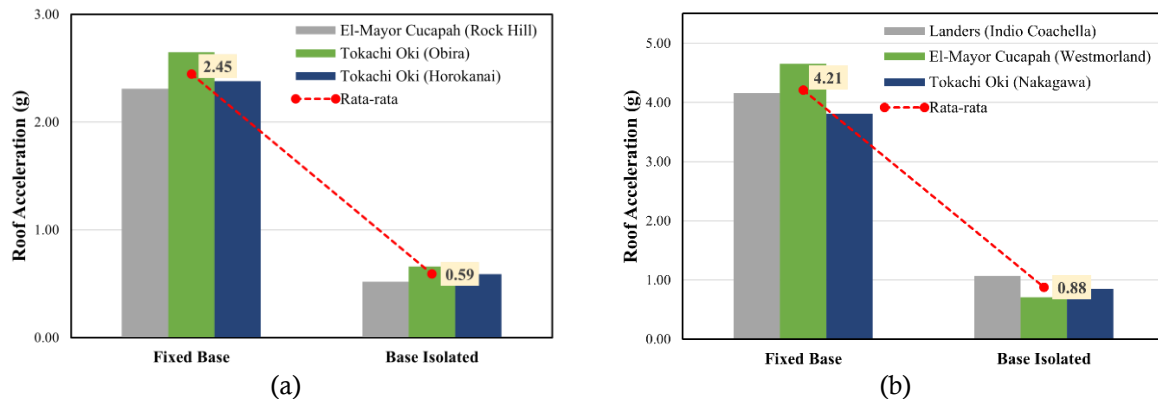


Figure 5. Comparison of roof acceleration: (a) BSE 1-E level (b) BSE 2-E level

Interstory Drift Ratio

The interstory drift ratio represents the ratio between the relative horizontal displacement of two consecutive floors and the story height and is used to evaluate the distribution of structural deformation. At the BSE-1E hazard level, as shown in Figure 6(a), the maximum drift of the fixed-base model is 0.26% at an elevation of 16.8 m, whereas the isolated system exhibits a maximum drift of 0.15% at an elevation of 4.2 m, indicating a reduction in deformation due to the implementation of base isolation. The drift distribution also shows a concentration of deformation at the lower level in the isolated system, accompanied by reduced drift in the upper stories. At the BSE-2E hazard level, as illustrated in Figure 6(b), the maximum drift reaches 0.48% for the fixed-base model and 0.37% for the isolated model. All values remain below the Immediate Occupancy (IO) limit of 1%, with the isolated system consistently exhibiting lower deformation.

Overall, the base isolation system consistently reduces interstory drift at both earthquake hazard levels, indicating its effectiveness in mitigating structural deformation and inertial forces.

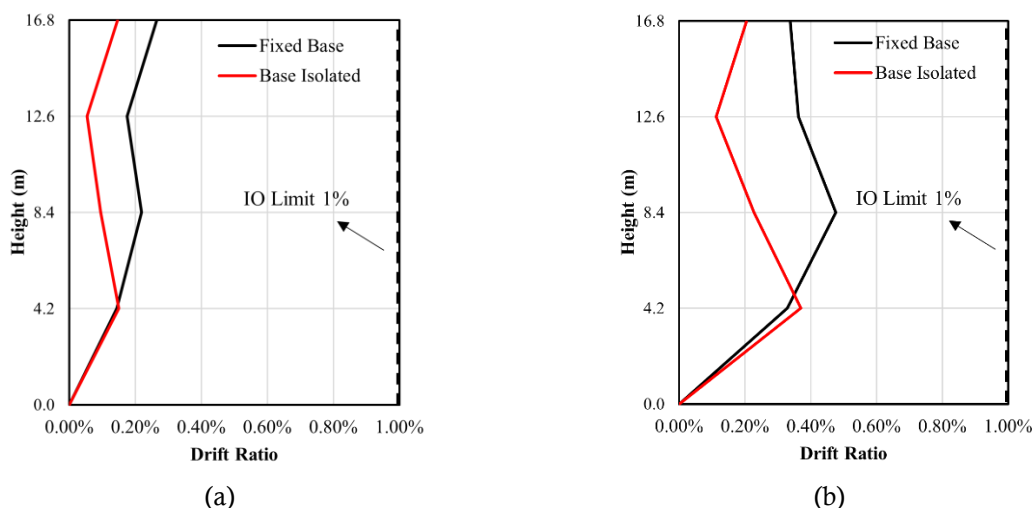


Figure 6. Comparison of interstory drift ratio: (a) BSE 1-E level (b) BSE 2-E level

Number of Plastic Hinges

The number of plastic hinges analyzed corresponds to hinges that have exceeded the yield rotation limit of structural elements, with the evaluation performed on both beams and columns to assess the level of inelastic damage caused by earthquake loading.

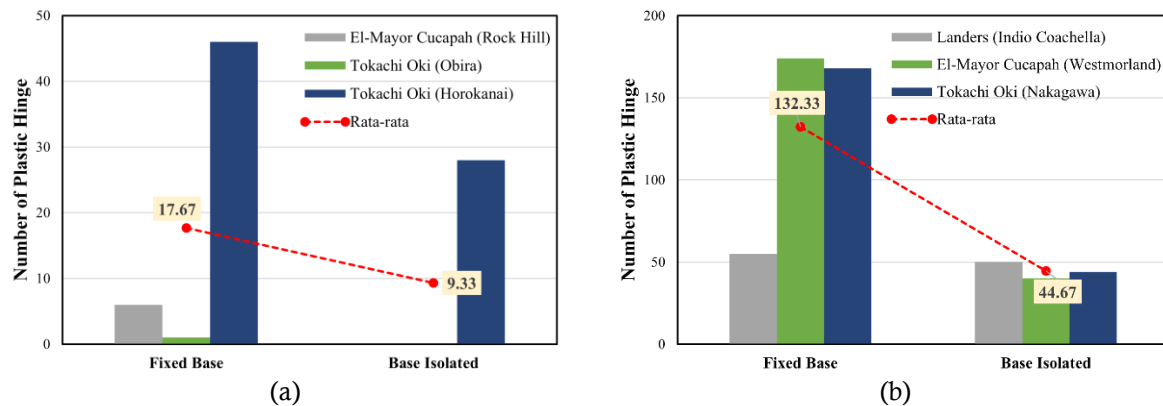


Figure 7. Comparison of number of plastic hinges: (a) BSE 1-E level (b) BSE 2-E level

At the BSE-1E hazard level, the average number of plastic hinges in the fixed-base system is 17.67, whereas the isolated system records an average of 9.33, indicating a reduction of approximately 47%, as shown in Figure 7(a). At the BSE-2E hazard level, illustrated in Figure 7(b), the average number increases to 132.33 in the fixed-base system and 44.67 in the isolated system, corresponding to a reduction of approximately 66%.

These findings indicate that base isolation significantly limits the formation of plastic hinges and reduces the inelastic response of structural elements, thereby improving the structural performance and resilience of the building against earthquake loading at both analyzed intensity levels.

Hinge Condition

The local performance level of the structure was evaluated based on the hinge condition ratio, defined as the ratio between the actual element rotation and the allowable rotation limit specified in ASCE 41-17. The evaluation focused on columns as the most critical elements due to the limited reinforcement detailing in the existing structure.

Based on Table 5, at the 250-year earthquake level (BSE-1E), all hinge conditions in the fixed-base model remain within the Immediate Occupancy (IO) category, with a maximum ratio of 0.217. The isolated system shows a smaller response, with a maximum ratio of only 0.062, which confirms the effectiveness of the isolation system in limiting inelastic rotations. At the 1000-year earthquake level (BSE-2E), the fixed-base model exhibits performance degradation, including one case reaching the Collapse Prevention (CP) level, with a rotation ratio of up to 1.708 relative to the IO limit. In contrast, the isolated system remains within the IO category with a maximum ratio of 0.196. These results indicate that base isolation consistently improves the local structural performance by controlling the development of plastic rotations in columns and preventing the transition toward more severe damage levels, even under higher seismic intensities.

Table 5. Comparison of the most critical hinge condition in both seismic level

Parameter	Earthquake Event	Fixed Base	Base Isolated
BSE 1-E level	El-Mayor Cucapah (Rock Hill)	0.075 IO	0.000042 IO
	Tokachi Oki (Obira)	0.024 IO	0.000043 IO
	Tokachi Oki (Horokanai)	0.217 IO	0.062 IO
BSE 2-E level	Landers (Indio Coachella)	10 CP	0.196 IO
	El-Mayor Cucapah (Westmorland)	0.468 IO	0.087 IO
	Tokachi Oki (Nakagawa)	1.708 IO	0.178 IO

Energy Dissipation

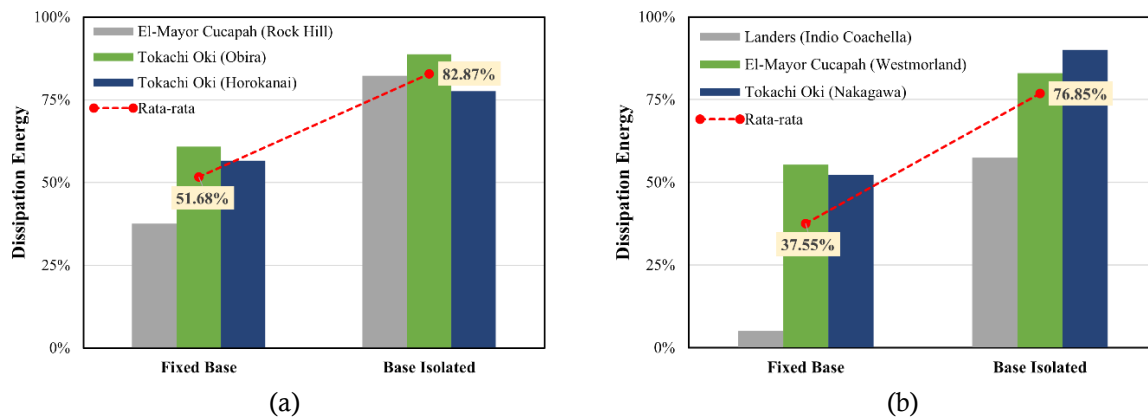


Figure 8. Comparison of number of plastic hinges: (a) BSE 1-E level (b) BSE 2-E level

Energy dissipation represents the ability of a structure to absorb and damp seismic energy, which is calculated as the ratio of dissipated energy to input energy. At the BSE-1E earthquake level, as shown in Figure 8(a), the average energy dissipation ratio increases from 51.68% in the fixed-base system to 82.87% in the isolated system, representing an increase of 31.19%. At the BSE-2E level, the corresponding values are 37.55% and 76.85%, respectively, indicating an increase of 39.30% due to the implementation of base isolation, as illustrated in Figure 9(b). Although increasing earthquake intensity reduces the energy dissipation ratio in the fixed-base system, the isolated system maintains a high dissipation capacity. These results confirm that the mechanisms of period lengthening and controlled deformation in the isolator effectively enhance energy absorption and reduce the transfer of inertial forces to the superstructure.

CONCLUSION

This study evaluates the effectiveness of the RB-HDRC base isolation system in improving the seismic performance of a four-story reinforced concrete building through nonlinear time-history analysis under the BSE-1E and BSE-2E earthquake levels. The results demonstrate that the implementation of RB-HDRC significantly improves the structural response by lengthening the fundamental period and reducing seismic demands.

Quantitatively, the base isolation system reduced peak base shear by approximately 48% at the BSE-1E level and 52% at the BSE-2E level, while roof acceleration decreased by about 76% and 79%, respectively. The maximum interstory drift ratio was also reduced, indicating improved deformation control in the isolated structural system. In addition, the number of plastic hinges decreased significantly, while the hysteretic behavior of the isolator enhanced the energy dissipation capacity of the structure.

Although the fixed-base model satisfies the Immediate Occupancy (IO) performance criterion, the implementation of base isolation still provides a significant reduction in seismic demand and an increased safety margin. Therefore, RB-HDRC shows strong potential as an effective strategy for improving the seismic performance, resilience, and reliability of reinforced concrete buildings subjected to strong earthquakes.

Future studies are recommended to investigate the experimental behavior of RB-HDRC isolators and evaluate their application in buildings with greater heights or different structural configurations.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support to perform the experimental and numerical study from the Indonesian National Research and Innovation Agency (BRIN) with grant number 1179/PKTS/ITS/2023 (RIIM Program).

REFERENCES

- Apostolidi, E., Dritsos, S., Giarlelis, C., Jara, J., Sutcu, F., Takeuchi, T., & White, J. (2021). Seismic Isolation and Response Control. In *Seismic Isolation and Response Control*. International Association for Bridge and Structural Engineering (IABSE). <https://doi.org/10.2749/sed019>
- Choun, Y. S., Park, J., & Choi, I. K. (2014). Effects of mechanical property variability in lead rubber bearings on the response of seismic isolation system for different ground motions. *Nuclear Engineering and Technology*, 46(5), 605–618. <https://doi.org/10.5516/NET.09.2014.718>
- Fakih, M., Hallal, J., Darwich, H., & Damerji, H. (2021). Effect of lead-rubber bearing isolators in reducing seismic damage for a high-rise building in comparison with normal shear wall system. *SDHM Structural Durability and Health Monitoring*, 15(3), 247–260. <https://doi.org/10.32604/SDHM.2021.015174>
- Fujino, Y., Siringoringo, D. M., Kikuchi, M., Kasai, K., & Kashima, T. (2019). Seismic monitoring of seismically isolated bridges and buildings in Japan—case studies and lessons learned. In *Springer Tracts in Civil Engineering* (pp. 407–447). Springer. https://doi.org/10.1007/978-3-030-13976-6_17
- Imran, I., Siringoringo, D. M., & Rainayana, S. S. (2024). Seismic evaluation and retrofit of a typical reinforced concrete hospital building in Indonesia with DCFP isolation system. *Structures*, 64. <https://doi.org/10.1016/j.istruc.2024.106593>
- Kelly, J. M. (1999). *The role of damping in seismic isolation*. *Earthquake Engineering & Structural Dynamics*, 28(1), 3–20. [https://doi.org/10.1002/\(SICI\)1096-9845\(199901\)28:1](https://doi.org/10.1002/(SICI)1096-9845(199901)28:1)
- Makris, N. (2019). Seismic isolation: Early history. In *Earthquake Engineering and Structural Dynamics* (Vol. 48, Number 2, pp. 269–283). John Wiley and Sons Ltd. <https://doi.org/10.1002/eqe.3124>
- Nasional, B. S. (2012). *SNI 1726-2012 Tata cara perencanaan ketahanan gempa untuk struktur bangunan gedung dan non gedung*. www.bsn.go.id
- Nasional, B. S. (2013). *Persyaratan beton struktural untuk bangunan gedung Badan Standardisasi Nasional*. www.bsn.go.id
- Nasional, B. S. (2019). *SNI 2847-2019 Persyaratan Beton Struktural Untuk Bangunan Gedung dan penjelasan*.
- Nasional, B. S. (2019). *SNI 1726-2019 Persyaratan Beton Struktural Untuk Bangunan Gedung*.
- Pianese, G., Habieb, A. B., Losanno, D., & Milani, G. (2025). *Numerical investigation of high-damping rubber cores to enhance the damping performance of elastomeric seismic isolators RB-HDRC*.
- Pianese, G., Van Engelen, N., Tait, M., & Milani, G. (2024). Shake table tests on a rigid block isolated with high-damping unbonded fiber-reinforced elastomeric isolators. *Structures*, 64. <https://doi.org/10.1016/j.istruc.2024.106595>
- Pianese, G., Van Engelen, N., Toopchi-Nezhad, H., & Milani, G. (2024a). An experimental and numerical insight into the unbonded and partially bonded high-damping fiber-reinforced elastomeric isolators. *Soil Dynamics and Earthquake Engineering*, 187. <https://doi.org/10.1016/j.soildyn.2024.109016>

- Pianese, G., Van Engelen, N., Toopchi-Nezhad, H., & Milani, G. (2024b). High-damping fiber-reinforced elastomeric seismic isolator in different boundary conditions: An experimental insight. *Engineering Structures*, 300. <https://doi.org/10.1016/j.engstruct.2023.117199>
- Pohl, H. R., Ingber, S. Z., & Abadin, H. G. (2017). Historical view on lead: Guidelines and regulations. In *Lead: Its Effects on Environment and Health* (Vol. 17, pp. 435–470). Walter de Gruyter GmbH. <https://doi.org/10.1515/9783110434330-013>
- Robinson, W. H. (1982). Lead-Rubber Hysteretic Bearings Suitable for Protecting Structures During Earthquakes. In *Earthquake Engineering and Structural Dynamics* (Vol. 10).
- American Society of Civil Engineers. (2017). *Seismic Evaluation and Retrofit of Existing Buildings* (ASCE 41-17). American Society of Civil Engineers. <https://doi.org/https://doi.org/10.1061/9780784414859>
- Sheikh, H., Van Engelen, N. C., & Ruparathna, R. (2022). A review of base isolation systems with adaptive characteristics. In *Structures* (Vol. 38, pp. 1542–1555). Elsevier Ltd. <https://doi.org/10.1016/j.istruc.2022.02.067>
- Tim Pusat Studi Gempa Nasional. (2022). *Peta Deagregasi Bahaya Gempa Indonesia untuk Perencanaan dan Evaluasi Infrastruktur Tahan Gempa*.