# A Study on the Effects of Implementing Base Isolation System for Existing RC Buildings on Soft Soil

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## Abstract

The occurrence of earthquakes is frequent in Indonesia due to its position in a highly active tectonic zone. One approach to improve the seismic performance of existing buildings is through the use of base isolation. The concept of using base isolation systems aims to increase the natural period of structures and provide additional damping to reduce seismic forces on the structures. A comparative study was performed between a fixed base system and base isolated system in a 13-story reinforced concrete building located in Surabaya on soft soil. Subsequently, these models were evaluated for their structural response using the nonlinear time history analysis. The results demonstrate that the use of base isolation systems can significantly elongate the building's natural period, resulting in a significant decrease in the base shear, acceleration response, drift, and the plastic hinge formed. This study proves that this technology is suitable to be applied to existing buildings with satisfactory results.

**Keywords**

Base isolation, lead rubber bearing, seismic protection, seismic response analysis, soft soil

## INTRODUCTION

Earthquakes frequently occur in Indonesia due to its location on the pacific ring of fire. Two major volcanic belts and three major tectonic plates between continents converging on Indonesia, causing high seismic activity [1]. The high seismic activity and earthquake potential in Indonesia is indicated by the fact that periodic changes are made to the earthquake-resistant design standard, such as the upgrade to newer standard from SNI 1726-2012 to SNI 1726-2019. Therefore, structural evaluation of an existing buildings is necessary to prevent material losses and casualties in the event of an earthquake.

Demolishing and rebuilding buildings that do not comply with new regulations will cause pollution to the surrounding environment and economically wasteful [2]. Therefore, structural retrofitting of existing buildings is an appropriate solution both economically and environmentally. An example of retrofitting method is by using steel jacketing, FRP reinforcement, or by using base isolation system [3,4,5]. Base isolation is a retrofitting methods that has undergone significant development in the last decade. This method of retrofitting has been used on the monumental San Francisco City Hall building in California. The building has stood since 1916, so it was not originally designed to withstand earthquakes [6].

The use of base isolation is one of the developments in earthquake engineering to seismically protect building from earthquakes. The concept of using base isolation is to increase the natural period of the structure and also provide additional damping, which can reduce the seismic load acting on the structure [7]. This is done by separating the structure from the foundation so that the seismic energy received by the foundation will be dampened first by the base isolation system before it reaches the structure [8]. The implementation of base isolation is capable of reducing interstory drift and lateral floor acceleration in structures, as well as reducing the amount of plastic hinge formed, resulting in a significant improvement on structural performance [9]. With these advantages, base isolation system can protect both structural and nonstructural components of building making it safer to stay inside the building in the event of an earthquake.

In general, the most common isolators can be divided into two major categories: elastomeric bearings and frictional bearings. Elastomeric bearings are made up of alternating layers of natural or synthethic rubber and steel plates, while frictional bearings consists of a sliding element with a given friction coefficient. Among these two categories, the most commonly used isolator is the lead rubber bearing (LRB), which was first used in the early 1970s on one of New Zealand's bridges [10].

LRB is an elastomeric bearing consisting of a thin layer of natural rubber with low damping and a layer of steel plates that are alternately installed with the rubber layer, as well as a lead plug that is tightly fitted in a hole in the middle. The function of the layer of rubber and steel plate is to provide high vertical stiffness so that it can support the weight of the structure. When subjected to lateral loads, the lead plug provides high elastic stiffness and when it yields, the lead plug deforms plastically, providing energy dissipation and increasing damping [11].

## RESEARCH SIGNIFICANCE

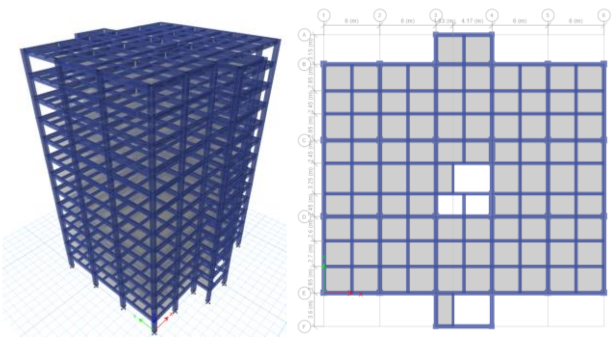
This study aims to investigate the effect of providing base isolation on the structure. The goal is to protect the existing structure to ensure that it remains safe to occupy during and earthquake.

## METHODOLOGY

This study has two main objectives, first is to evaluate the performance of the existing building structure with a conventional fixed base system. The second is retrofitting the existing buildings with the addition of a base isolation system and evaluating its performance. Gravity loads such as dead load due to self-weight (DL), additional dead load (SIDL), live load (LL) are applied to the slab and beam elements. The evaluated method uses nonlinear time-history analysis as required in Tier 3 analysis of ASCE 41-17. The observed parameters to be compared are the dynamic characteristics (natural period and modal mass participation factor), base shear, roof acceleration, roof drift ratio, interstory drift ratio, the number of plastic hinge formed, hinge condition, energy dissipation ratio.

### A. CASE STUDY

The reference building for the case study is a 48.75 m tall 13-story reinforced concrete existing building located in Surabaya. Each story has a uniform height of 3.75 m and structural configuration is as shown in Figure 1. The structure is designed as an educational facilities, which is classified as the Risk Category IV and the soil condition classified as SE (soft soil). The concrete compressive strength is 33.20 MPa and reinforcement bar tensile yield strength is 400 MPa. The structural system uses special moment resisting frame and fixed restraint at the base. The existing buildings were built in 2015 so it was designed according to SNI 1726-2012 for seismic code and SNI 2847-2013 for reinforced concrete code. Right now the newer seismic code is SNI 1726-2019 and the reinforced concrete code is SNI 2847-2019 so the existing buildings needs to be evaluated.



(a) (b)

Figure 1 Numerical modelling of existing buildings: (a) 3D view, (b) Plan view

The second model is the retrofitted buildings that utilize a base isolation system, specifically elastomeric lead rubber bearing (LRB). Two types of LRB have been selected based on the maximum vertical load on each column node, as shown in Figure 2. The process of designing the isolator follows SNI 1726-2019 section 12 and FEMA P-1051, which includes an iterative process until the difference between initial target period and the calculated period is less than 10% [12,13]. The main parameters of chosen LRB, according to the Bridgestone catalog, are shown in Table 1. These parameters include the isolator diameter ($D_B$), the lead diameter ($D_L$), the total rubber thickness (Tr), the isolator height (H), the effective stiffness ($K_{eff}$), the vertical stiffness (Kv), the effective damping ($\mathcal{E}_{eff}$), and the maximum vertical load ($P_{max}$).

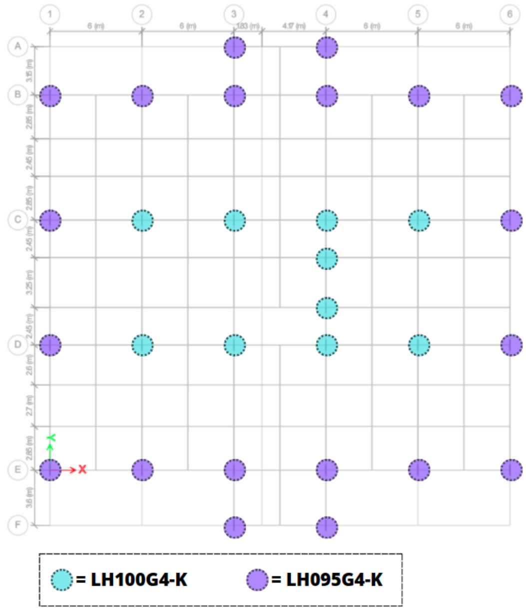



Figure 2 Isolator plan

Table 1 Characteristics of designed LRB

| Isolator Type | LH100G4-K | LH095G4-K |
|---|---|---|
| $D_B$ (mm) | 1000 | 950 |
| $D_L$ (mm) | 250 | 240 |
| $T_r$ (mm) | 201 | 198 |
| H (mm) | 400.6 | 402.4 |
| $K_{eff}$ (kN/m) | 1391.81 | 1276.04 |
| $K_v$ (kN/m) | 4610000 | 4210000 |
| $\mathcal{E}_{eff}$ (%) | 30% | 30% |
| $P_{max}$ (kN) | 9454.81 | 8110.73 |

### B. PERFORMANCE OBJECTIVES

Evaluating the structural performance is necessary to determine the performance objectives for ensuring structural safety during an earthquake. The basic performance objective is determined based on the building risk category and seismic hazard level, as per ASCE 41-17 Chapter 2 [14]. Since the existing buildings is in risk category IV, the targeted performance levels are Immediate Occupancy (IO) at the BSE-1E seismic hazard level (225-year return period earthquake) and Life Safety at the BSE-2E seismic hazard level (975-year return period earthquake). The acceptance criteria for structural performance levels can be determined in two ways: global performance (roof drift ratio) and local performance (element plastic rotation ratio).

Table 2 Selected Ground Motion Records

| Mechanism | Unique Code | Direction | Earthquake Events | Magnitude (M) | Distance ($R_{RUP}$) | PGA (g) | Duration (s) |
|---|---|---|---|---|---|---|---|
| Shallow Crustal | MEN360 | X | Loma Prieta, California 1989 | 6.93 | 45.58 | 0.11 | 30.09 |
| | MEN270 | Y | | | | 0.12 | |
| | MYG007EW | X | Iwate, Japan 2008 | 6.9 | 45.55 | 0.13 | 47.22 |
| | MYG007NS | Y | | | | 0.13 | |
| Megathrust | SZOH42W2 | X | Tohoku, Japan 2011 | 9.12 | 202.99 | 0.06 | 180.00 |
| | SZOH42S2 | Y | | | | 0.07 | |

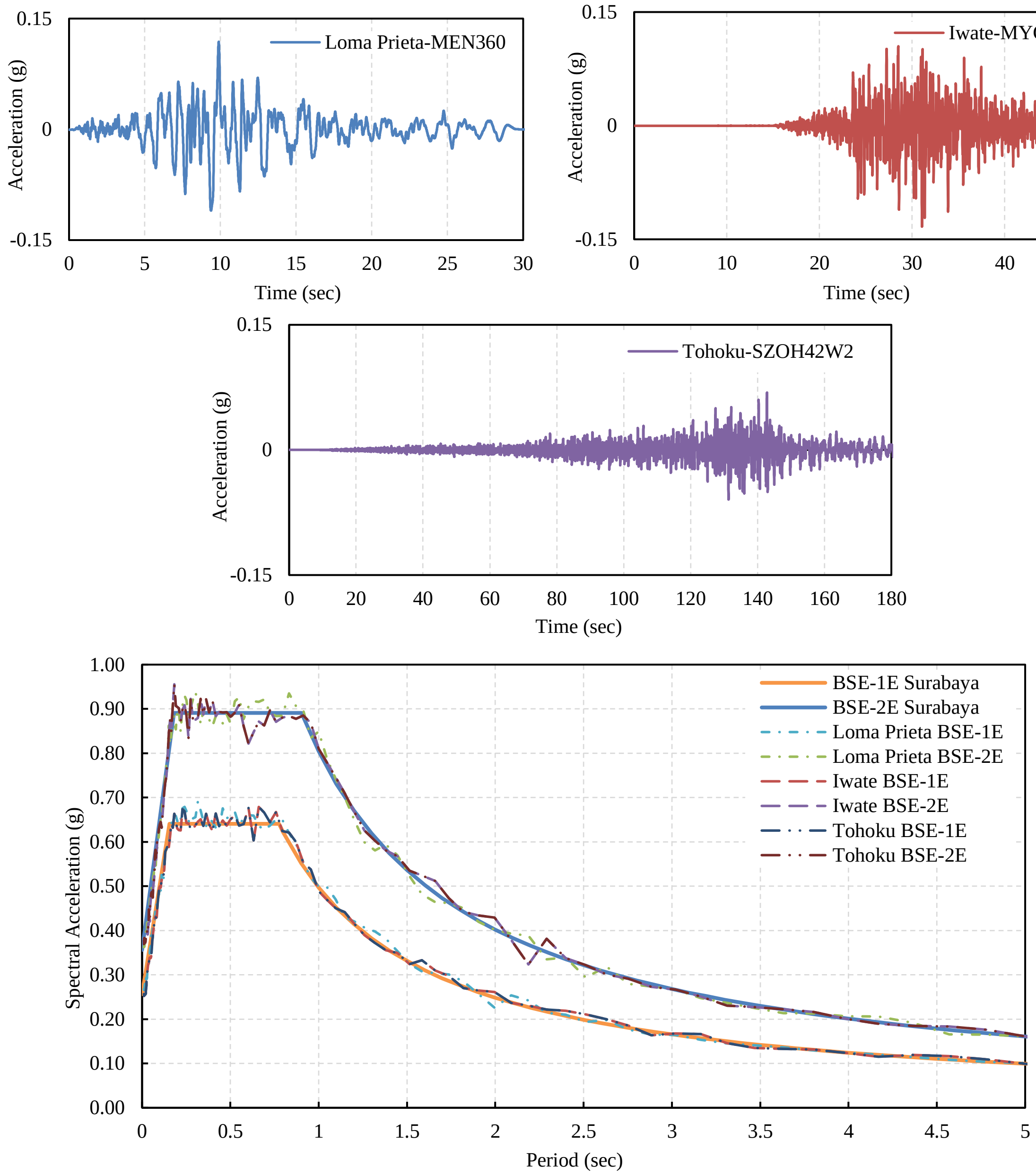



Figure 3 Spectrally matched ground motion records used for nonlinear time-history analysis: (a) Original accelerogram of three historical ground motion (b) Acceleration response spectra of the three ground motions matched to BSE-1E and BSE-2E level

## C. GROUND MOTION SELECTION

A seismic hazard deaggregation shall be conducted to obtain the Magnitude (M), the epicentrum depth ($R_{RUP}$), and the source mechanism of ground motion records representing the study location. Surabaya is located on the Baribis-Kendeng fault, so the senses mechanism are Reverse-slip [1]. The deaggregation process is carried out for both 225 and 975-year return period earthquakes. Table 2 shows three pairs of selected ground motion and their characteristics. The selected ground motion is then scaled to the targeted response spectra for Surabaya city with a 5% damping ratio for 225 and 975-year return period earthquakes, as shown in Figure 3. The ground motions is applied in X and Y direction, which are directions perpendicular and parallel to the building plan.

## RESULTS AND DISCUSSIONS

The results of the structural response from nonlinear time history analysis, which was peformed for the two structural models subjected to three pairs of ground motion, have been obtained. The values to be compared based on the maximum from three pairs of ground motion. The models are based on a fixed base and a base isolation system.

### A. DYNAMIC CHARACTERISTICS

The dynamic characteristics of the structures observed are natural period and modal mass participation factor. Table 3 shows that the retrofitted buildings effectively lengthen the natural periode two times in the first 3 modes. The advantage of longer natural period of structure is avoiding the predominant periods of earthquake, thus reducing the seismic load acting on structure. The mass participation value of the retrofitted buildings is already reached nearly 100% makes it the mode shape of the structures is dominant on the first 3 modes. The reduction in the contribution of higher modes causes the dynamic characteristics of the structure to improve because the influence of higher modes that produce irregular responses can be ignored.

Table 3 Comparison of the dynamic characteristics

| Dynamic Characteristics | | Fixed Base | Base Isolated |
|---|---|---|---|
| Period | Mode 1 | 1.801 | 3.857 |
| | Mode 2 | 1.778 | 3.851 |
| | Mode 3 | 1.660 | 3.603 |
| Mass Participation SumUX | Mode 1 | 0.06% | 7.81% |
| | Mode 2 | 79.86% | 98.98% |
| | Mode 3 | 79.91% | 99.16% |
| Mass Participation SumUY | Mode 1 | 76.67% | 89.27% |
| | Mode 2 | 76.75% | 97.25% |
| | Mode 3 | 79.13% | 99.09% |

### B. BASE SHEAR

Figure 4 and Figure 5 shows the comparisons of the peak base shear force in different earthquake return period. The maximum value for fixed base and base isolated at BSE-1E level are 22794.81 kN and 12665.69 kN, respectively, as shown in Figure 4. This gives the reduction of 44% with the addition of base isolator. For BSE-2E level, the maximum value for fixed base and base isolated are 26681.88 kN and 17832.98 kN, respectively, as shown in Figure 5. This gives the reduction of 33% with the addition of base isolation. The base shear force reduction occurs due to the lengthening of the natural period of structures, resulting in smaller seismic acceleration. The decreasing reduction of base shear with an increase of seismic load is because the effectiveness of the base isolation decreases when it is in a plastic state.

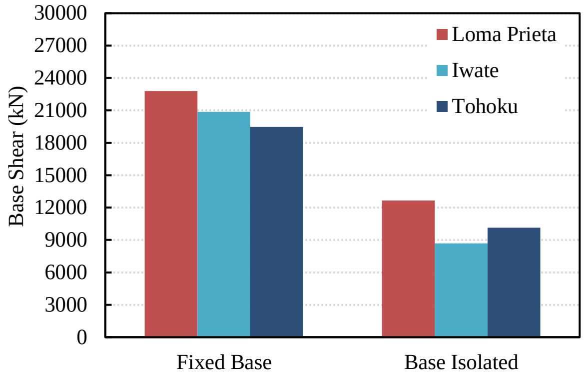



Figure 4 Comparison of base shear in BSE-1E level

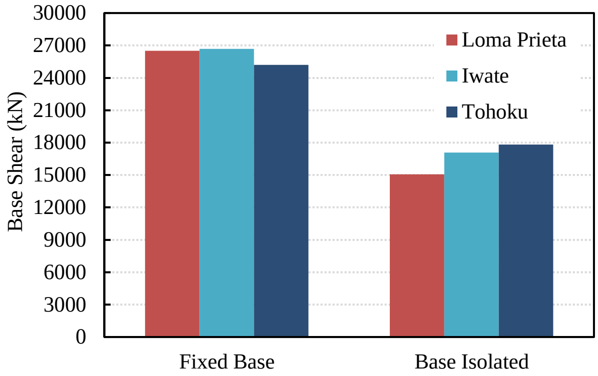



Figure 5 Comparison of base shear in BSE-2E level

### C. ROOF ACCELERATION

The roof acceleration is a critical factor in ensuring serviceability during an earthquake, as it prevents nonstructural component posing a hazard to occupants. The maximum value for fixed base and base isolated at the BSE-1E level are 0.53 g and 0.30 g, respectively, as shown in Figure 6. This gives the reduction of 45% with the addition of base isolator. At the BSE-2E level, the maximum value for fixed base and base isolated models are 0.60 g and 0.44 g, respectively, as shown in Figure 7. This gives the reduction of 28% with the addition of base isolation. The isolation system produces a lower stiffness with high damping in the base, causing a decrease in the story acceleration transmitted to the structure [15].

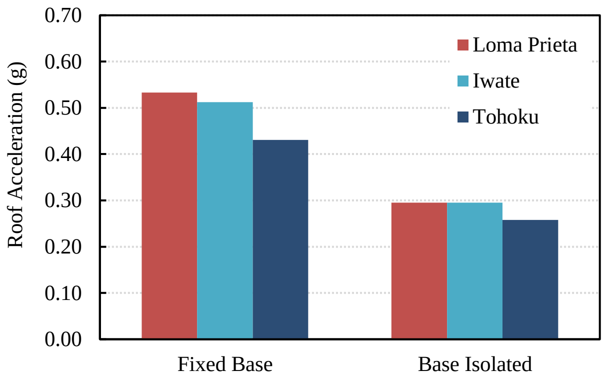



Figure 6 Comparison of roof acceleration in BSE-1E level

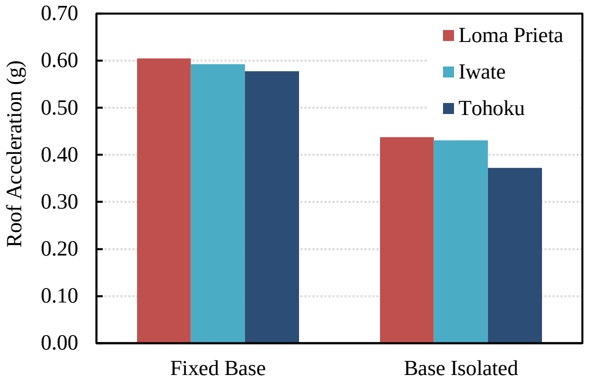



Figure 7 Comparison of roof acceleration in BSE-2E level

## D. ROOF DRIFT RATIO

The global performance levels of the structure are determined based on roof drift ratio values, which are obtained by dividing the total displacement at the roof level by the total height of the structure. The roof drift limits are set according to FEMA 356 Chapter 1.5.1 [16]. Figure 8 shows the maximum value of roof drift ratio is 0.63% for fixed base and 0.66% for base isolated. Figure 9 shows the maximum value of roof drift ratio is 1.03% for fixed base and 1.01% for base isolated. These results indicate that the installation of base isolation did not reduce the roof drift. At the BSE-1E level, both models have a global performance of Operational (<IO) because the roof drift value is still under the IO limit of 1%. At the BSE-2E level, both models have a global performance of Damage Control (IO-LS) because the roof drift values is still under the LS limit of 2%. It can be concluded that both models have satisfied the targeted performance level at BSE-1E seismic level (<IO limit) and BSE-2E seismic level (<LS limit).

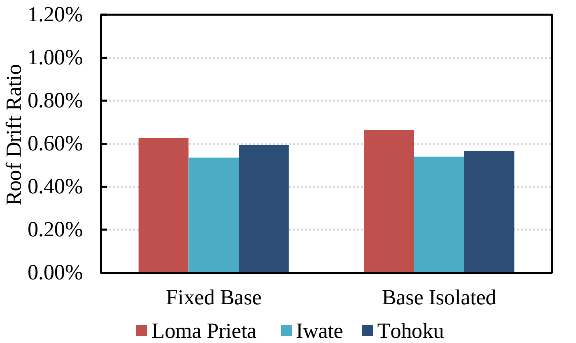



Figure 8 Comparison of roof drift ratio in BSE-1E level

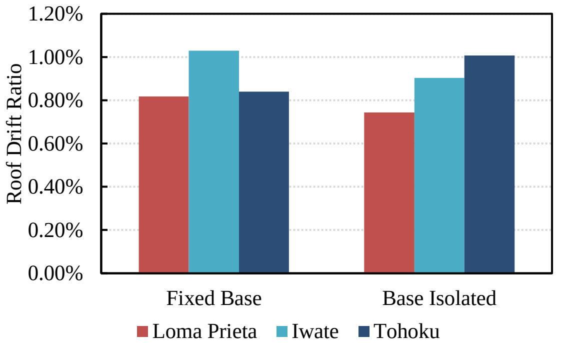



Figure 9 Comparison of roof drift ratio in BSE-2E level

## E. INTERSTORY DRIFT RATIO

Interstory drift ratio is defined as the relative horizontal displacement between two consecutive floors divided by the story height. Figure 10 shows the fixed base models have maximum drift values of 0.99% at the height of 11.25 m, which is still under the 1% IO limit. The base isolated models have maximum drift values of 1.10% at the height of 3.75 m, which exceeds the IO limit. The average drift value of the fixed base model is 0.68% and the base isolated model is 0.46%, indicating a 33% drift reduction at the BSE-1E level. Figure 11 shows that the fixed base models have maximum drift values of 1.48% at the height of 15 m, while the base isolated models have maximum drift values of 1.57% at the height of 3.75 m. The average drift value of the fixed base model in all stories is 1.03%, while that of the base isolated model is 0.52%, indicating a 23% drift reduction at the BSE-2E level. The fixed base model met the targeted performance levels in both seismic levels, while the base isolated model still has not met the targeted performance levels of BSE-1E. These results clearly indicate that the addition of base isolation reduces the interstory drift, resulting in smaller inertia force on the structure. It can be noticed from Figure 10 and Figure 11, the base isolation model has a higher interstory drift ratio compared to the fixed base model on the first floor, which significantly reduces starting on the next floor. The concerning issue is at the BSE-1E level, where it exceeds the IO limit, resulting in not meeting the targeted performance levels. This problem can be solved by increasing the structural stiffness at the first floor, such as using steel bracing, which has been proven to reduce interstory drift [17].

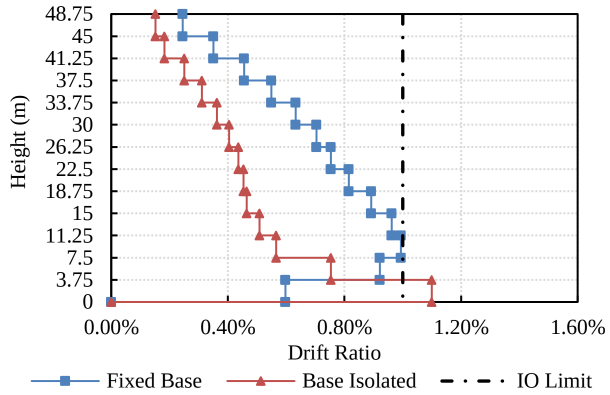



Figure 10 Comparison of interstory drift in BSE-1E level

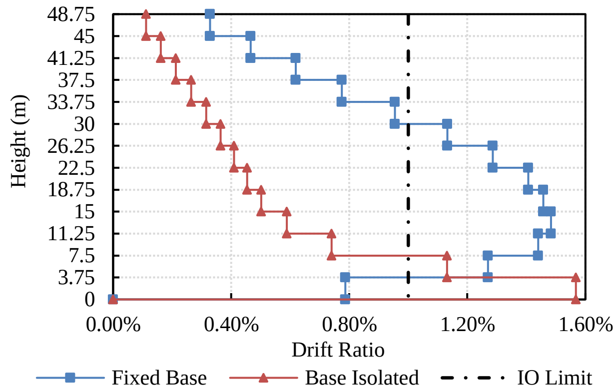



Figure 11 Comparison of interstory drift in BSE-2E level

F. NUMBER OF PLASTIC HINGES FORMED

The number of plastic hinges observed is hinges when it exceeds the yield rotation limit of structural members. Hinge analysis is performed on all structural elements, which includes a total of 1196 beams and 780 columns. Figure 12 and Figure 13 shows the comparisons of the total number of plastic hinges formed in different earthquake return period. At the BSE-1E level, the fixed base and base isolated models formed 871 and 156 plastic hinges, respectively, as shown in Figure 12. This indicates an 82% reduction in the number of plastic hinges formed with the addition of a base isolation. At the BSE-2E level, the fixed base and base isolated models formed 1143 and 471 plastic hinges, respectively, as shown in Figure 13. This indicates a 59% reduction in the number of plastic hinges formed with the addition of a base isolation. These results clearly show that the base isolation significantly reduces the number of damaged structural elements in the structure.

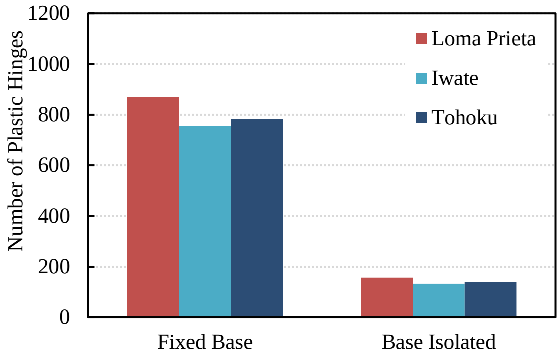



Figure 12 Comparison of number of plastic hinges formed in BSE-1E level

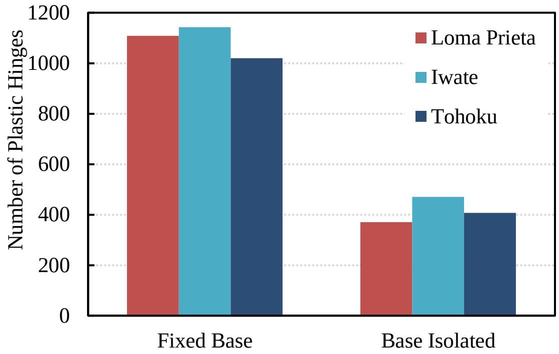



Figure 13 Comparison of number of plastic hinges formed in BSE-2E level

G. HINGE CONDITION

The local performance levels of the structure are determined based on hinge condition, which is obtained by dividing the member rotation subjected to loading by the rotation limit. The nonlinear parameters of the hinges are defined using an empirical method based on ASCE 41-17. All the most critical hinge condition values are based on columns because the existing structure ignores the detailing requirements specified in the reinforcement concrete code and the development of regulations that require stricter detailing than the previous version. Table 4 shows that at the BSE-1E level, the fixed base model did not meet the targeted performance of IO level because the hinge condition of some columns exceeded the CP level, with the most critical hinge condition being 829 CP. The addition of base isolation made the structure at the BSE-1E level meet the targeted performance, with the most critical hinge condition being 0.93 IO. The hinge condition for the fixed base model at the BSE-2E level was the same as BSE-1E level, and it worsened with the increase of seismic load. After the installation of base isolation, the structures met the targeted performance LS level with the most critical hinge condition being 0.85 LS.

Table 4 Comparison of the most critical hinge condition in both seismic level

| Parameter | Eathquake Event | Fixed Base | Base Isolated |
|---|---|---|---|
| BSE-1E Level | Loma Prieta | 829 CP | 0.93 IO |
| | Iwate | 745.02 CP | 0.88 IO |
| | Tohoku | 122.15 CP | 0.72 IO |
| | Maximum | 829 CP | 0.93 IO |
| BSE-2E Level | Loma Prieta | 10689.12 CP | 0.85 LS |
| | Iwate | 11395.45 CP | 0.81 LS |
| | Tohoku | 5735.84 CP | 0.68 LS |
| | Maximum | 11395.45 CP | 0.85 LS |

H. ENERGY DISSIPATION

Energy dissipation is the ability of a structure to absorb and dissipate the energy generated during an earthquake. The energy dissipation value is obtained by dividing the damped energy and the input energy. At the BSE-1E level, the minimum energy dissipation values for fixed base and base isolated models are 25.29% and 55.59%, respectively, as shown in Figure 14. This indicates a 30.30% increase in energy dissipation with the addition of base isolation. At the BSE-2E level, the minimum energy dissipation values for fixed base and base isolated models are 16.56% and 51.16%, respectively, as shown in Figure 15. This indicates a 34.60% increase in energy dissipation with the addition of base isolation. According to Figure 14 and Figure 15, an increase in seismic loads decreases the energy dissipation capabilites of the structures and isolators. The results evidently indicate that the absorbed energy significantly increase with the lengthening natural period effect from isolators, leading to a smaller seismic load received by the structure.

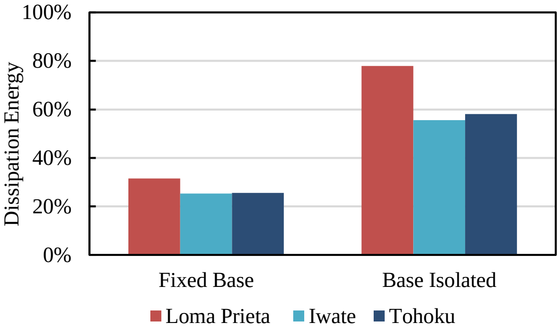



Figure 14 Comparison of dissipation energy in BSE-1E level

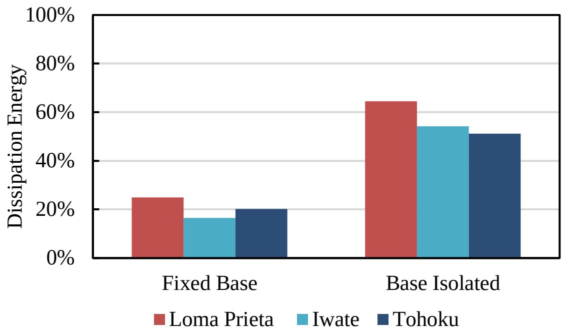



Figure 15 Comparison of dissipation energy in BSE-2E level

## CONCLUSIONS

This study has provided a comparation of seismic response of an existing building and the retrofitted building with the addition of base isolation system. Based on the obtained results from a series of nonlinear time history analyses, the following conclusions can be drawn:

1. The performance levels of fixed base at both the BSE-1E level and BSE-2E level are Not Considered (>CP). The existing buildings have not met the targeted performance level of IO and LS at the BSE-1E level and BSE-2E level, respectively. Therefore, a structural retrofitting is carried out to enhance the structural performance of existing buildings.
2. Results show that the base isolation retrofitting method is suitable for existing buildings, as the performance levels of the base isolated model are IO and LS at the BSE-1E and BSE-2E levels, respectively, meeting the targeted performance levels.
3. Base isolated models lengthen the natural period of a structure, resulting in a significant decrease in the base shear, roof acceleration, roof drift ratio, interstory drift ratio, the number of plastic hinge formed, and the hinge condition. This is due to the improved dissipation energy capabilities of the structures.

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