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Earthquake Resilience in Low-Rise Concrete Buildings: A Study on the Effectiveness of Base Isolators

Riza Suwondo [a,*], Dawson Susanto [a], Made Suangga [a], Mohammed Sohaib Alama [b]

[a] *Civil Engineering Department, Faculty of Engineering, Bina Nusantara University, Jakarta, Indonesia*
[b] *Civil Engineering Department, Faculty of Engineering, King Abdulaziz University, Saudi Arabia*
*Corresponding author: *riza.suwondo@binus.ac.id*

***Abstract*—Earthquakes pose significant challenges worldwide, causing severe structural damage, loss of life, and socioeconomic disruptions. To mitigate seismic effects, base isolators have emerged as an effective design strategy for reducing structural damage by decoupling buildings from ground motion. This study investigates the seismic performance of a low-rise concrete building equipped with base isolators, focusing on the influence of isolator mass, stiffness, and damping ratio on key structural responses, including the base shear, natural period, and inelastic storey drift. A symmetric three-storey building was analysed using linear time-history analysis. The ground motions were scaled according to the Indonesian Seismic Code (SNI 1726:2019) to reflect local seismic hazards. Base isolators were modelled as joint springs, and variations in mass (15, 30, and 45 kN), stiffness (1500, 3000, and 4500 kN/m), and damping ratios (20%, 30%, and 40%) were systematically evaluated. The results reveal that increasing the stiffness of the base isolators significantly increases the base shear and inelastic storey drift, whereas higher damping ratios effectively reduce both parameters. Variations in the isolator mass have a minimal impact on the structural response. Additionally, the natural period of the building remained constant across different damping ratios, highlighting the dominant role of the mass and stiffness in the period determination. These findings emphasise the importance of optimising isolator properties to balance seismic performance and structural safety. This study provides critical insights into the design of base-isolated buildings and offers a valuable reference for enhancing the resilience and safety of structures in earthquake-prone regions.**

***Keywords*—Seismic performance; base isolator; low-rise concrete building; damping ratio stiffness.**

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I. INTRODUCTION

Earthquakes are among the most destructive natural hazards, resulting in significant loss of life, extensive structural damage, and substantial socio-economic impact. Although preventing seismic events is impossible, structural engineers must focus on strategies to mitigate their effects. One approach is to enhance the structural capacity and ductility of buildings, whereas the other involves reducing the seismic demand of structures [1]–[5]. The latter can be effectively achieved through the implementation of base isolation systems, which reduce earthquake-induced damage by decoupling buildings from ground motions [6]–[8].

Seismic isolation systems are designed to reduce structural damage during earthquakes by limiting the transmission of lateral forces to the superstructure through isolators installed at the foundation level. These base isolation devices operate by extending the natural period of a building via increased horizontal movement at the base[9]–[12]. This prolonged period results in a decrease in the magnitude of the spectral accelerations generated by the earthquake, thereby minimizing the destructive impact of the earthquake as much as possible[13]–[17]. In addition, base isolation systems can diminish the effects of seismic amplification caused by near-fault pulses and address irregularities in structural design, such as in-plane and vertical irregularities [18]–[21].

The seismic performance of buildings equipped with base isolators has been extensively researched, particularly to understand how isolators mitigate seismic forces and protect structural integrity. Khosnudian and Motamedi [22] investigated this by analyzing a four-storey building with varying eccentricities supported by elastomeric isolators with different vibration periods and damping ratios. Their analysis utilized three distinct earthquake records to assess the impact of vertical seismic components on asymmetric steel-isolated structures. The key finding of this study was the pronounced effect of vertical ground motions on the axial forces, column uplift, overturning moments, and beam shear forces. While their model included nonlinear rubber isolators and a linear elastic superstructure, their focus on vertical forces provided a critical lens for understanding how low-rise buildings might behave under similar conditions.

Jalali et al.[23] analyzed the seismic performance of steel concentrically braced frames equipped with double friction pendulum bearings, focusing on two ductility levels. This study compares the responses of base-isolated buildings to their fixed-base counterparts. The results revealed that ductility levels play a critical role in influencing seismic responses. Superstructures with a special ductility level demonstrated a significant reduction in the peak floor acceleration, achieving a maximum reduction of approximately 20% compared to those with ordinary ductility levels. However, the special ductility level also led to an increase in the peak drift demand, with an observed increase of up to 75% in the base-isolated buildings. This highlights the trade-off between reduced acceleration and increased drift demand in seismic design.

Nawaz et al.[24] proposed a cost-effective base-isolation technique designed for masonry structures, emphasizing practicality and affordability. This study focuses on evaluating the use of unreinforced rubber as a seismic isolator. To assess its effectiveness, experimental tests were conducted to analyze the dynamic characteristics of the unreinforced elastomeric isolator. The findings demonstrated a substantial reduction in seismic responses, particularly roof acceleration. These results suggest that the proposed isolator offers a promising, low-cost solution for seismic isolation in low-rise buildings, particularly in developing countries.

Ziraoui et al.[25] investigated the effectiveness of base isolation systems, specifically those using Lead Rubber Bearings (LRB), in reducing seismic responses in multi-storey buildings. Their study highlighted the significant role of LRB isolators in enhancing the seismic performance of a building. By incorporating LRB isolators at the base, this method demonstrated a substantial reduction in seismic-induced floor drifts, which is a critical parameter for maintaining structural safety during earthquakes. The findings revealed that base isolation systems can effectively reduce the overall seismic responses by 50% to 70%, showcasing their potential to improve the resilience and stability of buildings in earthquake-prone regions.

A major factor influencing the efficiency of base isolation systems is the properties of the isolators, including the stiffness and damping ratios. Falborski and Jankowski [26] examined the effectiveness of polymer-based isolators for mitigating vibrations in asymmetric structures during seismic events. Through a dynamic analysis, they found that polymer supports significantly reduced structural damage, highlighting the potential of such materials in improving seismic resilience. However, their study concentrated on asymmetric structures, and while polymer isolators were effective, their application in low-rise regular concrete buildings remains unexplored. Your research will fill this gap by focusing on how various isolator properties, including stiffness and damping, impact the seismic behavior of low-rise concrete buildings. Similarly, Mahamied et al. [27] investigated the effects of pulse-like earthquake characteristics on low-rise, irregular, base-isolated reinforced-concrete buildings. Their study examined the efficiency of lead rubber bearing (LRB) isolators with varying damping ratios and found that both isolator properties and vertical irregularities played significant roles in the performance of the structures. Notably, pulse-like ground motions exacerbated the seismic response, suggesting that isolator damping was critical in such scenarios. This study closely aligns with your research focus on isolator damping and mass in low-rise buildings, reinforcing the importance of isolator properties in mitigating seismic damage.

Eccentricity and torsional effects present challenges in base-isolated buildings, particularly in asymmetric structures. Etedali and Sohrabi [28] proposed a method for reducing torsion in asymmetric isolated structures during earthquakes, demonstrating that base isolators could reduce storey rotations, though this effect was minimal at higher eccentricity levels. Their findings suggest that, while base isolators help mitigate torsion, they are less effective in highly eccentric structures. This underscores the importance of examining how torsion might manifest in low-rise symmetric concrete buildings, where isolators could potentially perform more efficiently owing to the lower inherent eccentricity of such structures.

Another critical factor in the seismic performance of base-isolated structures is the soil-structure interaction (SSI), which can significantly affect the overall response of the building. Luco [29] investigated the effects of SSI on a nonlinear seismic isolation system by using a simplified elastic model. The study revealed that incorporating SSI resulted in a greater seismic response compared with models that neglected these interactions. While Luco's research is primarily theoretical and focused on simplified elastic models, it highlights the need for more complex analysis in base-isolated systems where SSI might exacerbate seismic forces.

Although the reviewed studies offer valuable insights into the behavior of base-isolated structures, several gaps remain, particularly concerning low-rise concrete buildings. Most research focuses on high-rise structures or buildings with significant eccentricities, leaving low-rise, symmetric buildings underexplored. Furthermore, while the effectiveness of base isolators in reducing seismic forces is well documented, less attention has been paid to how specific isolator properties, such as mass, stiffness, and damping, affect the performance of low-rise structures. This gap in literature underscores the need for research aimed at exploring the seismic performance of low-rise concrete buildings equipped with base isolators, with a specific focus on isolator properties and their ability to mitigate seismic damage. Thus, the primary objective of this research is to investigate the seismic performance of low-rise concrete buildings equipped with base isolators to address the gaps identified in current studies. Specifically, this study aims to evaluate the influence of key base isolator properties, such as mass, stiffness, and damping, on the overall structural behavior during seismic events. By comparing the response of base-isolated buildings to traditional fixed-base structures, this study seeks to assess critical structural parameters, including reductions in base shear, inter-storey drift, and natural period.

II. Material and Method

This research aims to assess the seismic performance of a base-isolated three-storey concrete building through detailed finite element analysis. The study focuses on a symmetrical building model with a uniform storey height of 4 m and three bays, each spanning 8 m, as shown in Figure 1. The symmetrical design of the building ensured a balanced analysis of seismic responses and allowed for a clear evaluation of the effectiveness of the base isolator.

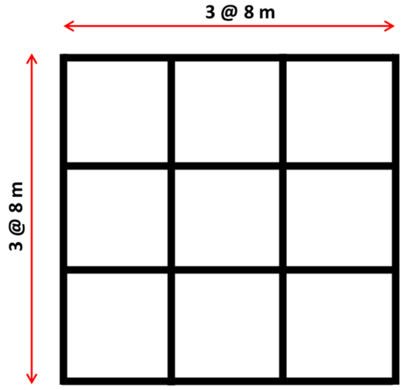

Fig. 1 Generic building plan

The design of the building incorporates various load types in accordance with Indonesian standards. Dead loads, including superimposed dead loads (SIDL), were assigned a value of 2 kN/m². Live loads were determined based on the residential occupancy criteria outlined in Indonesian Standard SNI 1727-2020[30]. For the seismic load analysis, the earthquake loads were calculated using Indonesia Standard SNI 1726-2019[31], with specific emphasis on the seismic characteristics pertinent to the Manado region. This approach ensures that the building design reflects realistic loading conditions in the targeted seismic zone.

Structural analysis was conducted using the commercial finite element software ETABS[32], which is renowned for its robust capabilities in modelling complex structural systems and performing advanced dynamic analyses. Beams and columns are modelled as beam elements which capture the axial and flexural behavior under seismic loads. Concrete slabs are discretized using shell elements. The base isolators were represented as joint springs to simulate the isolator's flexibility and damping characteristics at the base of the building. Figure 2 shows the three-dimensional finite element model.

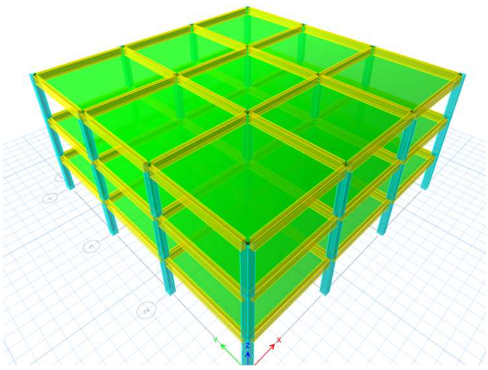

Fig. 2 ETABS 3D Model

This research employs linear time history analysis to evaluate the dynamic response of a building under seismic loading. This analysis method was chosen for its ability to capture time-dependent variations in structural responses, providing insights into the performance of the base isolation system during seismic events. The analysis utilized a set of scaled ground motion records to ensure that the seismic input reflected the intensity levels specified for the study. A suite of ground motion records scaled to represent a specific local seismic hazard was applied to the structure in both horizontal directions according to the Indonesian Seismic Code SNI 1726:2019[31]. The scaling parameters included a 0.2-second spectral acceleration (SS) of 1.125 g and a 1-second spectral acceleration (S1) of 0.574 g, with a site classification of SD indicative of stiff soil conditions. Ground motion records were meticulously selected to encompass a range of seismic event characteristics, ensuring a thorough evaluation of the seismic performance of the building across various scenarios. Each record was scaled in alignment with the seismic demand of the building to provide a consistent and realistic basis for assessing structural response, as illustrated in Figure 3.

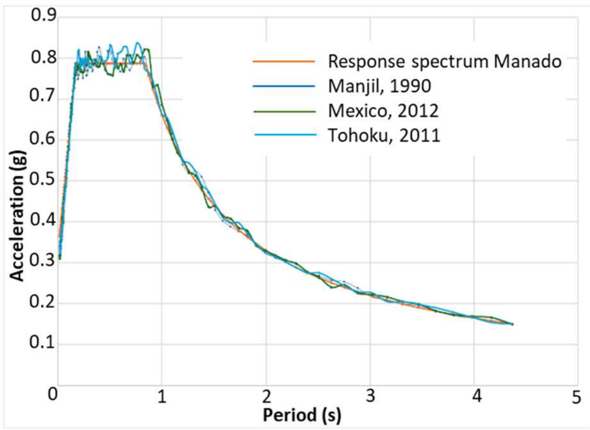

Fig. 3 Scaled ground motion

A key objective of this study is to evaluate the impact of various base isolator properties on the seismic performance of a building. This study systematically investigates variations in isolator mass, stiffness, and damping to assess their influence on critical structural responses such as base shear, storey drift, and overall building displacement. By exploring different configurations of base isolators, this study aims to identify the optimal properties that enhance seismic resilience and minimize damage to both structural and nonstructural components.

III. Results and Discussion

A. *Influence of base isolator mass*

The mass of a base isolator is a critical parameter that directly affects the dynamic behavior of a structure during seismic events. As the mass increases, the inertia of the isolator also increases, potentially influencing the overall seismic demand of the structure. In this study, the influence of three different base isolator masses (15, 30, and 45 kN) on the seismic performance of a building was analyzed.

The effect of the base isolator mass on base shear is shown in Figure 4. The base shear values show a gradual increase with an increase in the base isolator mass. Specifically, the base shear increased from 1520 kN for the 15 kN isolator to 1562 kN for the 45 kN isolator. This suggests that as the isolator mass increased, the structure experienced a marginally higher base shear, indicating a slight increase in the force transmitted through the isolator to the superstructure. This trend can be attributed to the higher inertia associated with larger isolator masses, which leads to a greater resistance to acceleration during seismic motion. However, the increase in the base shear between different isolator masses was relatively small, with a difference of only 42 kN between the lowest and highest mass values. This indicates that while the mass of the base isolator influences the seismic response, the effect on the base shear is not significant within the range of masses considered in this study.

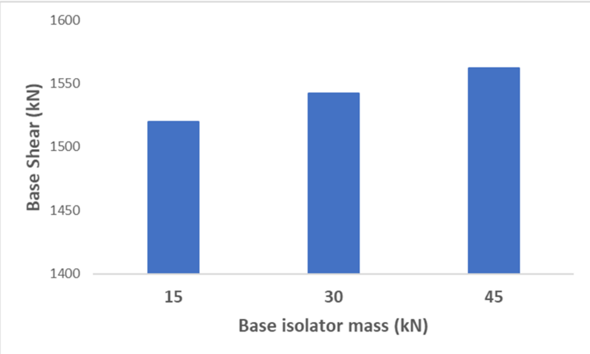

Fig. 4 Base Shear for Different Base Isolator Masses

Similarly, the building period shows a gradual increase from 1.857 seconds with a 15 kN isolator to 1.87 seconds with a 45 kN isolator as shown in Figure 5. The increase in the period is small (approximately 0.013 s across the tested masses), indicating that the added mass slightly lengthens the natural period of the building. A longer period is generally associated with reduced seismic acceleration demands, as it shifts the response of the structure away from higher-frequency ground motions. This behaviour supports the concept that heavier base isolators can offer stability by damping seismic forces more effectively, although the change is subtle in this case.

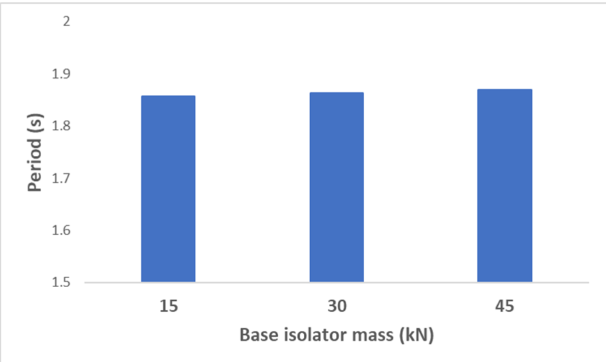

Fig. 5 Building period for Different Base Isolator Masses

Interestingly, the inelastic storey drift remained consistent across the different isolator masses, suggesting that the isolator mass did not significantly influence the lateral displacement of the building beyond its elastic range, as shown in Figure 6. This observation implies that the storey drift control provided by the base isolator system remains stable, regardless of the isolator mass variations within the range considered. In practical terms, this consistency in inelastic storey drift indicates that the deformation capacity of the building remains unaffected by changes in the isolator mass, thereby maintaining resilience against deformations during seismic events.

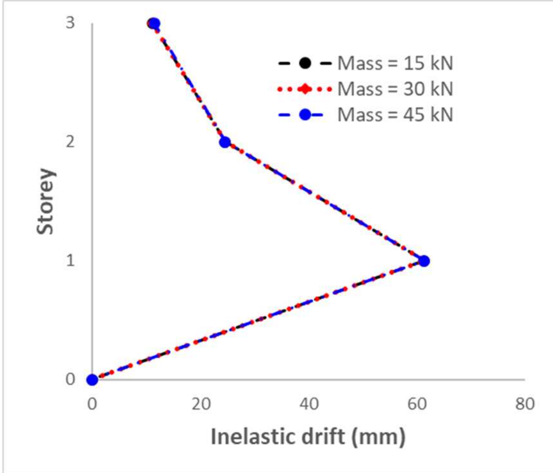

Fig. 6 Inelastic storey drift for Different Base Isolator Masses

These findings suggest that although the base isolator mass affects the base shear and building period, it has a minimal impact on the inelastic storey drift, which is a crucial parameter for assessing the structural damage potential. This insight reinforces the stability of the isolation system's performance, allowing flexibility in isolator mass selection without risking an increased lateral displacement or inelastic deformation. Consequently, optimising the base isolator mass offers an effective means of refining seismic performance while preserving drift control.

B. *Influence of base isolator stiffness*

Base isolator stiffness is a key factor influencing a building's seismic performance, particularly affecting the base shear forces and natural period of the building. To assess the influence of stiffness, three different isolator stiffness values, 1500, 3000, and 4500 kN/m, were analyzed.

Figure 7 shows the direct correlation between the stiffness of the base isolator and base shear experienced by the building. As stiffness increased from 1500 kN/m to 4500 kN/m, the base shear increased significantly from 1520 kN to 1926 kN. This increase can be attributed to the fact that stiffer isolators transfer more seismic force to the structure, resulting in a higher base shear. This finding suggests that, while increasing stiffness may enhance the structural rigidity of the isolation system, it also escalates the seismic forces acting on the building, which could increase the demand on the superstructure and its components.

In parallel, the natural period of the building decreased as the base isolator stiffness increased, as shown in Figure 8. For the isolator with a stiffness of 1500 kN/m, the building period was 1.857 s, whereas for the isolator with 4500 kN/m stiffness, the period was shortened to 1.443 s. This reduction in the natural period is expected because stiffer isolators tend to reduce the flexibility of the isolation system, causing the building to respond more quickly to seismic forces. Although this may reduce the displacement demand on the structure, the trade-off is that the building is subjected to higher accelerations, which can increase the forces transmitted to the superstructure.

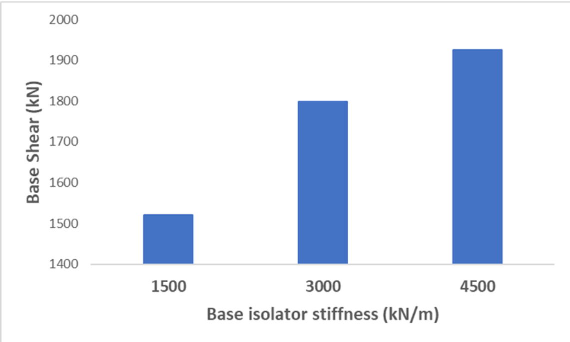

Fig. 7 Base Shear for Different Base Isolator stiffness

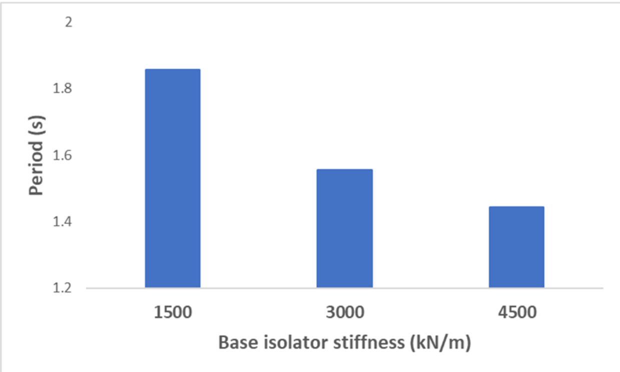

Fig. 8 Building period for Different Base Isolator Stiffness

The observed relationship between stiffness and building period highlights a crucial aspect of the base isolation design. A lower period, resulting from higher stiffness, brings the response frequency of the structure closer to that of typical ground motions, potentially amplifying the seismic demand. Therefore, selecting an appropriate isolator stiffness is critical for balancing the reduction in displacement and increase in the base shear forces.

In addition, the base isolator stiffness significantly affected the inelastic storey drift across the building height. The results for the inelastic storey drift at each storey level under varying isolator stiffness values are presented in Figure 9. As the stiffness of the base isolator increases, the inelastic drift of each storey also increases. For example, at the first-storey level, the storey drift increased from 61 mm for the 1500 kN/m isolator to 80 mm for the 4500 kN/m isolator. This trend is also consistent across the second and third stories, with the drift increasing from 24 to 31 mm on the second storey and from 11 to 14 mm on the third storey as the isolator stiffness increases.

The increase in storey drift with higher isolator stiffness can be attributed to the more rigid transfer of seismic forces through the stiffer isolators, causing larger deformations at each storey level. This phenomenon illustrates a crucial trade-off in seismic design: while a higher isolator stiffness can reduce the overall displacement of the building, it also results in increased storey drift, which can potentially impact the structural and non-structural elements of the building. In high-stiffness cases, larger inelastic storey drifts can lead to more pronounced local deformations, particularly in lower stories, which may require additional structural considerations to ensure safety and performance under seismic loading.

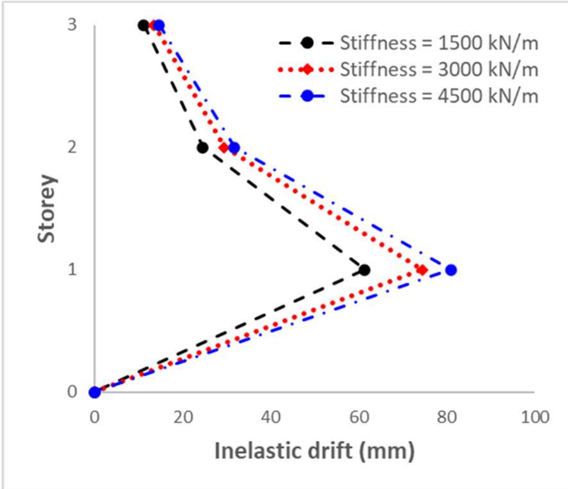

Fig. 9 Inelastic storey drift for Different Base Isolator Stiffness

C. *Influence of damping*

The damping ratio of a base isolator plays a crucial role in determining the response of a building to seismic forces, particularly in terms of reducing the base shear. Figure 10 presents the base shear values obtained for damping ratios of 20%, 30%, and 40%. As the damping ratio increases, the base shear decreases significantly. For instance, at a damping ratio of 20%, the base shear was 1520 kN. This value decreased to 1288 kN at a damping ratio of 30%, and was further reduced to 1124 kN at a damping ratio of 40%. This trend suggests that higher damping ratios allow the base isolator to dissipate more seismic energy, thereby effectively reducing the force transmitted to the upper structure.

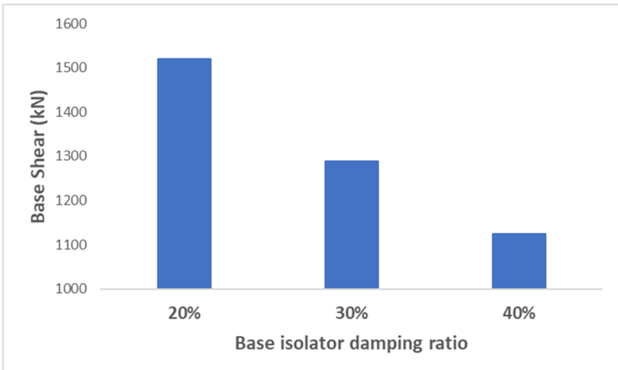

Fig. 10 Base Shear for Different Base Isolator Damping Ratio

The ability to decrease the base shear with increased damping provides valuable insights for the design of base-isolated structures, particularly in regions of high seismicity. By selecting isolators with appropriate damping properties, it is possible to achieve a substantial reduction in the seismic demand of the structure, thereby minimizing the potential for damage to structural and non-structural components.

Unlike the base shear, the natural period of the building remained constant at 1.857 s across all the tested damping ratios, as shown in Figure 11. This indicates that variations in the damping ratio do not influence the oscillation period of the building, as the period is primarily a function of mass and stiffness rather than damping. However, although the period remains unchanged, the increased damping helps control and dissipate the vibrational energy, thus moderating the intensity of the structural response under seismic loading.

In terms of the inelastic storey drift, a clear trend emerged, indicating that as the base isolator damping ratio increased, the inelastic storey drift experienced by the building decreased, as shown in Figure 12. These results indicate that higher damping ratios contribute to reduced inelastic deformations, thereby improving the capacity of a building to withstand seismic forces without incurring significant damage. The reduction in storey drift with increased damping reflects the effectiveness of damping mechanisms in controlling the response of structures during seismic events.

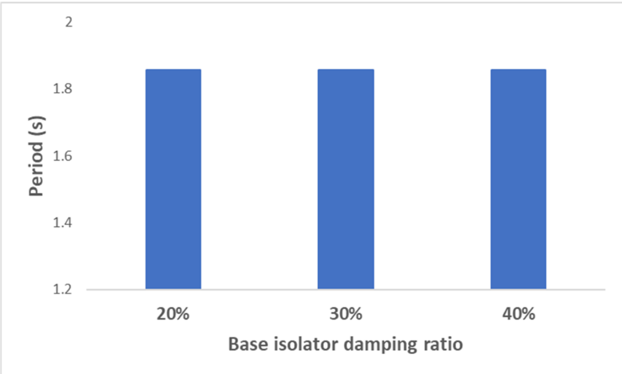

Fig. 11 Building period for Different Base Isolator Damping Ratio

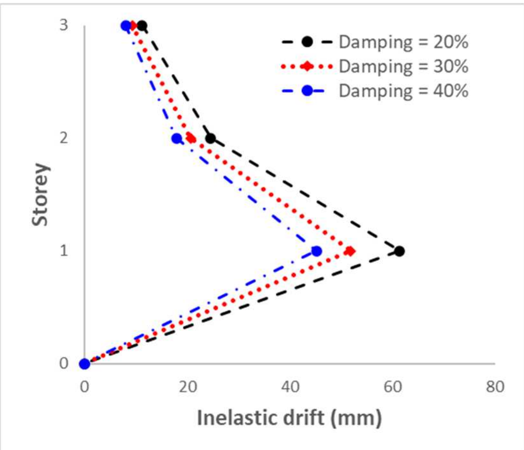

Fig. 12 Inelastic storey drift for Different Base Isolator Damping Ratio

IV. Conclusions

This study investigated the seismic performance of a three-storey building equipped with base isolators, focusing on the influence of base isolator mass, stiffness, and damping ratio. The analysis was conducted using advanced finite element modelling and linear time-history analysis. The results demonstrated that the base isolator's mass had a minor impact on the overall performance of the structure, with only slight variations in the base shear and building period observed across different isolator masses. The inelastic storey drift remained consistent, indicating that the structural behavior was largely unaffected by the changes in mass. Conversely, the base isolator stiffness has a significant influence on the seismic response of the building. As the stiffness of the isolators increased, the base shear and overall structural demands correspondingly increased. However, the inelastic storey drift also increased with higher stiffness, suggesting a complex interplay between stiffness and structural flexibility that must be carefully considered in the design.

In terms of damping ratio, it was found that higher damping ratios effectively reduced the base shear and inelastic storey drift. This reduction signifies the crucial role of damping in enhancing the seismic resilience of a structure, allowing for better control of seismic forces and minimizing damage during earthquakes. Notably, the natural period of the building was found to be unaffected by variations in the damping ratio, reinforcing the understanding that the structural period is primarily influenced by the mass and stiffness characteristics of the building, rather than the damping properties.

Overall, this research underscores the importance of optimizing base isolator properties in the design of seismically resilient structures. The findings provide valuable insights into how base isolator characteristics can be manipulated to enhance performance, ultimately informing engineers and designers in their efforts to develop safer buildings in earthquake-prone regions. Future research should explore the long-term performance of various isolator configurations and their effects on the structural integrity over multiple seismic events to further refine the design methodologies.

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Author contributions

RS: manuscript preparation; DS: Data collection and analysis; MS: reviewing and editing; MA: review and editing.

Data availability

https://zenodo.org/records/14004809

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