# Base Isolation for Earthquake Protection of Structures Considering Ethiopian Standard

**Daniel H. Zelleke[1, *] and Vasant A. Matsagar[2]**

[1, *] *Department of Civil Engineering, Haramaya Institute of Technology, Haramaya University, Haramaya, Ethiopia.*
[2] *Department of Civil Engineering, Indian Institute of Technology- Delhi, India.*
[*] *Corresponding Author's E-mail Address: E-mail address: daniel.habtamu@alumni.iitd.ac.in*

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## ABSTRACT

*An increase in construction activities and recent advances in structural engineering necessitated the major revision of the Ethiopian Building Code Standard (EBCS), published in* 1995*. The updated building code has introduced improved earthquake-resistant design considerations, including provisions for base-isolated (BI) structures. This study investigates the efficacy of the base isolation technique in earthquake protection of buildings considering Ethiopian standard. Moreover, the validity of the specific provisions of the Ethiopian seismic standard, i.e., Ethiopian Standard European Norm, (ES EN* 1998-1*:*2015) *on the choice of base isolator properties for analysis and design is investigated. Non-linear dynamic response history analyses of multi-story BI buildings are performed under synthetic earthquakes, matching with the response spectrum of the Ethiopian standard. Furthermore, the vibration response of fixed-base building models is reported for comparison. Four structural response quantities, i.e., the floor acceleration, base shear, inter-story drift, and isolator displacement, are studied. The findings demonstrate that the application of the base isolation technique reduces the dynamic response of multi-story buildings substantially. In addition, it is shown that some of the Ethiopian seismic standard provisions on isolator parameter consideration are not in logical agreement with the earthquake behavior of BI buildings observed in the current study.*

**Keywords:** Base isolation; Design response spectrum, Earthquake; EBCS, Ethiopian standard.

## 1. INTRODUCTION

The design and construction of structures in Ethiopia were governed by a building code issued in 1995, namely the Ethiopian Building Code Standard (EBCS), up to 2015. Since 1995, a vast amount of knowledge has come into picture in areas of civil engineering. Notable recent advances in the area include the improvement of knowledge about earthquakes and their effect on structures. These advances resulted in the revision of many international building codes. Our awareness of earthquakes around the East African region has also increased significantly [1, 2]. The presence of the East African Rift and data gained from the recent seismic events in the region has rendered the zone earthquake-prone. The 1983 Hawassa, 1985 Langano, 1989 Afar, 2002 Mekelle, 2009 Ankober, 2010 Hosanna, 2011 Yirgalem, 2011 Jinka, 2014 Asayta, and 2016 Hawassa earthquakes, which damaged buildings and injured many, are noteworthy. In light of this, researchers [3 - 5] raised their concerns regarding the adequacy of the seismic provisions stipulated in EBCS 8, 1995 [6] in accounting for the effect of earthquakes in the region. Furthermore, the researchers recommended the revision of the seismic design standard. It is also advocated that an updated design earthquake loading be introduced in the revised building code. For instance, it is suggested to: (a) use a return period of 475 years instead of the 100 years return period adopted in EBCS 8, (b) implement the recent worldwide seismicity data (map) published by the Global Seismic Hazard Assessment Program, GSHAP, and (c) adopt the new six site class system to account for site amplification effects properly [3 - 5].

Due to the concerns raised in light of the recent technological advances in structural engineering, the Ethiopian building standard has been revised. Several earthquakes have also occurred in Ethiopia since the revision of the Ethiopian seismic design standard. The latest notable seismic events include 18 earthquakes with magnitudes of more than five that occurred in various parts of Ethiopia between January 2024 and March 2025 [7]. Some of these frequent events have caused substantial damage to structures, which further justifies the efforts to install enhanced seismic provisions in the relevant seismic design standard.

A notable enhancement in the revised Ethiopian seismic design standard, i.e., Ethiopian Standard European Norm, (ES EN 1998-1:2015 2015) [8] is the inclusion of provisions for the protection of structures using base isolation. Base isolation is a structural response control technique that introduces very high lateral flexibility and shifts the fundamental frequency of the building away from the predominant frequencies of seismic ground motions. This shift in the vibration period of the structure significantly reduces the earthquake energy transmitted to the superstructure [9]. It is established that the technique enhances the protection of primary structural members and secondary systems (e.g., non-structural elements) of buildings from damage, especially during large earthquake events [10 - 14]. The base isolation technique has been successfully implemented in several countries, such as the USA, Japan, India, New Zealand, Yugoslavia, and South Africa. Worldwide, base isolation has been used for high importance structures, such as bridges, industrial structures, hospitals, computer service (internet data) centers, and nuclear power plants. Also, the technique was successfully implemented on various types of building projects, such as hotels, offices, condominiums, schools, and dormitories [15 - 16]. Observed records from the real-life implementations have demonstrated that buildings equipped with the technique have shown excellent performance during earthquake events [15].

Although design provisions are included in the revised Ethiopian seismic standard, i.e., ES EN 1998-1:2015, for structures equipped with seismic isolation devices, the base isolation technique is not yet implemented for any structure in Ethiopia. Moreover, there are no studies that investigate the provisions of the standard in contrast to the behavior of base-isolated (BI) systems. Therefore, it is interesting and useful to study the structural merits of the base isolation technique in protecting important structures against the undesirable effects of seismic activity in the Ethiopian context. Moreover, it is also useful to study the provisions of the Ethiopian standard on base isolation. The objectives of this study include: (a) to assess the efficacy of base isolation technique in mitigating the earthquake-induced vibration of multi-story buildings considering the Ethiopian standard; (b) to explore the influence of the properties of three seismic isolation devices (i.e., laminated rubber bearing, LRB; lead-core rubber bearing, LCRB; and friction pendulum system, FPS) on the behavior of BI buildings; and (c) to study the validity of the Ethiopian seismic standard provisions on the consideration of base isolation device parameters for response assessment.

## 2. MATERIALS AND METHODS

### 2.1. Mathematical Modeling of Base-Isolated Building

The schematic representation of the multi-story BI building is presented in Figure 1, wherein the placement of the base isolators is depicted. Moreover, the three-dimensional (3D) schematic diagrams and idealized models of the three types of base isolators (i.e., LRB, LCRB, and FPS) used in this investigation are shown in Figures 2(a) and 2(b), respectively. The reasons for the selection of these three types of isolation systems are threefold. First, these three types of base isolation devices are among the most popular choices in the practice. Second, they represent the two primary categories of isolators (i.e., elastomeric (rubber-based) and sliding types of isolation systems). Third, their characteristics encompass a range of linear and nonlinear force-deformation characteristics. In this study, equal seismic masses are considered at all floor and base slab levels, whereas all stories are assigned the same lateral stiffness. Here, the superstructure of the building is assigned a modal damping ratio ($\xi_s$) of 0.02. The stiffness of the stories and the floor masses are decided to achieve the desired fixed-base (FB) fundamental time period ($T_s$).

For both the FB and BI buildings, the equations of motion are derived considering earthquake excitation. Here, the derived equations of motion of the BI building are arranged in the state-space form as given in Equation (1) [17].

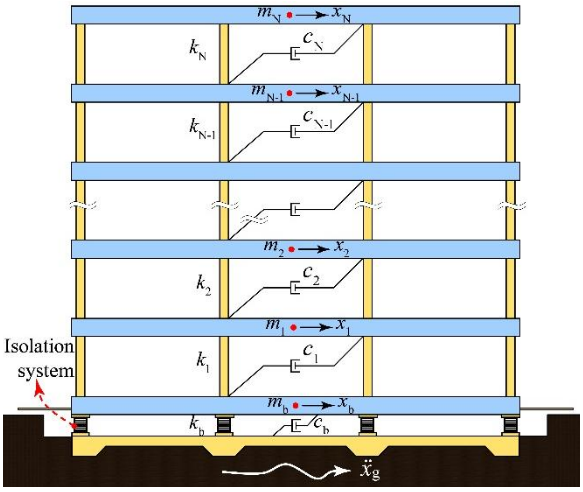


**Figure 1** The schematic representation of the multi-story BI building.

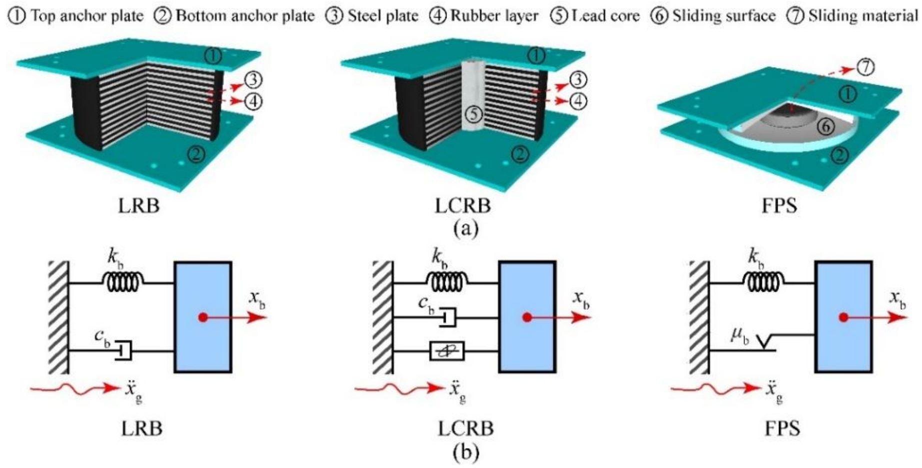


**Figure 2** Details of LRB, LCRB, and FPS: (a) 3D schematic diagrams and (b) idealized mathematical models.

$$\begin{Bmatrix}\dot{\bar{\boldsymbol{X}}}\\ \ddot{\bar{\boldsymbol{X}}}\end{Bmatrix} = \begin{bmatrix}\vec{\mathbf{0}} & \boldsymbol{I}\\ -\bar{\boldsymbol{M}}^{-1}\bar{\boldsymbol{K}} & -\bar{\boldsymbol{M}}^{-1}\bar{\boldsymbol{C}}\end{bmatrix}\begin{Bmatrix}\bar{\boldsymbol{X}}\\ \dot{\bar{\boldsymbol{X}}}\end{Bmatrix} + \begin{bmatrix}\vec{\mathbf{0}}\\ -\bar{\boldsymbol{M}}^{-1}\end{bmatrix}\begin{Bmatrix}-1\\ \mathbf{0}^{T}\end{Bmatrix} f_b - \begin{bmatrix}\vec{\mathbf{0}}\\ -\bar{\boldsymbol{M}}^{-1}\end{bmatrix}\bar{\boldsymbol{M}}\begin{Bmatrix}-\ddot{x}_g\\ -\boldsymbol{r}(\ddot{x}_g+\ddot{x}_b)\end{Bmatrix}, \qquad (1)$$

where the mass, damping, and stiffness matrices, i.e., $\bar{\boldsymbol{M}}$, $\bar{\boldsymbol{C}}$, and $\bar{\boldsymbol{K}}$, of the BI building are defined in Equations (2), (3), and (4), respectively; $\bar{\boldsymbol{X}}=\{x_b \quad \boldsymbol{X}_s^T\}^T$ is the vector of structural displacements; $f_b$ is the force in the seismic isolator; $\ddot{x}_g$ is the ground acceleration induced by earthquake; $x_b$ and $\ddot{x}_b$, respectively, are the lateral displacement and acceleration response quantities of the base slab relative to the ground; $\boldsymbol{X}_s=\{x_1,x_2,...,x_N\}^T$ is a vector containing lateral floor displacements measured relative to the base slab; $\boldsymbol{I}$ is an identity matrix of size $N$+1; $N$ represents the number of floors/stories in the structure; $\mathbf{0}$ is a null column vector; $\boldsymbol{r}=\{1,1,...,1\}^T$ is a column vector of influence coefficients; and $\overleftrightarrow{\mathbf{0}}$ is a null matrix.

$$\bar{\boldsymbol{M}}=\begin{bmatrix} m_b & \mathbf{0} \\ \mathbf{0}^T & \boldsymbol{M}_s \end{bmatrix}, \tag{2}$$

$$\bar{\boldsymbol{C}}=\begin{bmatrix} 0 & c_1\boldsymbol{r}^b \\ \mathbf{0}^T & \boldsymbol{C}_s \end{bmatrix}, \tag{3}$$

$$\bar{\boldsymbol{K}}=\begin{bmatrix} 0 & k_1\boldsymbol{r}^b \\ \mathbf{0}^T & \boldsymbol{K}_s \end{bmatrix}. \tag{4}$$

Here, $m_b$ = mass of the base slab; $c_1$ = dashpot constant of the building's first story; $k_1$ = stiffness of the first story; $\boldsymbol{r}^b$={-1,0,0,...,0} is a row vector of size $N$; and $\boldsymbol{M}_s$, $\boldsymbol{C}_s$, and $\boldsymbol{K}_s$, respectively, are the superstructure mass, damping, and stiffness matrices. Moreover, the compact form of Equation (1) can also be written as $\dot{\bar{z}}=\bar{\boldsymbol{A}}\bar{z}+\bar{\boldsymbol{B}}\bar{\boldsymbol{F}}_c-\bar{\boldsymbol{B}}\bar{\boldsymbol{F}}_{exc}$, where $\bar{z}=\{\bar{\boldsymbol{X}} \quad \dot{\bar{\boldsymbol{X}}}\}^T$ is the state vector. Also, the excitation vector ($\bar{\boldsymbol{F}}_{exc}$) and $\bar{\boldsymbol{F}}_c$ are given as

$$\bar{\boldsymbol{F}}_{exc}=-\bar{\boldsymbol{M}}\{\ddot{x}_g \quad \boldsymbol{r}(\ddot{x}_g+\ddot{x}_b)\}^T, \tag{5}$$

$$\bar{\boldsymbol{F}}_c=\{-1 \quad \mathbf{0}^T\}^T f_b. \tag{6}$$

The state-space solution [18], i.e., given in Equation (7), is implemented to quantify vibration response of the BI buildings under seismic excitation.

$$\bar{z}_t=e^{\bar{A}\Delta t}\bar{z}_{t-\Delta t}+e^{\bar{A}\Delta t}\Delta t\bar{\boldsymbol{B}}(\bar{\boldsymbol{F}}_c-\bar{\boldsymbol{F}}_{exc}), \tag{7}$$

where $\bar{z}_t$ represents the state vector at time instant $t$.

The force in the LRB ($f_b$), given in Equation (8), is quantified as a function of the dashpot constant ($c_b$) and the lateral isolator stiffness ($k_b$). The damping coefficient is quantified as $c_b=2\xi_b M\omega_b$, where $\xi_b$, $\omega_b=2\pi/T_b$, $T_b$, and $M$ are the damping ratio of isolation system, isolation angular frequency, isolation time period, and the total mass of the BI building, respectively. Further, the isolation stiffness is evaluated as $k_b=M\omega_b^2$. The force in the LCRB ($f_b$) is defined in Equation (9) [19] in terms of the damping coefficient, lateral stiffness, post-yield stiffness ratio ($\alpha=k_b/k_i$), and normalized yield strength ($F_0$). Here, the normalized yield strength can be obtained as $F_0=F_y/W$, where $F_y$ and $W$, respectively, are the isolator yield strength and the weight of the BI building. Further, the initial stiffness is defined as $k_i=F_y/q$, where $q$ = bearing yield displacement. The force in the FPS is given in Equation (10) as a function of the coefficient of friction of the FPS ($\mu_b$) and isolator stiffness ($k_b$). For the FPS, the isolation stiffness is computed as $k_b=W/r_b$, where $r_b$ is the radius of curvature of the FPS sliding surface.

$$f_b=c_b\dot{x}_b+k_b x_b, \tag{8}$$

$$f_b=c_b\dot{x}_b+k_b x_b+(1-\alpha)F_0 W h_x, \tag{9}$$

$$f_b=k_b x_b+\mu_b W\,\mathrm{sgn}(\dot{x}_b). \tag{10}$$

where $\dot{x}_b$ = velocity of the base slab relative to the ground; $h_x$ = nondimensional hysteretic displacement component [14]; and sgn(•) represents the signum function.

### 2.2. Numerical Assessment under Earthquake

Synthetic earthquakes compatible with a response spectrum of the Ethiopian standard, ES EN 1998-1:2015, are generated and used for non-linear response history analysis of the FB and BI building models. Figure 3 shows the normalized elastic response spectra of the ES EN 1998-1:2015 for the five ground types specified in the standard. In this investigation, the design response spectrum corresponding to Ground Type E is considered to generate the synthetic earthquake time histories. Moreover, the ground acceleration corresponding to Seismic Zone IV has been implemented. The 1940 Imperial Valley (IV1940), 1994 Northridge (NR1994), and 1995 Kobe (KB1995) ground motion data (i.e., recorded at the El Centro, Sylmar, and Kobe Japan Meteorological Agency - KJMA Stations) are used as reference time histories to generate synthetic earthquakes. The peak ground accelerations (PGAs) of the considered earthquakes are 0.32 $g$, 0.60 $g$, and 0.83 $g$, respectively. Response spectrum compatible synthetic earthquakes are used in this study because of the absence of readily available recorded real earthquake data for the region. The considered synthetic earthquake data represent site-specific ground motions that reflect the expected seismic hazard accounting for local conditions.

The earthquake response of the six-story FB and BI building models are investigated under synthetic ground motions. The synthetic earthquakes are generated to be compatible with the response spectrum of the Ethiopian seismic standard for Ground Type E. The three synthetic earthquake time histories and their frequency content are presented in Figure 4, whereas the response spectra of the synthetic earthquakes are shown in Figure 5.

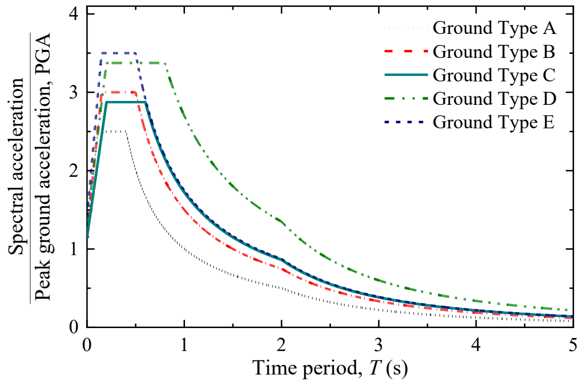


**Figure 3** Normalized elastic response spectra of the ES EN 1998-1:2015 for the five ground types.

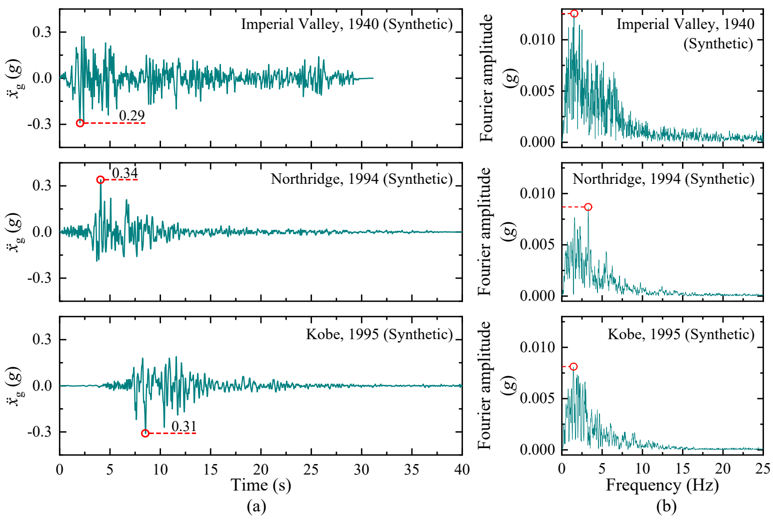


**Figure 4** Details of the synthetic earthquakes compatible with the response spectrum of ES EN 1998-1:2015: (a) earthquake time histories and (b) frequency content.

Throughout the study, five buildings (i.e., two-, four-, six-, eight-, and ten-story buildings) with FB fundamental time period ($T_s$) values of 0.2 s, 0.4 s, 0.6 s, 0.8 s, and 1 s, respectively, are used. Also, the same buildings are isolated using elastomeric and sliding bearings, and evaluated under the three synthetic seismic ground motions. Here, $T_b$ and $\xi_b$ are considered to characterize the LRB. In contrast, the LCRB is characterized considering $T_b$, $\xi_b$, $F_0$, and $q$. Further, the coefficient of friction ($\mu_b$) and the isolator stiffness ($k_b$) are considered to characterize the FPS. The non-linear dynamic response history assessment of the multi-story buildings fitted with the LRB, LCRB, and FPS is performed using the state-space method. Four vibration response quantities of the multi-story buildings: (a) the top floor absolute acceleration, $\ddot{x}_{N,Abs}=\ddot{x}_N+\ddot{x}_b+\ddot{x}_g$; (b) normalized base shear, i.e., $V_n$, (c) inter-story drift ratio, and (d) isolator displacement, $x_b$, are studied. The values of $V_n$ and the inter-story drift ratio of the $j^{th}$ story ($\Delta_j$) are computed as

$$V_n=V_1/W, \tag{11}$$

$$\Delta_j=(x_j\text{-}x_{j-1})/H_j\times 100, \tag{12}$$

where $V_1$ is the base shear; and $H_j$ is the height of the $j^{th}$ story, which is considered to be 3.5 m here.

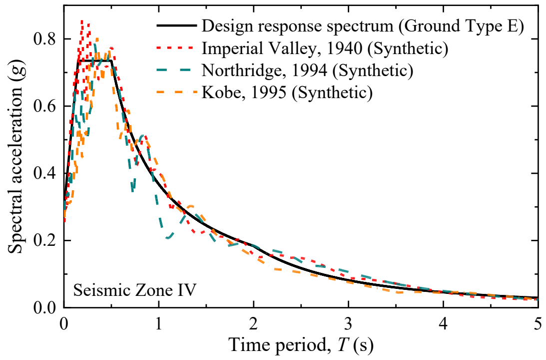


**Figure 5** Response spectra of the synthetic earthquake time histories used in the investigation.

Table 1 outlines a summary of the key parameters of the superstructure and three types of isolators considered in the investigation.

**Table 1** Key parameters of the superstructure and base isolators considered in the numerical assessment.

| Structural Component | | Parameter | Value(s) of the Parameter |
|---|---|---|---|
| Superstructure | | Fixed-base fundamental time period, $T_s^*$ (s) | 0.2, 0.4, 0.6, and 0.8 |
| | | Superstructure damping ratio, $\xi_s$ | 0.02 |
| | | Story height, $H_j$ (m) | 3.5 |
| Base isolator | LRB | Time period of isolation, $T_b$ (s) | 2, 2.5, 3, and 3.5 |
| | | Isolation damping ratio, $\xi_b$ | 2.5 % to 20 % |
| | LCRB | Time period of isolation, $T_b$ (s) | 2, 2.5, 3, and 3.5 |
| | | Isolation damping ratio, $\xi_b$ | 5 % |
| | | Normalized yield strength, $F_0$ | 0.025 to 0.2 |
| | | Isolator yield displacement, $q$ (cm) | 2.5 |
| | FPS | Time period of isolation, $T_b$ (s) | 2, 2.5, 3, and 3.5 |
| | | Friction coefficient of isolator, $\mu_b$ | 0.025 to 0.2 |

The fundamental natural frequencies of the two-, four-, six-, eight-, and ten-story fixed-base buildings are 31.416 rad/s, 15.708 rad/s, 10.472 rad/s, 7.854 rad/s, and 6.283 rad/s, respectively. In contrast the fundamental natural frequencies of the five buildings isolated using LRB ($T_b$ = 2.5 s) are 2.508 rad/s, 2.490 rad/s, 2.460 rad/s, 2.417 rad/s, and 2.364 rad/s, respectively. This shows that the introduction of base isolation has significantly reduced the natural frequencies of the buildings, especially for the short buildings.

The numerical study is conducted by performing two-dimensional (2D) non-linear time history analyses wherein the contributions of all modes of vibration are accounted for. Here, the structures are considered regular in plan and elevation. Also, the vertical vibration and torsional response of the structures due to the seismic action are considered to be negligible. Furthermore, the properties of the superstructure and isolation systems are considered deterministic, and degradations in the properties of the structures and isolation systems are not considered. Therefore, the findings, discussions, and conclusions presented in the subsequent sections shall be viewed in consideration of the aforementioned assumptions.

## 3. RESULTS AND DISCUSSION

The merits of the base isolation method in the context of Ethiopian seismic standard, the influence of isolator properties on the vibration response, and the provisions of the seismic standard on base isolation are studied. The results are discussed in this section.

### 3.1. Efficacy of Base Isolation

The efficacy of the seismic isolation strategy in protecting structures is assessed considering the six-story multi-story building ($T_s$ = 0.6 s, and $\xi_s$ = 0.02), and the results are presented herein. The values of $\ddot{x}_{N,Abs}$, $V_n$, and $x_b$ of the six-story BI buildings installed with the LRB, LCRB, and FPS are evaluated here. The time histories of the four response quantities of the six-story BI building models subjected to the synthetic Northridge, 1994 ground motion data are presented in Figure 6. The vibration response quantities of the FB building are depicted in the figure for comparison. The merit of isolating the superstructure from the ground motion using various base isolators is highlighted through the results shown in Figure 6. The presented results demonstrate that the placement of the isolators substantially reduces the seismic response of the buildings, i.e., $\ddot{x}_{N,Abs}$ and $V_n$, throughout the duration of the earthquakes.

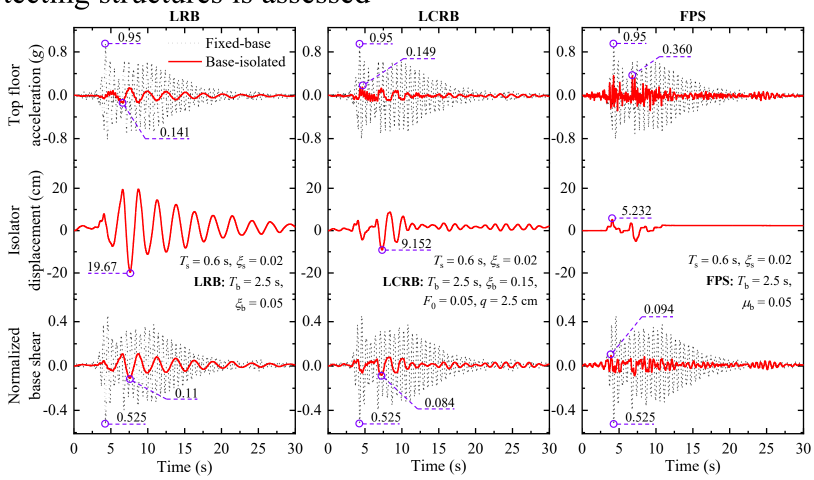


**Figure 6** Time histories of floor acceleration, isolator displacement, and normalized base shear of the six-story BI building under the synthetic NR1994 earthquake.

The floor acceleration, $\ddot{x}_{N,Abs,p}$, of the FB building under the synthetic Northridge earthquake is obtained to be 0.95 *g*. It is seen in Figure 6 that the peak floor absolute acceleration is reduced to 0.141 *g*, 0.149 *g*, and 0.36 *g* for the buildings equipped with the LRB, LCRB, and FPS, respectively. The peak normalized base shear ($V_{n,p}$) is also reduced from 0.525 (for the FB building) to 0.11, 0.084, and 0.094 for the buildings installed with LRB, LCRB, and FPS, respectively. Table 2 presents a comparison of the peak values of $\ddot{x}_{N,Abs,p}$, $V_{n,p}$, inter-story drift ratio ($\Delta_{r,p}$), and isolator displacement ($x_{b,p}$) of the FB and BI buildings. It is observed that $\ddot{x}_{N,Abs,p}$, $V_{n,p}$, and $\Delta_{r,p}$ of the building are reduced significantly when seismic isolation is used. Based on the data presented in Table 2 on the building considered in this study, the average reductions in the $\ddot{x}_{N,Abs,p}$, $V_{n,p}$, and $\Delta_{r,p}$ are about 78 %, 83 %, and 88 %, respectively. Although the amount of reduction varies based on the type of isolator, earthquake, and isolator parameters, the reduction of the seismic response quantities due to the base isolation is typically considerable.

**Table 2** Peak response quantities of the six-story building with and without base isolation under the synthetic IV1940, NR1994, and KB1995 earthquakes ($T_s$ = 0.6 s, $T_b$ = 2.5 s).

| Base Isolator | Ground Motion | Response Quantity | Fixed-Base | Base-Isolated | Response Reduction ( %) |
|---|---|---|---|---|---|
| LRB $T_b$ = 2.5 s, $\xi_b$ = 0.1 | IV1940 (Synthetic) | $\ddot{x}_{N,Abs,p}$ ($g$) | 1.0582 | 0.1567 | 85.2 |
| | | $V_{n,p}$ | 0.5637 | 0.1075 | 80.9 |
| | | $\Delta_{r,p}$ | 0.0059 | 0.0007 | 88.4 |
| | | $x_{b,p}$ (cm) | - | 18.3514 | - |
| | NR1994 (Synthetic) | $\ddot{x}_{N,Abs,p}$ ($g$) | 0.9508 | 0.1273 | 86.6 |
| | | $V_{n,p}$ | 0.5246 | 0.0987 | 81.2 |
| | | $\Delta_{r,p}$ | 0.0055 | 0.0006 | 88.7 |
| | | $x_{b,p}$ (cm) | - | 17.0477 | - |
| | KB1995 (Synthetic) | $\ddot{x}_{N,Abs,p}$ ($g$) | 0.8624 | 0.1056 | 87.8 |
| | | $V_{n,p}$ | 0.5061 | 0.0806 | 84.1 |
| | | $\Delta_{r,p}$ | 0.0052 | 0.0005 | 90.4 |
| | | $x_{b,p}$ (cm) | - | 13.7971 | - |
| LCRB $T_b$ = 2.5 s $\xi_b$ = 0.05, $F_0$ = 0.05, $q$ = 2.5 cm | IV1940 (Synthetic) | $\ddot{x}_{N,Abs,p}$ ($g$) | 1.0582 | 0.1454 | 86.3 |
| | | $V_{n,p}$ | 0.5637 | 0.0903 | 84.0 |
| | | $\Delta_{r,p}$ | 0.0059 | 0.0006 | 89.3 |
| | | $x_{b,p}$ (cm) | - | 9.5805 | - |
| | NR1994 (Synthetic) | $\ddot{x}_{N,Abs,p}$ ($g$) | 0.9508 | 0.1493 | 84.3 |
| | | $V_{n,p}$ | 0.5246 | 0.0836 | 84.1 |
| | | $\Delta_{r,p}$ | 0.0055 | 0.0006 | 89.6 |
| | | $x_{b,p}$ (cm) | - | 9.1524 | - |
| | KB1995 (Synthetic) | $\ddot{x}_{N,Abs,p}$ ($g$) | 0.8624 | 0.1466 | 83.0 |
| | | $V_{n,p}$ | 0.5061 | 0.0920 | 81.8 |
| | | $\Delta_{r,p}$ | 0.0052 | 0.0006 | 87.8 |
| | | $x_{b,p}$ (cm) | - | 10.5245 | - |
| FPS $T_b$ = 2.5 s, $\mu_b$ = 0.05 | IV1940 (Synthetic) | $\ddot{x}_{N,Abs,p}$ ($g$) | 1.0582 | 0.3428 | 67.6 |
| | | $V_{n,p}$ | 0.5637 | 0.1020 | 81.9 |
| | | $\Delta_{r,p}$ | 0.0059 | 0.0008 | 85.7 |
| | | $x_{b,p}$ (cm) | - | 6.7799 | - |
| | NR1994 (Synthetic) | $\ddot{x}_{N,Abs,p}$ ($g$) | 0.9508 | 0.3596 | 62.2 |
| | | $V_{n,p}$ | 0.5246 | 0.0945 | 82.0 |
| | | $\Delta_{r,p}$ | 0.0055 | 0.0009 | 84.3 |
| | | $x_{b,p}$ (cm) | - | 5.2317 | - |
| | KB1995 (Synthetic) | $\ddot{x}_{N,Abs,p}$ ($g$) | 0.8624 | 0.3744 | 56.6 |
| | | $V_{n,p}$ | 0.5061 | 0.0797 | 84.3 |
| | | $\Delta_{r,p}$ | 0.0052 | 0.0008 | 85.5 |
| | | $x_{b,p}$ (cm) | - | 5.1688 | - |

The reductions in the vibration response quantities of the building are achieved because of the change in the dynamic behavior (shift in the fundamental frequency) of the building caused by the isolation systems. The increment in the isolation time period changes the natural frequency of the building away from the predominant frequencies of earthquakes, which reduces the earthquake energy transferred to the superstructure by avoiding resonance in those modes. The hysteretic behavior of the isolators also contributes to the dissipation of the energy imparted from the earthquakes. Accordingly, the findings presented in Figure 6 and Table 2 demonstrate that the seismic isolation technique considerably reduces the seismic response of buildings considering the Ethiopian standard seismic provision. Therefore, the base isolation technique can suitably be used for earthquake protection of high importance structures, as per the Ethiopian standard, especially in regions of high seismicity.

The reduction in the lateral floor vibration as a result of seismic isolation improves the building behavior during earthquakes in various ways. Damage sustained by structural and non-structural components of BI buildings will be significantly reduced. This reduces the risk of loss of human life and injuries to a minimum, if any. In addition, it makes the BI buildings easily habitable after a large earthquake event and significantly reduces associated maintenance costs.

The technique also protects secondary systems such as expensive equipment and goods installed inside buildings from damage. This helps avoid unnecessary loss of money and assures continued functioning of the buildings and equipment during and after earthquakes, which is especially crucial for important structures, such as hospitals. The seismic protection benefits, as discussed herein, highlight the merits of considering base isolation in Ethiopia to protect important structures from earthquakes effectively. Therefore, the base isolation technique can be used as an effective alternative earthquake-resistant design technique for earthquake-prone areas of Ethiopia, especially for important and lifeline structures, such as hospitals, bridges, industrial structures, and power plants.

### 3.2. Effect of Base Isolation System Properties and Provisions of Ethiopian Standard

The influence of the properties of the three seismic isolators on the response quantities of the six-story BI building is investigated here. The influence of the isolator properties on the vibration response (i.e., $\ddot{x}_{N,Abs,p}$, $V_{n,p}$, $\Delta_{r,p}$, and $x_{b,p}$) is assessed through a detailed numerical investigation conducted by varying the isolation system characteristic parameters. The six-story building with $T_s$ of 0.6 s and $\xi_s$ of 0.02 is considered in the assessment. The isolation damping ratio of the LRB is varied from 2.5 % to 20 %, whereas $F_0$ values ranging between 0.025 and 0.2 are considered to model the LCRB. Moreover, the range of $\mu_b$ considered for the FPS is 0.025 to 0.2. The values of $q$ and $\xi_b$ of the LCRB are taken as 2.5 cm and 5 %, respectively.

The effect of the properties of the LRB, LCRB, and FPS on the $\ddot{x}_{N,Abs,p}$ of the BI building is presented in Figure 7. The results show that an increase in the $\xi_b$ of the LRB typically causes the reduction of $\ddot{x}_{N,Abs,p}$. This indicates that, when a range of LRB damping ratios shall be considered during design, it is essential to consider the lower (minimum) possible value of the isolation damping ratio to compute the design floor acceleration response. Such a choice of the parameter is necessary to ensure the safety of the structure under the least favorable scenario. Justifiably, Section 10.8(2) of the seismic provisions of the Ethiopian standard, i.e., ES EN 1998-1:2015, specifies that the minimum value of the isolation damping shall be considered in the evaluation of acceleration response.

The influences of the $F_0$ of the LCRB and $\mu_b$ of the FPS on the $\ddot{x}_{N,Abs,p}$ are presented in Figure 7. For the LCRB, an increase in the value of $F_0$, in most cases, has caused in the increment of the $\ddot{x}_{N,Abs,p}$. However, it is also found that an increase in $F_0$ could, in some cases, result in the reduction of $\ddot{x}_{N,Abs,p}$. For instance, for the relatively small isolation time period value (i.e., $T_b$ = 2 s) considered in this study, the $\ddot{x}_{N,Abs,p}$ is found to reduce with an increase in $F_0$ value up to about $F_0$ = 0.05. Beyond $F_0$ value of about 0.05, the floor acceleration response reverts to the increasing trend. For the FPS, it is seen that an increase in $\mu_b$ causes a consistent increment of the top floor absolute acceleration response. Although Section 10.8(2) of ES EN 1998-1:2015 does not comment on the normalized yield strength of the LCRB, it is specified in the standard that the minimum value of $\mu_b$ shall be considered in the determination of the acceleration response of BI structures. Based on the findings presented in Figure 7, consideration of the minimum (smaller) value of $\mu_b$ leads to the consideration of a smaller value of acceleration in design. Therefore, choosing the minimum possible isolation friction coefficient does not account for the least favorable scenario and may lead to an unsafe design.

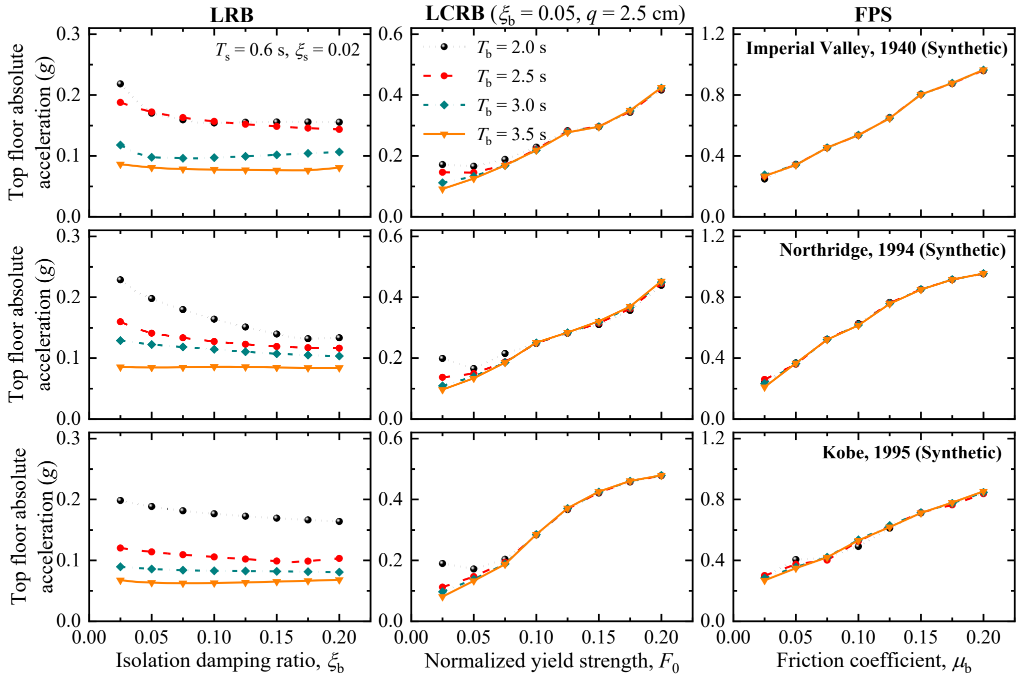


**Figure 7** Effect of isolator parameters on the top floor acceleration of the six-story BI building under IV1940, NR1994, and KB1995 ground motions.

The influence of the properties of the three base isolators on the $V_{n,p}$ and $\Delta_{r,p}$ of the BI building is presented in Figure 8 and Figure 9, respectively. Both $V_{n,p}$ and $\Delta_{r,p}$ are found to reduce with an increase in the $\xi_b$ of the LRB. This behavior necessitates the consideration of the minimum possible value of the isolation damping to quantify the design shear force in the building, which is consistent with the provision of Section 10.8(2) of ES EN 1998-1:2015. On the contrary, normalized base shear and inter-story drift reduce for an initial increment of $F_0$ of the LCRB (up to about $F_0 = 0.05$). Beyond $F_0 = 0.05$, the dynamic response quantities increase for an increase in the value of $F_0$.

In addition, it is established from the results that an increase in the FPS friction coefficient leads to an increment of $V_{n,p}$ and $\Delta_{r,p}$. The increasing trends of the dynamic response quantities under increasing values of $F_0$ and $\mu_b$ are attributed to the high-frequency vibration associated with large initial stiffness and large frictional resistance. However, the provisions of the ES EN 1998-1:2015 recommend using the minimum value of friction and do not seem to account for the undesirable effects of large frictional resistance fully. Here, it is important to note that results with similar implications have been reported in existing studies [20, 21]. Specifically, the findings of the optimization studies conducted by Jangid [20] and Rong [21] have shown that the optimum values of $F_0$ and $\mu_b$ suitable to achieve reduced floor accelerations are not necessarily the larger values. This demonstrates that the findings of the current study are in alignment with those reported in previous studies.

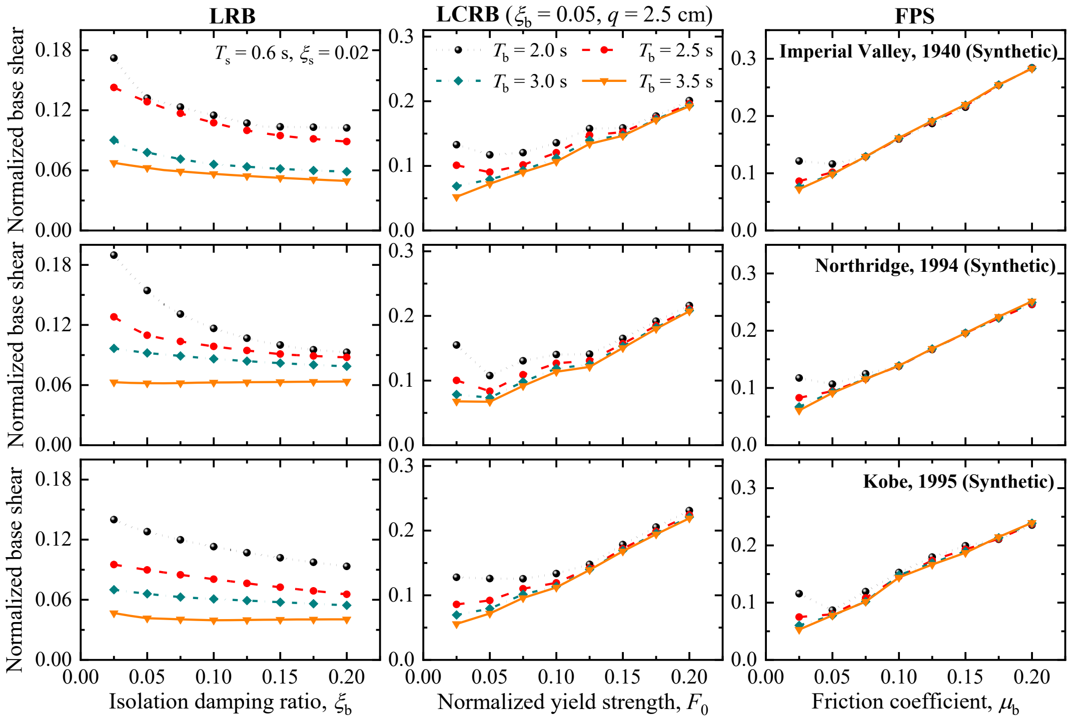


**Figure 8** Effect of parameters of base isolators on the normalized base shear of the six-story BI building under IV1940, NR1994, and KB1995 ground motions.

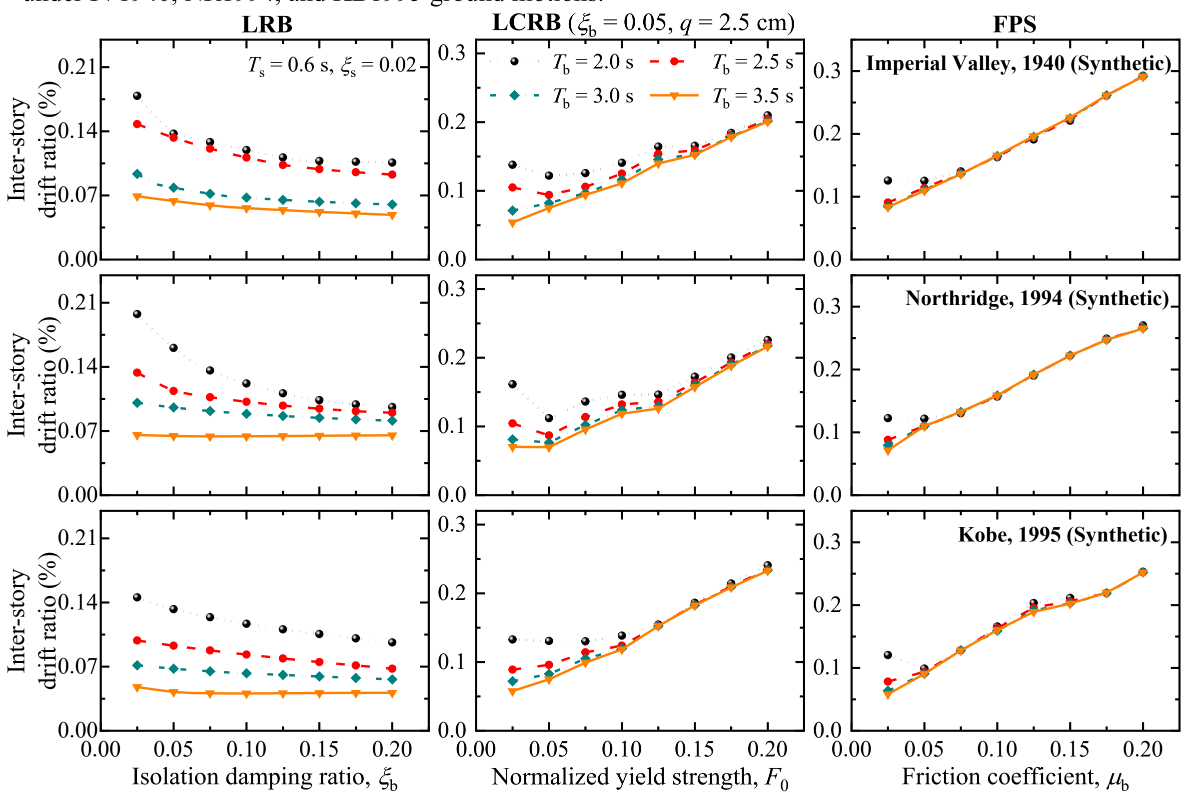


**Figure 9** Effect of characteristic parameters of base isolators on the inter-story drift of the six-story BI building under IV1940, NR1994, and KB1995 ground motions.

The effect of the properties of the LRB, LCRB, and FPS on the isolator displacement of the six-story BI building is depicted in Figure 10. The results show that $\xi_b$ of the LRB, $F_0$ of the LCRB, and $\mu_b$ of the FPS influence the isolator displacement response similarly. It is found that an increase in the three parameters results in the reduction of the isolator displacement. Accordingly, the critical design isolator displacement shall be computed considering the least favorable scenario of the minimum values of isolation damping ratio, normalized yield strength, and friction coefficient. The provision specified in Section 10.8(3) of ES EN 1998-1:2015 dictates that the displacement (isolator displacement response) should be evaluated considering the minimum values of isolation damping and coefficient of friction, which agrees with the findings presented here.

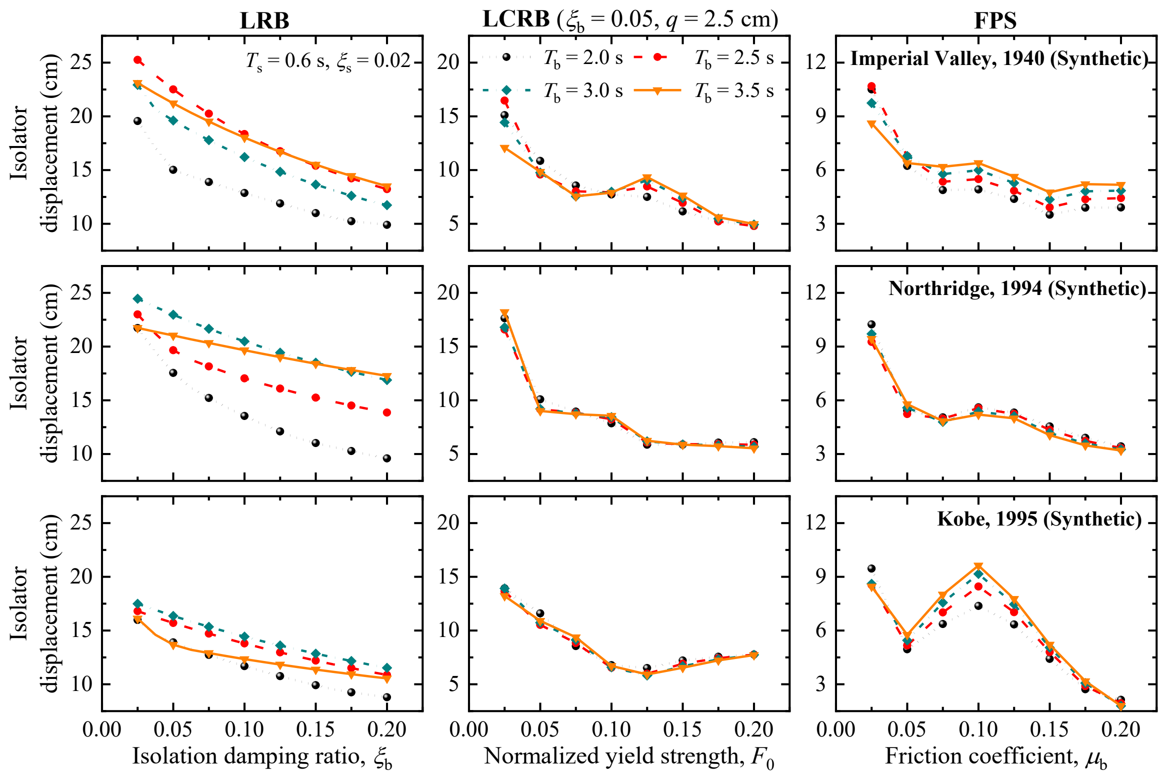


**Figure 10** Effect of parameters of base isolators on the isolator displacement of the six-story BI building under IV1940, NR1994, and KB1995 ground motions.

### 3.3. Influence of Building Height on Choice of Isolator Parameter for Response Evaluation

The height of the building is one of the important factors that could influence the behavior of BI buildings. Therefore, it is essential to investigate its effect on the choice of the values of the isolator mechanical properties to be used for response evaluation. Five BI buildings with a different number of stories ($N$) are considered here to investigate the effect of building height. The FB fundamental time periods of the five buildings considered here are 0.2 s, 0.4 s, 0.6 s, 0.8 s, and 1 s for the two-, four-, six-, eight-, and ten-story buildings, respectively. Moreover, $\xi_s = 0.02$ is used for the five buildings, whereas $T_b = 2.5$ s is considered for all the BI buildings equipped with the LRB, LCRB, and FPS. In addition, $\xi_b$ and $q$ of the LCRB are taken as 0.05 and 2.5 cm, respectively.

Considering that each mechanical property of a base isolator could vary during the lifetime of a BI building, the quantification of the vibration response quantities of the BI building requires to be done considering the values of isolator mechanical properties that result in the least favorable dynamic response. Each mechanical property of the base isolators with a mean value of $\chi_b$ could vary between a minimum value, i.e., $\chi_{b,Min}$, and a maximum value, i.e., $\chi_{b,Max}$. In practice, the quantification of a response quantity to be used for the design of the BI building shall be evaluated considering the least favorable value of the isolator property, either $\chi_{b,Min}$ or $\chi_{b,Max}$, whichever results in the worst scenario. Here, the response assessment of the five buildings equipped with LRB, LCRB, and FPS is conducted considering the minimum and maximum possible values of the respective mechanical properties of the isolators. For the LRB, the mean value of the isolation damping ratio is taken as $\xi_b = 0.1$. Accordingly, the minimum and maximum values of $\xi_b$ are taken as $\xi_{b,Min} = 0.085$ and $\xi_{b,Max} = 0.115$, respectively, considering 15 % variation. For the LCRB, the minimum and maximum values of the normalized yield strength, i.e., $F_{0,Min}$ and $F_{0,Max}$, are taken as 0.0425 and 0.0575, respectively. Similarly, the minimum and maximum values of $\mu_b$ of the FPS, i.e., $\mu_{b,Min}$ and $\mu_{b,Max}$, are taken as 0.0425 and 0.0575, respectively.

The effect of the choice of the isolator property value, either $\chi_{b,Min}$ or $\chi_{b,Max}$, on four dynamic response quantities of BI buildings is investigated considering the five buildings having different heights, and the findings are presented in Figure 11. The four response quantities evaluated here are the $\ddot{x}_{N,Abs,p}$, $V_{n,p}$, $\Delta_{r,p}$, and $x_{b,p}$. The results depicted in Figure 11 show that the consideration of the minimum value of the isolation damping ratio of the LRB ($\xi_{b,Min}$) leads to larger values of the four response quantities than that of the case where the maximum isolation damping ratio ($\xi_{b,Max}$) is considered. Importantly, the results demonstrate that $\xi_{b,Min}$ causes in the unfavorable values of the four response quantities for all five buildings of different heights.

For the LCRB-controlled buildings, it is found that the unfavorable values of the peak top floor absolute acceleration, peak normalized base shear, and peak inter-story drift ratio are obtained when the maximum value of the normalized yield strength ($F_{0,Max}$) is considered. On the contrary, the minimum value of the normalized yield strength ($F_{0,Min}$) has resulted in the unfavorable value of the bearing displacement response for all the five buildings of different heights. For the buildings equipped with the FPS, the unfavorable values of the peak top floor absolute acceleration, peak normalized base shear, and peak inter-story drift ratio are obtained when the maximum value of the friction coefficient ($\mu_{b,Max}$) is considered. In contrast, the unfavorable value of the isolator displacement is associated with the consideration of the minimum value of the coefficient of friction of the FPS ($\mu_{b,Min}$) for all five buildings of different heights.

Yet again, the findings of the assessment conducted on the BI buildings of different heights (i.e., two-, four-, six-, eight-, and ten-story BI buildings) highlight that the isolator displacement response should be computed considering the minimum values of isolation damping ratio and coefficient of friction. These findings agree with the provision specified in Section 10.8(3) of ES EN 1998-1:2015. On the contrary, for all BI buildings of different heights considered in this study, the critical (unfavorable) values of the floor acceleration, base shear, and inter-story drift shall be obtained using the maximum values of the isolation damping ratio and coefficient of friction. This observation contradicts the provision specified in Section 10.8(2) of ES EN 1998-1:2015. In summary, it is established through the findings that the provision of

Section 10.8(2) of ES EN 1998-1:2015 does not necessarily agree with the expected behavior of BI buildings. Therefore, the provision must be carefully considered during the design of BI buildings. Finally, it is to be noted that provisions of other international seismic codes, such as AIJ-2016 [22] and ASCE 7-16 [23], dictate that the design of seismically isolated structures must consider the likely variations in the isolation device parameters. Particularly, the ASCE 7-16 [23] specifies that both the upper bound and lower bound properties of the isolation system shall be independently considered in the structural analyses of BI structures, the results of which are used to determine the governing demand parameters. These particular provisions are consistent with the findings of the current study and further reiterate the need for careful consideration of Section 10.8(2) of ES EN 1998-1:2015.

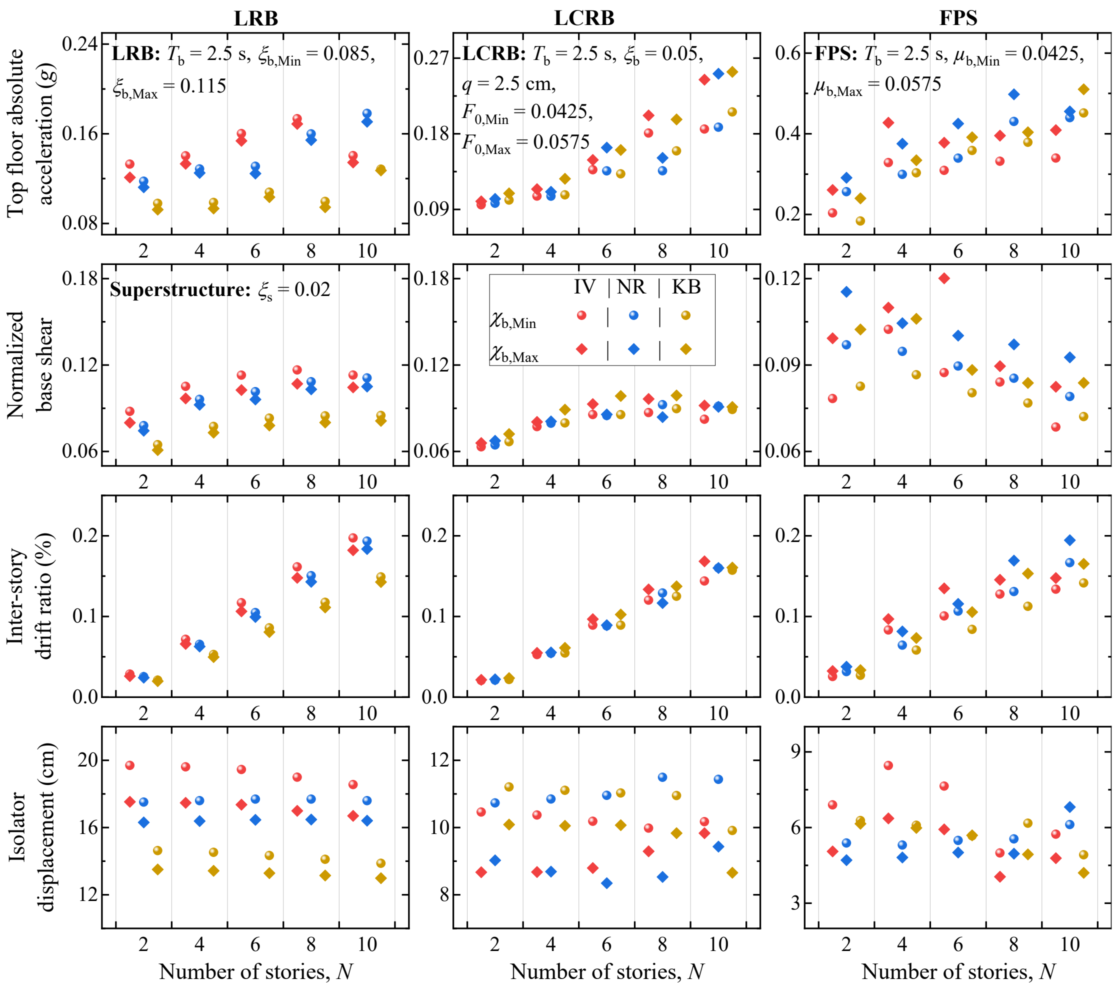


**Figure 11** Comparison of the peak response quantities of BI buildings considering the minimum and maximum values of the mechanical properties of base isolators (i.e., LRB, LCRB, and FPS).

## 4. CONCLUSIONS

The efficacy of the base isolation technique in earthquake protection of multi-story buildings is studied considering the seismic provisions of the Ethiopian standard. The influence of isolator properties is investigated, and the findings are considered to evaluate the provisions of the Ethiopian seismic standard on consideration of base isolation system parameters. The following conclusions are drawn based on the findings.

Base isolation significantly reduces the seismic response quantities (i.e., the top floor absolute acceleration, base shear, and inter-story drift ratio) of the multi-story buildings.

For the six-story building considered in this study, the average reductions in the top floor absolute acceleration, normalized base shear, and inter-story drift achieved due to the implementation of base isolation are about 78 %, 83 %, and 88 %, respectively.

An increase in the damping ratio of the LRB causes the reduction of the peak top floor absolute acceleration, normalized base shear, and inter-story drift ratio. This behavior is consistent with the provisions of Section 10.8(2) of the seismic provisions of the Ethiopian standard (ES EN 1998-1:2015) in that the minimum value of the isolation damping shall be taken into account in the evaluation of acceleration response and shear forces in the structure.

For the building equipped with the LCRB, an increase in $F_0$ (yield strength) results in an initial reduction of the top floor absolute acceleration, normalized base shear, and inter-story drift ratio up to about $F_0 = 0.05$. Further increase in $F_0$ results in a consistent increment of the three response quantities.

An increase in the coefficient of friction of the FPS causes an increment of the top floor absolute acceleration, normalized base shear, and inter-story drift ratio response of the base-isolated building. Accordingly, to account for the least favorable scenario, the maximum possible value of the friction coefficient of the isolator shall be used in computing the design values of the three response quantities. On the contrary, Section 10.8(2) of ES EN 1998-1:2015 recommends the use of the minimum friction coefficient. Such a recommendation does not necessarily account for the undesirable effects of the frictional force and may lead to an inadequate design. Therefore, it is recommended that Section 10.8(2) of ES EN 1998-1:2015 be updated to consider the maximum friction coefficient as a possible scenario that likely causes the critical (design) values of the three response quantities.

Increase in the damping ratio of the LRB, normalized yield strength of the LCRB, and friction coefficient of the FPS results in the reduction of the isolator displacement. Therefore, the evaluation of the critical design isolator displacement shall be computed considering the least favorable scenario of the minimum values of isolation damping ratio, normalized yield strength, and friction coefficient, which is consistent with the recommendation of Section 10.8(3) of ES EN 1998-1:2015.

The LRB, LCRB, and FPS can be used as effective isolation systems for the protection of important structures in earthquake-prone areas of Ethiopia. However, the provisions of Section 10.8(2) of ES EN 1998-1:2015 must be carefully considered during design.

In summary, the base isolation technique, which delivers superior seismic protection of important structures, is recommended as an excellent strategy to help achieve enhanced community resilience against earthquakes. Notable focus areas for future research in the domain include the economic feasibility of base isolation and the development of comprehensive guidelines for testing and monitoring the behavior of isolation devices in the Ethiopian context.

## CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

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