Comparative Study on Seismic-Resistant Design Using Base Isolation System

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Abstract

Earthquakes are the most destructive natural hazards throughout human history. Seismic-resistant design is important in areas of the world where earthquakes are common as it can help to reduce the risk of loss of life and property damage. To reduce the effects of earthquakes on buildings, a base isolation system is a type of seismic-resistant design to improve the seismic performance of the buildings. This study investigates and compares the seismic performance of the buildings with and without the base isolation system. A seven-storey RC building is used as a target numerical model. The high-damping rubber bearings with three different damping ratio values are used as the seismic isolation device. The isolators are placed at the base of all columns of the building to lengthen the period of vibration of the building. This affects the reduction of the base shear which induced by the earthquake. According to International guidelines, isolators are designed based on support reaction under only gravity load after performing static analysis to obtain unfactored column loadings. The response spectrum analysis is used in dynamic analysis. The displacement of the base isolation system is larger than that of the fixed base buildings even as having lower story accelerations, story drifts ratios, and story shears. The high-damping rubber bearings have a high damping coefficient which can dissipate a significant amount of energy during an earthquake, reducing the seismic forces and displacements on the structure.

Keywords: Seismic-resistant design, High-damping rubber bearing, Damping ratio, Isolator.

1. Introduction

Earthquakes are the most destructive natural disasters that can cause significant damage and loss of life, especially in areas with high seismic activity.[1-3] In recent years, the importance of seismic-resistant design has become more apparent due to the increase in the frequency and intensity of earthquakes worldwide. Seismic-resistant design, also known as earthquake-resistant design, is the practice of designing buildings and other structures to withstand the forces generated by earthquakes. This includes designing the structure to have sufficient strength, stiffness, and ductility to withstand seismic forces, as well as designing its components and systems to function properly during and after an earthquake.[4] The goal of seismic-resistant design is to ensure that a structure remains safe and functional in the event of an earthquake, and that the risk of injury or death to its occupants is minimized. One of the most widely accepted seismic protection systems is base isolation.

Seismic isolation is more frequently used currently in place of the original term "base isolation". Seismic isolation is a design approach that aims to reduce the demand earthquakes make on a structure, rather than increasing the capacity of structure to resist them. Traditional design strategy concentrates on strengthening a building to meet earthquake demands, but this can be expensive and lead to higher floor accelerations, which may cause more damage to building contents. Limiting the elastic strength and designing for ductility may cause damage to structural components that may not be repairable. Seismic isolation prevents earthquake motions from being transmitted from the foundation into the structure above, reducing demand and mitigating earthquake effects. [5]

This study investigates and compares the seismic performance of the buildings with and without the base isolation system. The high-damping rubber bearing with three different damping ratios are used as the seismic isolation devices to assess the performance of the building. Different kinds of isolation technologies can be used to lengthen the natural period of a structure and reduce the dynamic response. The frequently used isolation devices include rubber bearings and friction pendulum bearings. Rubber bearings represent one of the most popular isolation bearings in the base isolation design, including laminated rubber bearings, lead rubber bearings and high-damping rubber bearings. [3]

The term high-damping rubber bearing, HDRB, as shown in figure 1 is applied to elastomeric bearings where the elastomer used provides a significant amount of damping. The basic component of rubber bearings are steel and rubber plates in the alternate layer. The rubber layers constituting the high damping rubber are usually made of materials that are highly nonlinear in terms of shear strains. On top and bottom, the bearing is fitted with steel plates which are used to attach the bearing to the building and foundation. The bearing is very stiff and strong in the vertical direction, but flexible in the horizontal direction. Vertical rigidity assures the isolator will support the weight of the structure, while horizontal flexibility converts destructive horizontal shaking into gentle movement. Effective damping in the range of 0.1 to 0.2 of critical can easily be exhibited by the HDRB. The stiffness and damping of the HDRB are required to be large enough to resist wind and earthquake. [6, 7]

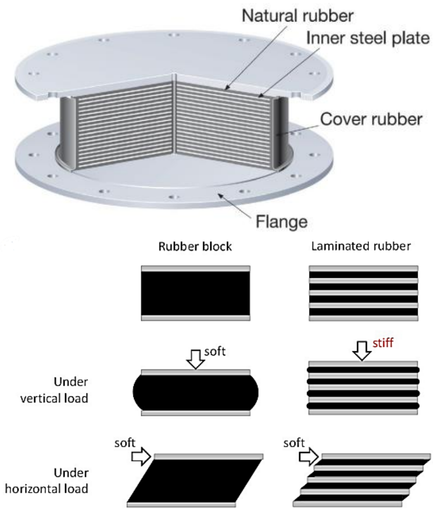


Fig. 1. High-damping rubber bearing [8]

Seismic isolation is a method that is implemented to shift the natural vibration period of a structure to the long period range of approximately 2.0 ~ 4.0 secs by placing isolation bearings usually at the foundation level in order to physically decouple the structure from the ground.[8] Firstly, a seven story RC building has been analysed by static analysis and then isolators are designed based on support reaction under only gravity load according to IBC 2000 guidelines. The natural vibration period of fixed base building is 0.9709 sec from first mode shape and this period is transformed to the long period of the base isolated building as 2.9 sec, which corresponds to the suggested value between 2.0~4.0 sec described in [8]. High-damping rubber bearing (HDRB) isolation devices with three different damping ratio values such as, ξ 10%, 15%, 20% have been used in this study to mitigate the effects of earthquakes on structures and to determine how the damping ratio affects the seismic isolation performance of HDRB isolation devices. Based on the results, HDRB isolation devices with higher damping ratios provide better seismic isolation performance by reducing the magnitude of seismic response and mitigating the forces transmitted to the structure. Conversely, high-damping rubber bearing isolation devices with lower damping ratios exhibit greater displacement and residual deformation due to the less effective energy dissipation capacity.

2. Design of High-damping rubber bearing

2.1 Structural analysis of fixed base building

This study involves analyzing the behavior of the fixed base building and base isolated building during an earthquake, and comparing the results to evaluate the effectiveness of the base isolation system in improving the seismic performance of the building. The case study is a seven-storey residential RC building located in Myanmar and it is simple rectangular shape situated in high seismic zone, Mandalay. The length and width of the building are 66 ft and 62 ft respectively as shown in figure 2. The typical story height is 10 ft and the overall height of the building is 86 ft above existing ground level as shown in figure 3. A concrete with a cylinder strength equal to 20 MPa and a steel with a yield strength equal to 345 MPa have been assumed. All reinforced concrete members are designed using American Concrete Institute (ACI 318-99).[9] Loading consideration and checking of the stability is based on Uniform Building Code (UBC-97).[10] The static and dynamic analysis of the RC structure has been analysed by using ETABS software. [11] The design results of cross section of beam and column according to the static analysis are shown in Table.1. and Table.2. The structural stability of fixed base building is checked under the safety limit according to dynamic analysis as shown in Table.3. The natural vibration period and the support reactions obtained from the unfactored column loading of fixed base building are used for isolator design with three different damping ratios.

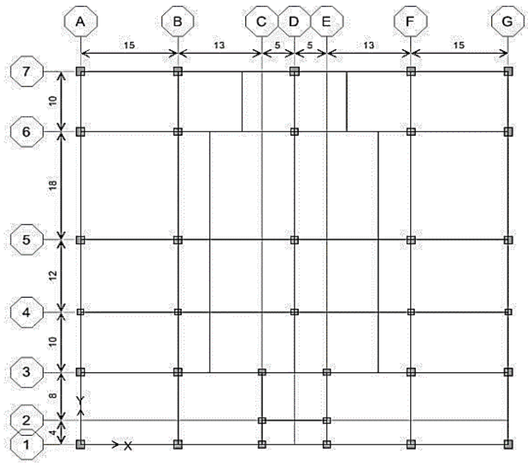


Fig. 2. Typical Floor Plan (unit-feet)

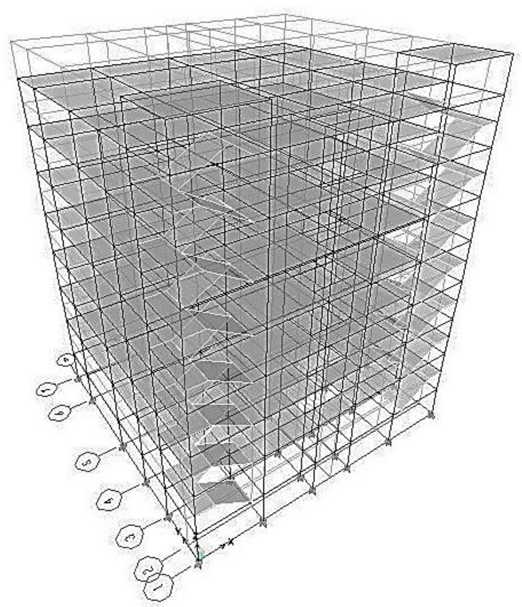


Fig. 3. 3D- Elevation of Seven-storey R.C. Building

Table 1 Design results of beams.

Level	Beams	Size (in × In)
GF	B1	10×12
From 1F to 6F	B2	10×12
		10×14
		10×16
RF to SFR	B3	10×12

The unfactored column loading is considered under only gravity load ie, dead load and live load combination as the required load capacity of the isolator device based on the weight of the structure. In this study, the support reactions are divided into three groups to design the base isolator shown in the Table.4. and the maximum support reaction in each group is represented as the load capacity of the isolator device.

Table 2 Design results of columns.

Columns	Size (in x in)		
	From GF to 2F	From 3F to 5F	From 6F to RF
C1	18 ×18	16 ×16	16 ×16
C2	18 ×18	16 ×16	14 ×14
C3	16 ×16	14 ×14	12 ×12
C4	14 ×14	14 ×14	12 ×12
C5	14 ×14	14 ×14	14 ×14

Table 3 Structural stability check of fixed base building.

Checking	Safety Factor Value		Limit	Remark
	X-direction	Y-direction		
Overturning	5.77	5.49	> 1.5	Satisfied
Sliding	3.03	3.03	> 1.5	Satisfied
Torsional irregularity	1.01	1.01	< 1.2	Satisfied
Story drift	1.7758	1.5755	< 2.64	Satisfied
P-Δ effect	0.002261	0.002006	<0.002353	Satisfied

Table 4 Load capacity of the isolators.

Isolator Group	Reaction (Kips)	No of Isolators
1	137~200	10
2	234~295	14
3	319~478	10

2.2 Design results of high-damping rubber bearing

The isolation layer is made up of horizontally flexible components that can combine structural re-centering and energy dissipation capabilities to reduce the lateral stiffness of the superstructure. Energy dissipation in the bearings can increase the effective damping ratio of the whole system. The acceleration and shear force response are decreased as a result. This method is best suited for low- to mid-rise stiff structures because it minimizes the transfer of lateral accelerations by clearly separating the natural period of the flexible isolator bearings from the stiff superstructure. In these situations, it is usually possible to build a seismic isolation system that permits the superstructure to continue to be elastic even after a Maximum Considered Earthquake (MCE) event. [8]

The performance of the HDRB isolator was evaluated based on the effectiveness in reducing the peak responses of the isolated structure, including acceleration, displacement, and residual deformation. By comparing the performance of the devices with three different damping ratios, this study aims to determine how the damping ratio affects the seismic isolation performance of HDRB isolation devices.

This section briefly describes the design procedure of the isolator with the selected high-damping rubber bearing. Based on the unfactored column loading of fixed based building, the required load capacity of isolators can be obtained by using maximum value in each group as shown in Table.4. The shear modulus of the rubber material has been taken equal to G = 16.915 kips/ft^2 in the design. Based on the load capacity and the allowable bearing pressure, the required area of the isolator can be calculated from equation (4) to support the load by selecting maximum value of the effective area. The damping ratio of the isolator is selected as the value of ξ 10%, 15%, 20% and the thickness of top and bottom cover plate is assumed as 1 inch in this study. The required design parameter of the isolator can be obtained by using the following equations and the design results of the isolator with three damping ratio is described in Table. 5-7.

$$\sigma_c = \frac{P_{DL+LL}}{A_0} \leq 163.719 \quad (\text{kip/ft}^2) \tag{1}$$

Where σ_c is the allowable axial stress, P_{DL+LL} is the unfactored column load and A_0 is the effective area of the bearing.

$$\gamma_{cDL+LL} = 6s\frac{P_{DL+LL}}{E_c A_1} \leq \frac{\varepsilon b}{3} \tag{2}$$

Where γ_{cDL+LL} is the shear strain, s is the shape factor, εb is the elongation at break of the device, E_c is the compression modulus of the rubber steel and A_1 is the effective area of the bearing for the shear strain condition.

$$A_2 = \frac{d^2}{4}(\beta\text{-}\sin\beta) \tag{3}$$

Where β is the damping coefficient and d and A_2 are diameter and the effective area of bearing based on failure of the bearing.

$$A = max\,(A_0, A_1, A_2) \tag{4}$$

Where A is the design cross sectional area of bearing selected the maximum value from (A_0, A_1, A_2).

$$t_s \geq \frac{2(t_i+t_{i+1})P_{DL+LL}}{A_{re}F_s} \geq 0.08 \quad (\text{inch}) \tag{5}$$

Where t_s is the steel plate thickness of the bearing, t_i, t_{i+1} are single rubber layer thickness and A_{re} is the reduced area of the bearing.

$$h = N\times t + N_s \times t_s + (\textit{top and bottom cover plate thickness}) \tag{6}$$

Where h is the total height of the bearing, N is the number of rubber layer, N_s is the number of steel shim plate, t is the rubber layer thickness and t_s is the steel plate thickness.

Table 5 Design Result of HDRB with damping ratio ξ_{eff} = 10%.

Group 1	HDRB 1	HDRB 2	HDRB 3
ξ_{eff} (%)	**10**	**10**	**10**
P_{DL+LL} (Kip)	200	295	478
A (in^2)	314.16	452.39	754.77
d (in)	20	24	31
h (in)	28.5	23.5	21
N	46	38	29
t (in)	0.33	0.4	0.52
N_s	45	37	28
t_s (in)	0.25	0.17	0.14
Cover plate (in)	1	1	1

Table 6 Design Result of HDRB with damping ratio ξ_{eff} = 15%.

Group 2	HDRB 1	HDRB 2	HDRB 3
ξ_{eff} (%)	**15**	**15**	**15**
P_{DL+LL} (Kip)	200	295	478
A (in^2)	283.53	415.48	660.52
d (in)	19	23	29
h (in)	24.1	20.4	19.2
N	42	35	28
t (in)	0.32	0.38	0.48
N_s	41	34	27
t_s (in)	0.21	0.15	0.14
Cover plate (in)	1	1	1

Based on the design results of the isolator, it can be clearly noted that the size of the isolator can be varied by adjusting the effective damping ratio as the area of isolator decrease with the increase of the damping ratio. The size of the isolator can also be varied depending on the value of the rubber hardness and the isolated period. The rubber hardness may affect the value of A_1.

Table 7 Design Result of HDRB with damping ratio ξ_{eff} = 20%.

Group 3	HDRB 1	HDRB 2	HDRB 3
ξ_{eff} (%)	**20**	**20**	**20**
P_{DL+LL} (Kip)	200	295	478
A (in ^{2})	254.47	380.13	615.75
d (in)	18	22	28
h (in)	21.4	18.7	17.5
N	40	33	26
t (in)	0.3	0.37	0.47
N_s	39	32	25
t_s (in)	0.19	0.14	0.13
Cover plate (in)	1	1	1

3. Isolation Analysis

3.1 Structural analysis of base isolated building

This section briefly describes the structural analysis of original and base isolated buildings using ETABS. To illustrate the seismic mitigation effect of the isolation system proposed in this study, response spectrum analysis was used to evaluate the seismic performance of original and isolated buildings.

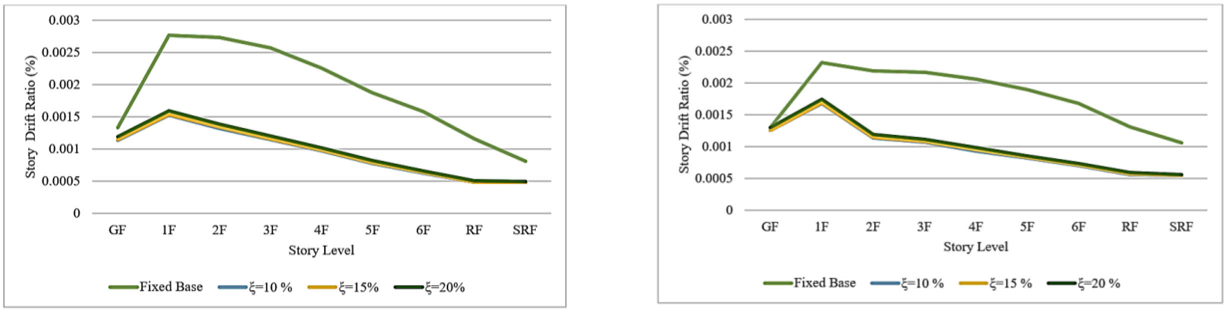
A typical seven-story RC residential building is chosen as a proposed model and the fixed base building was carried out to know the natural period of the structure as 0.9709 sec under gravity load condition. Based on the unfactored column load reactions of fixed base building using static analysis, the design parameter of HDRB isolators is obtained depending on three different damping ratios. The design results of isolators and the isolated period, 2.9 sec, are applied to investigate the seismic performance by using ETABS software. The base isolation devices are installed between the building and the supporting foundation, so as to separate or isolate the motion of the building from that of the ground making them basically uncoupled. The key finding of this study include the effectiveness of high-damping rubber bearing isolation devices in mitigating the forces transmitted to the structure during seismic event and the impact of different damping ratios on the peak response of the isolated structure, including acceleration, displacement, and other deformation.

The base shear force and interstory drift of the isolated and original structures were compared in this study. Figure 4 shows the maximum interstory drift of the original and isolated structures. As illustrated in the figures, the interstory drifts of the structure with isolator is considerably smaller than that of the structure without the isolator. To further examine the seismic mitigation of the proposed isolation system, the maximum base shear force of the original and isolated structures was compared. Figure 5 shows the base shear force of the original and isolated structures. It can be clearly noted that the base shear force of the isolated structure is smaller than that of the original structure, which verifies that the proposed isolation system can effectively reduce the base shear force of the structure.

Moreover, the acceleration and point displacement of the isolated and original structures were also compared to illustrate the seismic performance. Figure 6 shows the comparison of the acceleration of the original and isolated structures. Figure 7 shows the comparison of the point displacement of the original and isolated structures. In this comparison, the maximum point displacement is considered at point (4) for X-direction and point (1) for Y-direction. It can be seen from the figures that the acceleration of the isolated structure is smaller than that of the original structure whereas the point displacement of the isolated structure is greater than that of the original structure. In addition to, the acceleration and point displacement of the isolated structure increase at the base compared to that of the original structure and the point displacement decrease while the damping ratio increase.

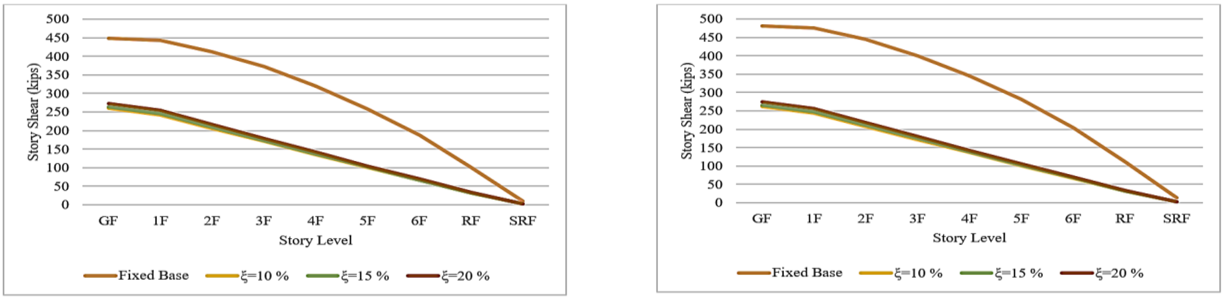
3.2 Performance comparison of the damping ratio

This study investigates the seismic performance of isolated building with three different damping ratios. To summarize the compared results, structural responses such as storey drifts, storey shears and storey accelerations in base isolated buildings significantly decreases than those of fixed base original building during earthquake load effect. However, the point displacements of base isolated building are greater than those of fixed base



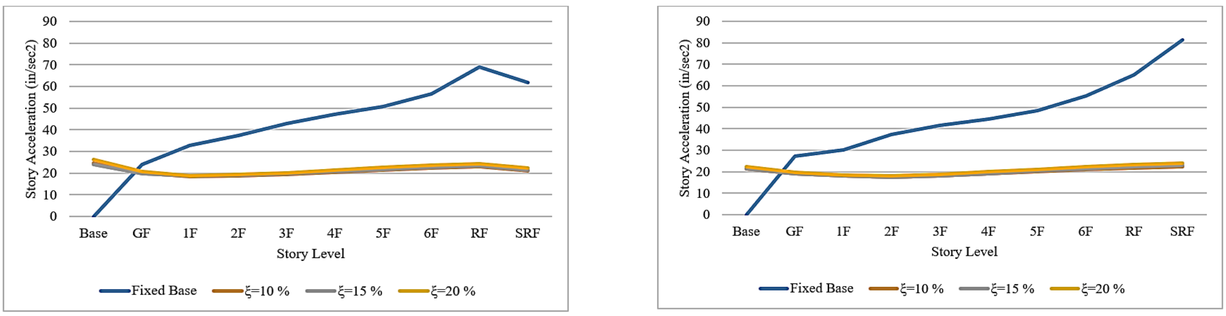
(a) X-direction (b) Y-direction

Fig. 4. Maximum Story Drift Ratio of the Fixed Base and Isolated Structures with Three Different Damping Ratios



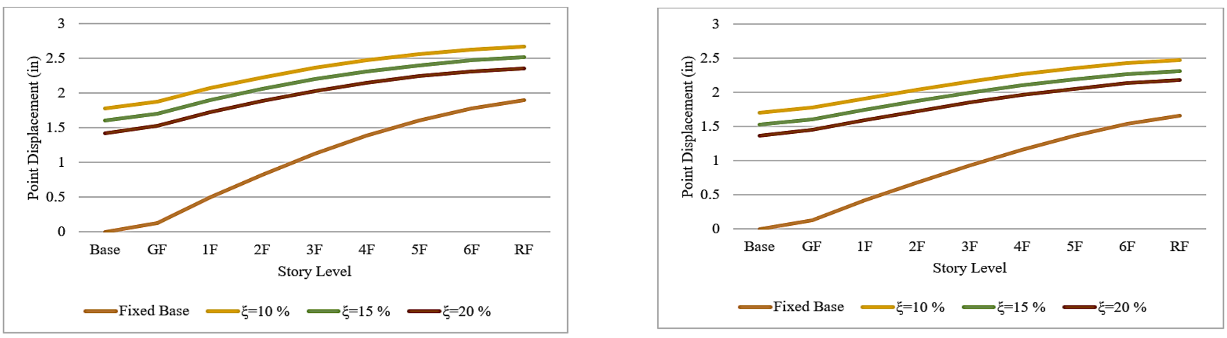
(a) X-direction (b) Y-direction

Fig. 5. Maximum Storey Shear of the Fixed Base and Isolated Structures with Three Different Damping Ratios



(a) X-direction (b) Y-direction

Fig. 6. Maximum Storey Acceleration of the Fixed Base and Isolated Structures with Three Different Damping Ratios



(a) X-direction (At Point 4) (b) Y-direction (At Point 1)

Fig. 7. Maximum Point Displacement of the Fixed Base and Isolated Structures with Three Different Damping Ratios

building. Furthermore, the greater value of effective damping ratio can increase the structural response value such as storey drift, shear and acceleration but it can also decrease the results of point displacement. This section briefly shed light on the fact how the damping ratio of HDRB isolation devices impact the structural performance in seismic-resistant design.

For HDRB devices with a low damping ratio of 10%, the maximum displacement and acceleration of the isolated structure are significantly higher compared to the other two cases. However, the isolated structure experienced a lower base shear force than the other two cases, indicating that the low damping ratio device is more effective in reducing the lateral force demands on the structure. For HDRB devices with a moderate damping ratio of 15%, the maximum displacement, acceleration, and base shear force are all reduced compared to the low damping ratio device. This indicates that the moderate damping ratio device provides a better balance between reducing the lateral force demands on the structure while also limiting its maximum response.

For HDRB devices with a high damping ratio of 20%, the maximum displacement, acceleration, and base shear force are all further reduced compared to the moderate damping ratio device. However, the high damping ratio device also results in a longer duration of the response of the isolated structure. This indicates that the high damping ratio device can potentially increase the damage to the structure if the earthquake lasts for an extended period.

Overall, the results suggest that HDRB isolation devices with a moderate damping ratio of 15% provide the best balance between reducing lateral force demands and limiting the maximum response of the isolated structure. Figure (8) shows the effectiveness of damping ratio compared to the displacement results.

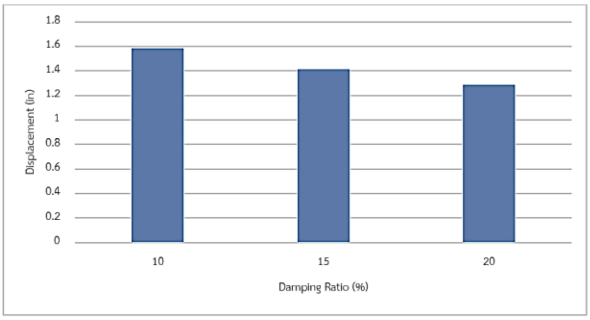


Fig. 8. Comparison on Damping Ratios and Point Displacement

4. Conclusions

In this study, the applicability of seismic isolation to residential RC building with HDRB isolation devices was investigated by numerical approach. Three different damping ratios of HDRB were selected as the value ξ 10, 15, 20 % to compare the seismic performance of structures. The analysis of design parameters showed that the load capacity, damping ratio, and thickness of steel plates can be optimized to achieve the desired performance of the device as the area of the isolator varying with the damping ratio. This study clearly showed that HDRB isolation devices are effective in reducing the seismic response of structures, with higher damping ratio resulting in greater reduction of acceleration and displacement. This study suggests that further research is needed to investigate the performance of other rubber bearings under different loading scenarios and to evaluate their ability to serve for various applications. To summarize, the study highlights the importance of seismic-resistant design and the potential of high-damping rubber bearing isolation devices as an effective solution for improving building safety in earthquake-prone regions.

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