Available online www.ejaet.com

European Journal of Advances in Engineering and Technology, 2025, 12(2):10-19

Research Article ISSN: 2394 - 658X

Seismic Retrofitting of Reinforced Concrete Structures: A Comparative

Mohamed Algamati[1,2], Abobakr Al-Sakkaf[1,3,*], Ashutosh Bagchi[1]

[1]Department of Building, Civil, and Environmental Engineering, Concordia University, Montréal, QC H3G 1M8, Canada
[2]Department of Civil Engineering, Azzaytuna University, Tarhuna, CJHM+XW5, Libya
[3]Department of Architecture & Environmental Planning, College of Engineering & Petroleum, Hadhramout University, Mukalla, Yemen
*Correspondence: mohqmati85@yahoo.com

ABSTRACT

One of the main goals of retrofitting reinforced concrete (RC) structures is to enhance their safety against natural disasters like earthquakes. A significant number of RC buildings in Canada were constructed several decades ago and may be vulnerable to earthquakes due to the absence of modern design considerations. Therefore, seismic retrofitting of RC buildings is essential to minimize earthquake damage. This study compares two of the most popular techniques used for retrofitting such structures. A six-story RC building located in a high-seismicity zone is retrofitted using a base isolator and a tuned mass damper. The retrofitting systems are designed using routine methods, and their ability to reduce earthquake damage is evaluated. Buildings upgraded with two different retrofitting systems are modeled in the OpenSees software package and subjected to several seismic events. According to the results, the routine methods used for designing the optimal linear TMD and base isolation may not be sufficient to ensure highly efficient performance, as their effectiveness depends on the intensity of seismic excitation.

Keywords: RC Buildings, Base Isolation, Tuned Mass Damper, Seismic Retrofitting

---

INTRODUCTION

Reinforced concrete (RC) buildings with various occupancies are essential components of modern cities, making it crucial to ensure their safety. Building codes are updated annually, and incorporating new design provisions is essential. In developed countries like Canada, a significant portion of buildings were constructed decades ago, and retrofitting these older structures can help reduce long-term costs. In recent years, many researchers have studied the retrofitting of RC buildings. Seismic retrofitting is a critical aspect of building upgrades, necessary for minimizing potential earthquake damage. Common seismic retrofitting measures include jacketing RC sections, adding new lateral-force-resisting systems, implementing base isolation, and using energy dissipation devices such as tuned mass dampers (TMDs) [1]. Jacketing is typically used for local retrofitting, while TMDs, base isolators, and other energy dissipation devices are employed for global retrofitting of the building system [1].

Base isolation has been widely used to enhance the seismic performance of RC buildings. Implementing base isolation beneath buildings typically minimizes the transfer of seismic vibrations to the main structure, thereby improving overall safety. However, using base isolation for retrofitting may not always be suitable, particularly for buildings with high natural periods, those situated on soft soil, or structures exceeding 15 stories [2].

The following section discusses recent approaches used by scholars to retrofit buildings using TMDs and base isolators. Imran et al. conducted a case study on the seismic performance of RC buildings equipped with double friction pendulum base isolation systems [3]. They also evaluated and retrofitted a typical RC hospital building in Indonesia using a double-concave friction pendulum (DCFP) isolation system [4].

A probabilistic and reliability-based approach is another useful technique for evaluating base-isolated buildings subjected to seismic events. Liu et al. studied a reliability-based design optimization scheme for the isolation capacity of nonlinear vibration isolators [5]. Wang and Qu investigated the advantages of base isolation in reducing reliability sensitivity to structural uncertainties in buildings [6]. Davas and Alhen examined the reliability of semi-active seismically isolated buildings under near-fault seismic events [7]. Kitayama and Constantinou conducted a probabilistic seismic performance assessment of seismically isolated buildings designed according to ASCE/SEI 7 provisions [8]. Micozzi et al. analyzed the seismic reliability of base-isolated buildings and their sensitivity to design choices [9]. Peng et al. [10] carried out a reliability-based design optimization of an adaptive sliding base isolation system to improve the seismic performance of structures.

Installing TMD devices in buildings is another alternative for retrofitting. A classical optimal linear TMD consists of linear springs and one or more dampers connected to a mass. The dampers used in TMDs can be of viscous, friction, or hysteretic types. The ratio of the TMD's mass to the host structure's mass typically ranges from 0.1% to 10%, depending on the number of stories in the building. However, classical linear dampers have some drawbacks, such as sensitivity to mistuning and effectiveness within a relatively narrow frequency band. To overcome these limitations, researchers have proposed various techniques, including the use of semi-active TMDs, TMDs with negative stiffness, nonlinear TMDs, and increasing the mass of the TMDs. Hao et al. introduced a multi-performance-oriented seismic design for structural retrofitting using viscoelastic dampers. Their study considered the structural seismic capacity redundancy ratio and was applied to a mid-rise building [11]. Monti et al. investigated direct displacement-based design of dissipative bracing for seismic retrofitting of reinforced concrete buildings [12]. Zhang et al. analyzed the seismic performance of retrofitted RC frames with sector lead viscoelastic dampers through both numerical and experimental methods [13]. Eskandari Nasab et al. studied the seismic retrofitting of a soft first-story building using viscoelastic dampers while accounting for inherent uncertainties [14]. Marrazzo et al. examined the seismic retrofitting of buildings with high-mass-ratio TMDs [15]. Wang et al. explored the use of adaptive passive negative stiffness and damping for retrofitting existing tall buildings with TMDs [16]. Miyamoto et al. conducted a study on the seismic retrofit of a landmark structure using a TMD [17].

Among the numerous studies on seismic retrofitting of buildings, relatively little attention has been given to comparing different retrofitting systems. Conducting a comparative study helps engineers understand the advantages and disadvantages of each system, enabling them to select the most appropriate method for upgrading buildings. This paper presents a comparative study of two widely used retrofitting techniques: base isolation and tuned mass dampers (TMDs). The retrofitting systems are designed using common approaches, and the upgraded buildings are subjected to earthquake simulations through dynamic time-history analysis. The performance of the retrofitted RC buildings is then evaluated using performance indices based on acceleration and displacement of the main structure. The organization of this paper is as follows: Section 2 presents the modeling details, Section 3 discusses the numerical results, and Section 4 provides the conclusions. This study aims to answer the following key questions:

- How do TMDs and base isolators improve the performance of a real building under seismic loading?
- What are the benefits and drawbacks of each system for seismic retrofitting of a real building?

It is important for engineers to select an appropriate technique for retrofitting the structures, and the therefore, a comparative study between two popular retrofitting techniques is presented in this paper. The retrofitting measures considered in this paper are installing base isolation and TMD. The upgrading systems are designed according to common approaches, and then, the retrofitted buildings are exposed to the earthquake through dynamic time history analysis. Finally, the performance of the upgraded RC buildings is compared by performance indices considering the acceleration and displacement of the main building. The organization of current paper is as follows. In Section 2, the modeling details are presented, and in Section 3, numerical results are discussed. Finally, conclusions are included in the Section 4.

METHODOLOGY

The methodology of this paper is divided into three main stages, as shown in Figure 1. The first step involves collecting relevant data and conducting a comprehensive review of published articles and documents on seismic retrofitting. During this phase, more than 100 articles on the seismic retrofitting of buildings, published between 2010 and 2024, were studied to determine whether any research focused on a comparative study of two popular retrofitting techniques. Next, to evaluate the effects of seismic upgrading on RC buildings, a real RC structure is modeled based on the NBCC 2005 provisions. The OpenSees software platform is selected for this purpose. In the final stage, two widely used retrofitting techniques—TMDs and base isolators—are designed for the proposed buildings and modeled using appropriate materials and geometry. The retrofitted buildings are then subjected to various seismic events with different parameters, and the performance of each retrofitting technique is assessed using defined performance indices.

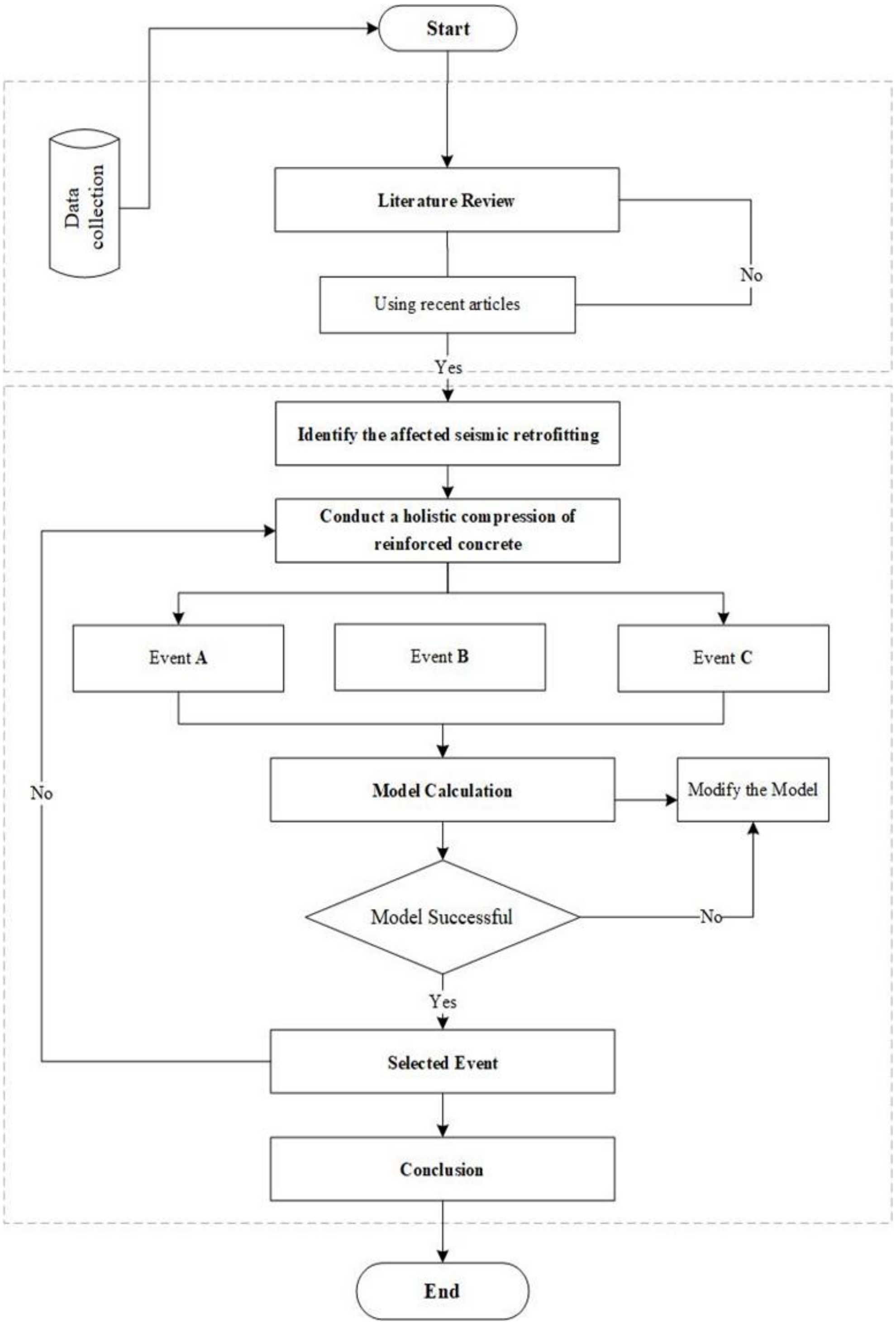


Figure 1: Methodology flowchart.

MODELING DETAILS

The structural system considered in this study is a six-story building designed according to NBCC 2005 provisions. The building features a moment-resisting frame in two horizontal orthogonal directions and is located in Vancouver, British Columbia, a region with high seismicity in Canada [18]. Figure 1 illustrates the frame structure in the X direction. The building's beams and columns have rectangular cross-sections with dimensions of 400 × 600 mm and 450 × 450 mm, respectively. Each beam is reinforced with eight longitudinal bars of 20 mm diameter at the top and five longitudinal bars at the bottom. The columns are reinforced with twelve longitudinal bars of 20 mm diameter. The spacing between frames in the X direction is 6 m. The live load considered for the building is 2.4 kN/m² in the interior bay and 4.8 kN/m² in the exterior bay, while the snow load is assumed to be 2.2 kN/m². Additional details about the frame can be found in [18] and are shown in Figure 2.

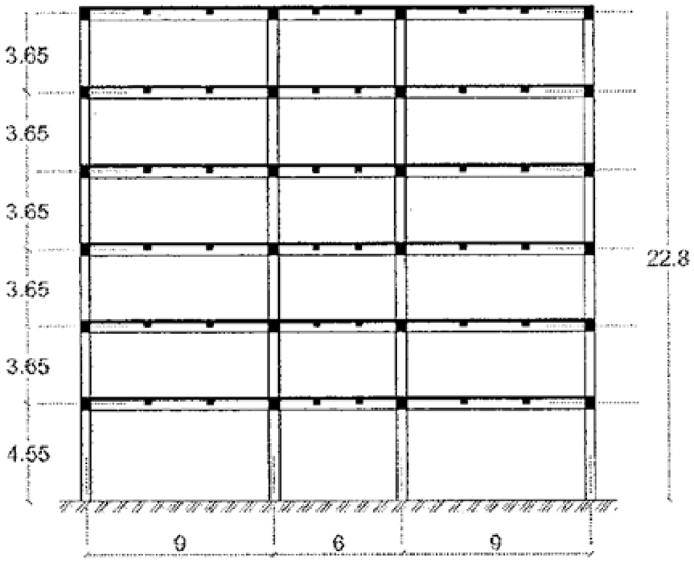
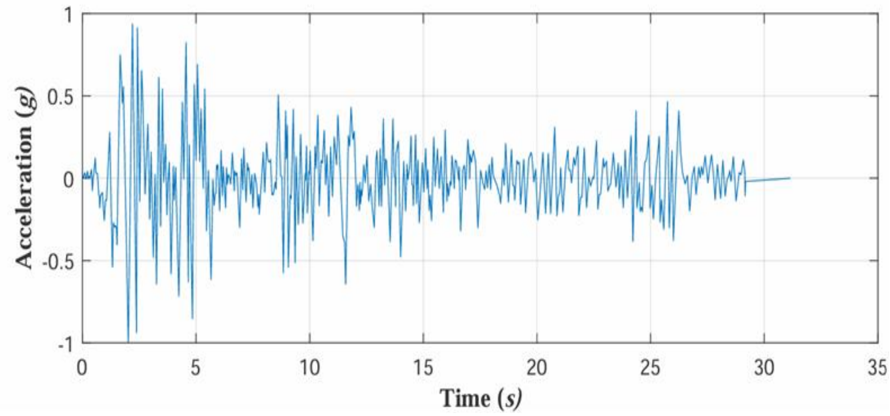


Figure 2: The two-dimensional frame modeled in OpenSees.

The material properties considered for modeling the buildings in OpenSees are as follows. The concrete used for modeling has a maximum compressive strength of 30 MPa, and the initial tangent elasticity modulus is set to 24,500 MPa. Additionally, the unit weight of concrete is selected to be 24 kN/m³. The yield stress of the longitudinal steel rebar is set to 400 MPa, and the elasticity modulus of the steel material is 200,000 MPa. In addition, the material models selected for concrete and steel in OpenSees are Steel01 and Concrete01 [19]. The load combination imposed on the structure during the time-history analysis is D + 0.5L + E, where D, L, and E represent the dead, live, and earthquake loads, respectively, as shown in Figure 3.

The analysis conducted in this study is time-history analysis, and three seismic events are selected to be applied to the main building with and without retrofitting measures. The selected events are El Centro (1940), Kobe (1995), and Tabas (1978). Among these, Kobe (1995) represents a near-fault earthquake, while the other two correspond to far-field earthquakes. Furthermore, the damper type chosen for the TMD is a viscous damper, and the ratio of the TMD's mass to the total mass of the main structure is 0.04. The optimization and design procedure of the linear viscous TMD is as follows: The main building equipped with the TMD is assumed to be a linear structure, and harmonic ground excitations with different frequencies are applied to the system. The frequency band selected for harmonic excitation is considered to be between ω_1 and ω_2, where ω_1 represents the natural frequency of the main structure in its first mode. This excitation frequency band is chosen as the range in which the maximum response of the structure occurs.

Next, the maximum displacement response of the top story of the main building is recorded for each frequency. The goal of the optimization process is to minimize the top story displacement across all harmonic excitation frequencies. It is important to note that the recorded displacement is considered during the steady-state phase. In OpenSees, the zeroLength element is used to model the dampers and springs connected to the TMD [19].



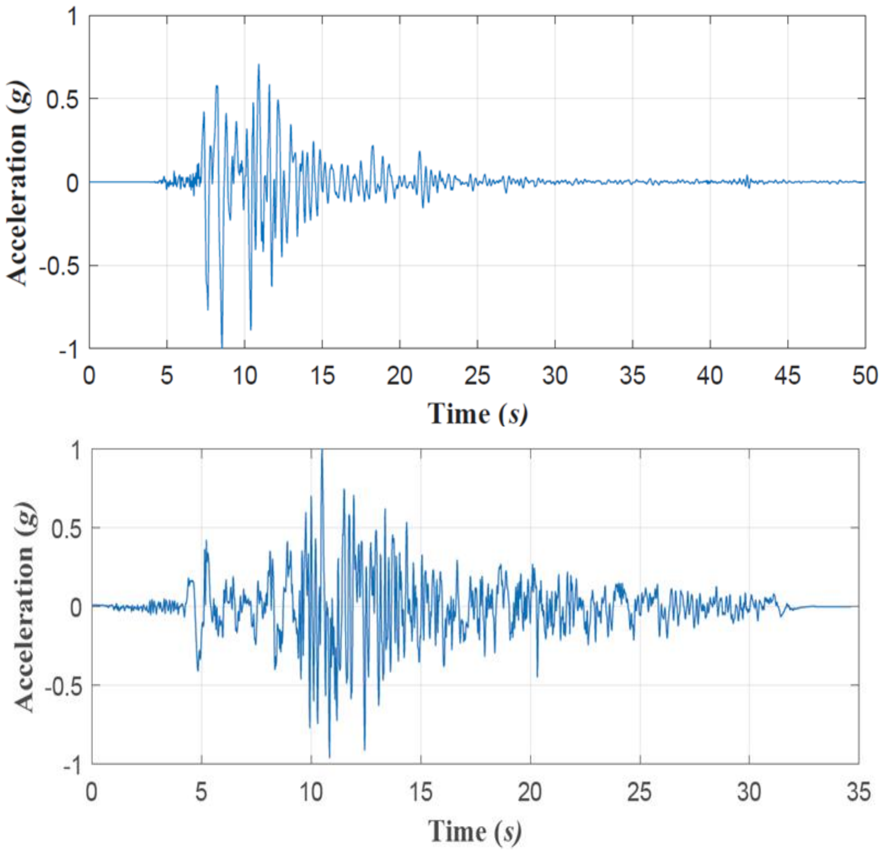


Figure 3: Seismic events selected to be imposed on the buildings with and without retrofitting measures: a) El Centro (1940); b) Kobe (1995); c) Tabas (1978).

In this paper, the design process of the base isolators beneath the building is based on the provisions recommended by FEMA P-1051, which are briefly discussed. The type of base isolation designed here is lead rubber bearing (LRB) due to its wide applications in the retrofitting of buildings.The most significant parameters in the design of the LRB are the diameter of the lead core (D_a), bonded rubber diameter (D_l), and total thickness of rubber (T_r). In the proposed building and two-dimensional model, the LRBs are placed at the bottom of each column, with a total of four LRBs used. The material used for modeling the LRBs is shown in Figure 4.The parameters Qd and kd, known as the system characteristic strength and system post-elastic stiffness, can be calculated using the following equations:

$$Q_d = \frac{\pi D_{L\sigma_{YL}}^2}{4} \quad (1)$$

$$Q_d = \frac{\pi D_{L\sigma_{YL}}^2}{4} \quad (2)$$

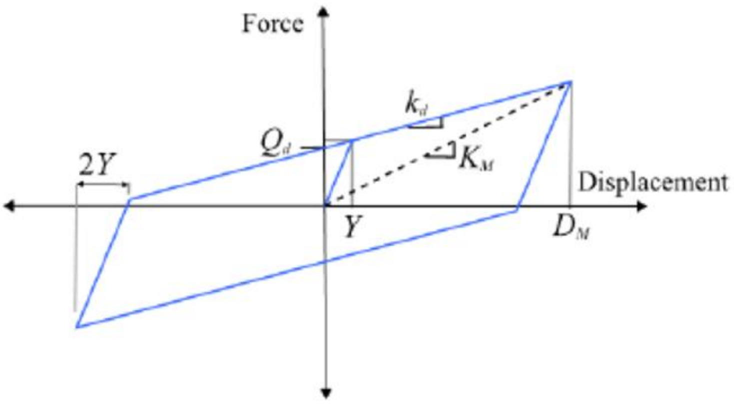


Figure 4: Design of the material used for the LRB

where σ_{YL} and G denote the effective yield stress and the shear modulus of the rubber. Additionally, f_L accounts for the effect of lead core on the k_d ranges in value from *1.0* to *1.2*. In this study, the parameter f_L is assumed to be *1.0*, and the variables G and σ_{YL} are assumed to be 60 *psi* (0.413 *MPa*) and 1450 *psi* (*10 MPa*). According to the FEMA P-1051 provisions the value of D_B should be between $3D_L$ and $6D_L$, while the value of T_r should be larger or equal to D_L.

OpenSees libraries provide suitable materials for modeling the LRBs. Herein, the element of LeadRubberX in OpenSees is used for modeling the LRBs beneath the structures [19-25].

NUMERICAL RESULTS

In this section, the results of the time-history analysis using the finite element method are presented [26-30]. Additionally, performance indices are defined to compare the effectiveness of the two retrofitting strategies. The seismic events are scaled, with their maximum peak ground acceleration (PGA) set at 0.1g, 0.4g, and 0.6g.Figure 5 illustrates the displacement response of the 6th story under the Kobe seismic event at different PGAs. It is observed that both retrofitting measures have led to a reduction in the displacement of the top floor.

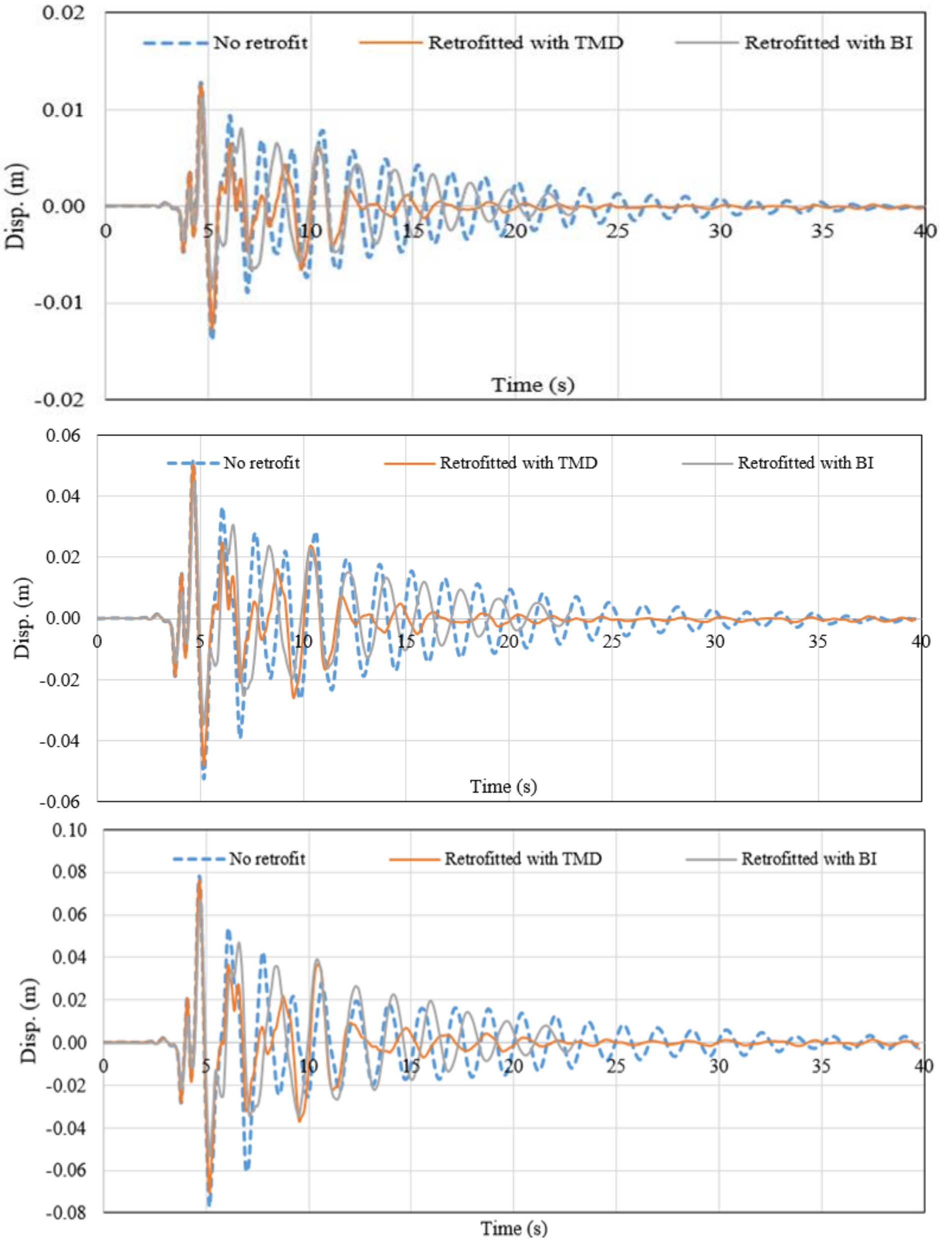


Figure 5: Time history response of the 6th flood displacement relative to ground under Kobe event: a) PGA=0.1g ; b) PGA=0.4g ; c) PGA=0.6g.

Figure 6 represents the time-history of the acceleration of the 6th story. Like Figure 4, the acceleration response of the top story is reduced, and retrofitting measures have worked effectively [31, 32]. In order to make a better comparison between the structure without retrofit and the retrofitted buildings, three performance indices are defined denoted by J_1, J_2, and J_3 and defined by:

$$J_1 = \frac{max|U_{top\ retrofitted}|}{max|U_{top\ no\ retrofit}|} \tag{3}$$

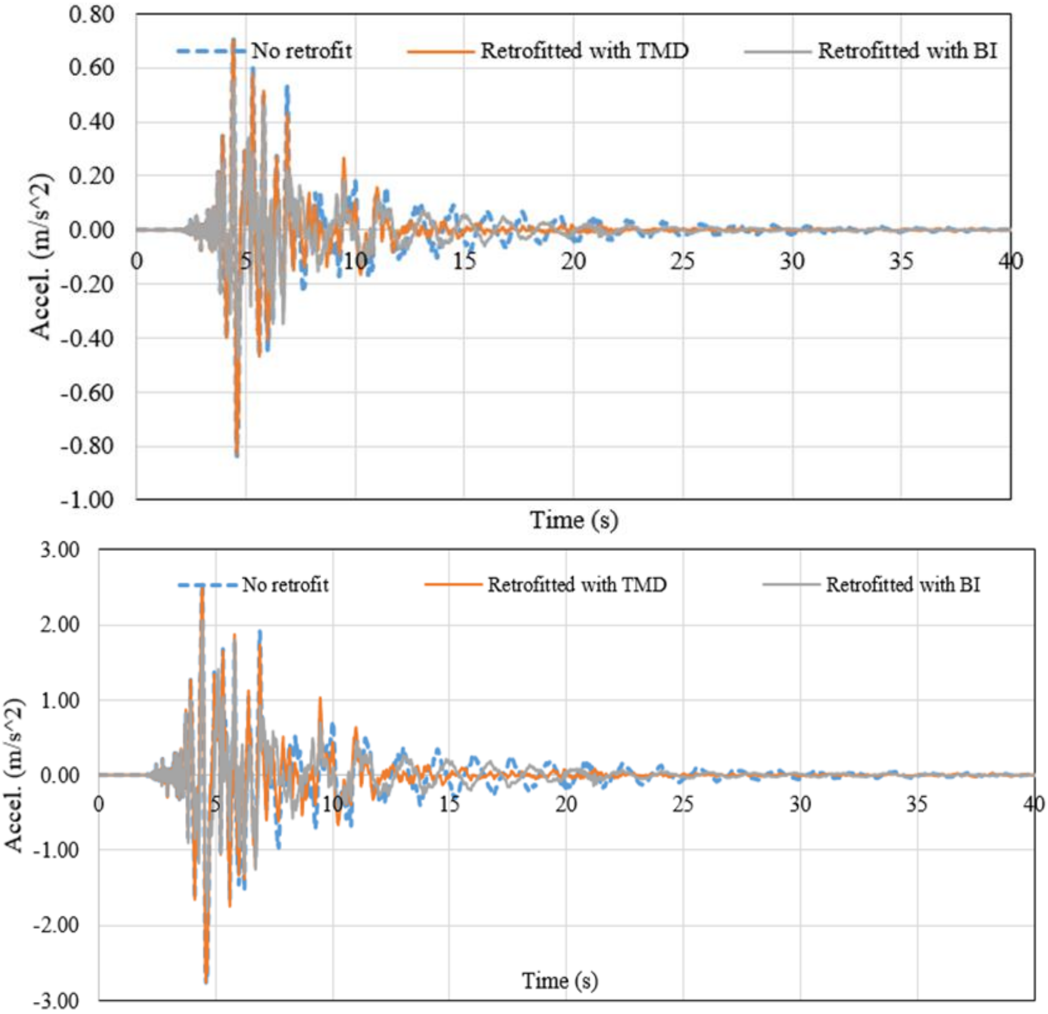
$$J_2 = \frac{max|\ddot{U}_{top\ retrofitted}|}{max|\ddot{U}_{top\ no\ retrofit}|} \tag{4}$$

$$J_3 = \frac{RMS|U_{\ retrofitted}|}{RMS|U_{\ no\ retrofit}|} \tag{5}$$

where $U_{retrofitted}$,$U_{no\ retrofit}$ denote the displacement of the 6th story for the buildings with and without retrofitting measures, respectively. Moreover, in the equation, RMS stands for root mean square.

In Tables 1–3, the values of three performance indices are listed for the two retrofitted buildings. In some cases, the values for J_1 are equal to or greater than 1.0 for both retrofitted buildings, indicating that drift and displacement in the retrofitted buildings can sometimes exceed those of buildings without retrofitting. For both upgrading techniques, the values of J_1 depend on the excitation amplitude. Therefore, it is crucial to consider the PGA of the excitation imposed on the main structure during the retrofitting system design process.

It is important to note that during the design of typical buildings, the design PGA is unlikely to exceed 0.4g, even in zones with very high seismicity. Using base isolation has resulted in up to a 19% reduction in the displacement of the top story, while using the TMD has led to a maximum 15% reduction in the displacement of the top story.



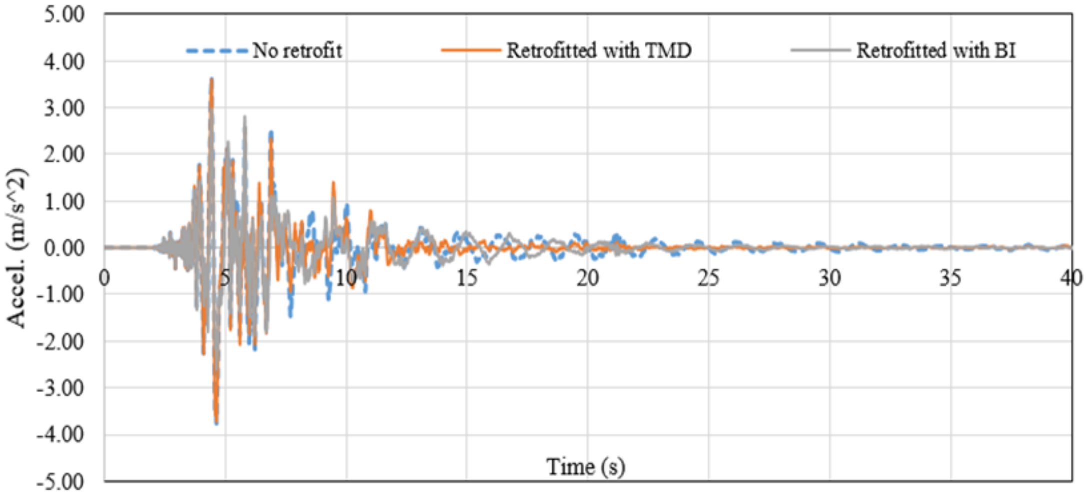


Figure 6: Time history response of the 6th flood acceleration: a) PGA=0.1g; b) PGA=0.4g ; c) PGA=0.6g.

In Tables 1–3, for the performance index J_2, the base isolation system displays better performance than the TMD, because all of the J_2 values for the building retrofitted with the base isolators are less than 1. However, for the TMD, the values of J_2 can exceed 1, especially for higher PGAs. One reason for the weaker performance of the TMDs at higher excitation amplitudes (PGA = 0.4g, 0.6g) is that the structural system becomes nonlinear, and therefore, the natural period of the building changes. It is a well-known fact that TMDs are sensitive to mistuning, and mistuning is more likely if the structure exhibits nonlinear behavior. For both retrofitting systems, the value of J_3 is less than 1 when PGA = 0.1g, 0.4g. For PGAs smaller than or equal to 0.40g, installing the TMD can reduce the RMS of the top floor displacement from 53% to 7%, while using the base isolators can decrease J_3 from 34% to 9%.

For both of the retrofitting systems, the value of J3 is less than unit while PGA=0.1g, 0.4g. For PGAs smaller and equal to the 0.40g, installing the TMD can reduce the RMS of the top floor displacement from 53% to 7%, while using the base isolators can decrease the J3 from 34% to 9%.

Table 1: The values of J_1 for two retrofitted buildings.

	J_1					
Event	**TMD**			**BI**		
	PGA (g)			**PGA (g)**		
	0.1	***0.4***	***0.6***	***0.1***	***0.4***	***0.6***
Kobe	0.92	0.96	0.98	0.81	0.85	0.86
Tabas	1.00	0.97	1.03	0.95	0.80	1.00
El Centro	0.85	0.96	1.31	1.31	1.00	1.02

Table 2: The values of J_2 for two retrofitted buildings.

	J_2					
Event	**TMD**			**BI**		
	PGA (g)			**PGA (g)**		
	0.1	***0.4***	***0.6***	***0.1***	***0.4***	***0.6***
Kobe	0.99	1.00	0.99	0.66	0.74	0.79
Tabas	0.95	1.03	1.05	0.92	0.97	0.98
El Centro	0.99	1.07	1.08	0.74	0.85	0.90

Table 3: The values of J_3 for two retrofitted buildings.

	J_3					
event	**TMD**			**BI**		
	PGA (g)			**PGA (g)**		
	0.1	***0.4***	***0.6***	***0.1***	***0.4***	***0.6***
Kobe	0.47	0.51	0.63	0.70	0.66	0.87
Tabas	0.62	0.76	0.93	0.97	0.70	0.82
El Centro	0.49	0.65	1.08	0.83	0.82	0.91

CONCLUSION

In this study, two of the most popular retrofitting techniques for upgrading RC buildings were investigated and compared: base isolation and TMD. A six-story building was modeled in OpenSees, and the retrofitting systems were designed and optimized. The TMD was designed under harmonic dynamic loads, considering the linear behavior of its structural elements. For the TMD-equipped building, harmonic ground vibrations with different frequencies were applied to achieve optimization goals. The TMD parameters were then selected to minimize top-story displacement relative to the ground. The damper and spring used for the TMD were a linear spring and a viscous damper, functioning similarly to classical TMDs.

On the other hand, the base isolator was designed using the equivalent linear static method recommended by FEMA P-1051. Furthermore, during the design process, the building was assumed to be a single-degree-of-freedom system. Afterward, the retrofitted buildings were subjected to ground vibrations with different PGAs, and three performance indices were defined to evaluate the performance of the two retrofitting techniques. The performance indices were based on top-story displacement and acceleration.

Moreover, the PGAs selected for evaluating the performance indices reflected three levels: 0.1g, 0.4g, and 0.6g. The PGA of 0.1g represented an excitation intensity in which the building's structural elements remain in the elastic range, while PGA = 0.4g is close to the excitation intensity recommended for the design of buildings with a 500-year return period in zones with very high seismicity. In addition, PGA = 0.6g represents an earthquake event much stronger than those considered in well-known building codes, even for regions highly exposed to earthquake risk.

Considering top-floor displacement as a performance index, base isolation demonstrates better performance in most cases. The best performance of base isolation in reducing top-floor displacement occurs at PGA = 0.4g, while the TMD performs best at PGA = 0.1g. Moreover, in some seismic events, the retrofitting measures were not successful in reducing top-floor displacement.

In general, the base isolator performed better in reducing top-floor acceleration. In all considered cases, installing the base isolator led to a decrease in top-story acceleration, reducing it by 2% to 36%. The best performance of the base isolator in reducing top-floor acceleration was observed for PGA = 0.4g, while its effectiveness diminished for PGAs higher than 0.4g. However, the TMD did not perform well in reducing top-floor acceleration, and in most cases, the difference between the top-floor acceleration of the retrofitted structure and the structure without retrofitting was negligible.

Both retrofitting measures demonstrated acceptable performance in reducing the RMS of the top story. For PGA ≤ 0.4g, both retrofitting measures successfully reduced the RMS of the top story, decreasing displacement by 53% to 3%. Generally, for PGA ≤ 0.4g, the TMD system performed better in reducing the RMS of top-story displacement. However, for higher PGAs, base isolation showed better performance in most cases.

As a general result, the performance of both upgraded structures depends on the excitation PGA. Passive TMDs are usually designed considering the linear properties of the main structure, while the stiffness of the structure can change due to geometric and material nonlinearities, especially under stronger ground motions. Additionally, the base isolation system is a nonlinear system, and therefore, it exhibits different behavior when exposed to seismic vibrations of varying intensities. Moreover, in one of the seismic events modeled in this study, the base isolation did not perform well under relatively weak excitation. According to the results of this paper, the typical well-known design procedures for the LRB and TMD may sometimes be insufficient, and a more detailed design may be necessary to ensure the appropriate performance of the TMDs and LRBs.

The performance of both upgraded structures is dependent on the excitation PGA. Passive TMDs are usually designed considering the linear properties of the main structure, while the stiffness of the structure can be changed due to geometrical and material nonlinearities, specifically under stringer ground motions. Additionally, the base isolation system is nonlinear system, and therefore, it displays different behavior while it is exposed to seismic vibration with different intensities. Moreover, in one of the seismic events modeled in this study, the base isolation did not show a good performance under a relatively weak excitation. According to the results of this paper, the typical well-known design procedures for the LRB and TMD may sometimes not be enough, and a more detailed design may be essential to make sure about the appropriate performance of the TMDs and LRBs.

REFERENCES

[1]. Gkournelos PD, Triantafillou TC, Bournas DA. Seismic upgrading of existing reinforced concrete buildings: A state-of-the-art review. Engineering Structures. 2021 Aug 1;240:112273.

[2]. Constantinou MC, Soong TT, Dargush GF. Passive energy dissipation systems for structural design and retrofit.

[3]. Imran I, Siringoringo DM, Michael J. Seismic performance of reinforced concrete buildings with double concave friction pendulum base isolation system: case study of design by Indonesian code. InStructures 2021 Dec 1 (Vol. 34, pp. 462-478).

[4]. Imran I, Siringoringo DM, Rainayana SS. Seismic evaluation and retrofit of a typical reinforced concrete hospital building in Indonesia with DCFP isolation system. InStructures 2024 Jun 1 (Vol. 64, p. 106593).

[5]. Liu H, Huang X, Jiang Z, Li S, Rong Z. Reliability-based design optimization scheme of isolation capacity of nonlinear vibration isolators. Engineering Structures. 2024 Feb 1;300:117220.

[6]. Wang X, Qu Z. Advantages of base isolation in reducing the reliability sensitivity to structural uncertainties of buildings. Engineering Structures. 2025 Jan 15;323:119235.

[7]. Öncü-Davas S, Alhan C. Reliability of semi-active seismic isolation under near-fault earthquakes. Mechanical Systems and Signal Processing. 2019 Jan 1;114:146-64.

[8]. Kitayama S, Constantinou MC. Probabilistic seismic performance assessment of seismically isolated buildings designed by the procedures of ASCE/SEI 7 and other enhanced criteria. Engineering Structures. 2019 Jan 15;179:566-82.

[9]. Micozzi F, Scozzese F, Ragni L, Dall'Asta A. Seismic reliability of base isolated systems: sensitivity to design choices. Engineering Structures. 2022 Apr 1;256:114056.

[10]. Peng Y, Ma Y, Huang T, De Domenico D. Reliability-based design optimization of adaptive sliding base isolation system for improving seismic performance of structures. Reliability Engineering & System Safety. 2021 Jan 1;205:107167.

[11]. Hao L, Liu M, Li J, Tan P, Wu D. Multi-performance oriented seismic design of viscoelastic dampers for structural retrofitting. Journal of Building Engineering. 2024 Jun 1;86:108657.

[12]. Monti G, Rabi RR, Vailati M. Direct displacement-based design of dissipative bracings for seismic retrofit of reinforced concrete buildings. Journal of Building Engineering. 2024 Apr 1;82:108208.

[13]. Zhang C, Huang WY, Zhou Y. Experimental and numerical investigation on seismic performance of retrofitted RC frame with sector lead viscoelastic damper. J Build Eng 44: 103218. 2021.

[14]. Nasab MS, Guo YQ, Kim J. Seismic retrofit of a soft first-story building using viscoelastic dampers considering inherent uncertainties. Journal of Building Engineering. 2022 Apr 15;47:103866.

[15]. Marrazzo PR, Montuori R, Nastri E, Benzoni G. Advanced seismic retrofitting with high-mass-ratio Tuned Mass Dampers. Soil Dynamics and Earthquake Engineering. 2024 Apr 1;179:108544.

[16]. Wang M, Nagarajaiah S, Chen L. Adaptive passive negative stiffness and damping for retrofit of existing tall buildings with tuned mass damper: TMD-NSD. Journal of Structural Engineering. 2022 Nov 1;148(11):04022180.

[17]. Miyamoto HK, Gilani AS, Garza J, Mahin SA. Seismic retrofit of a landmark structure using a mass damper. InImproving the Seismic Performance of Existing Buildings and Other Structures 2009 Dec (pp. 879-891).

[18]. El Kafrawy O. Seismic performance evaluation of reinforced concrete moment resisting frames (Doctoral dissertation, Concordia University).

[19]. McKenna F, Fenves GL. The OpenSees command language manual. University of California, Berkeley (opensees. ce. berkeley. edu). 2001 Aug 20.

[20]. Seismic Retrofit of Soft-First-Story Structures Using Rotational Friction Dampers.

[21]. Novel design procedure for steel hysteretic dampers in seismic retrofit of frame structures.

[22]. Seismic loss assessment of a structure retrofitted with slit-friction hybrid dampers.

[23]. Seismic design and performance assessment of a retrofitted building with tuned viscous mass dampers (TVM).

[24]. Latosh, F., Al-Sakkaf, A., & Bagchi, A. (2023). Feasibility Study on the Effect of FRP Shear Reinforcements on the Behaviour of FRP-Reinforced Concrete Deep Beams. CivilEng, 4(2), 522-537.

[25]. Algamati, M., Al-Sakkaf, A., Mohammed Abdelkader, E., & Bagchi, A. (2023). Studying and Analyzing the Seismic Performance of Concrete Moment-Resisting Frame Buildings. CivilEng, 4(1), 34-54.

[26]. Markou, G. (2021). A new method of seismic retrofitting cost analysis and effectiveness for reinforced concrete structures. Engineering Structures, 246, 113083.

[27]. Al-Sakkaf, A., Bagchi, A., Zayed, T., & Mahmoud, S. (2021). Sustainability assessment model for heritage buildings. Smart and Sustainable Built Environment, 12(1), 105-127.

[28]. Eweda, A., Al-Sakkaf, A., Zayed, T., & Alkass, S. (2021). Condition assessment model of building indoor environment: a case study on educational buildings. International Journal of Building Pathology and Adaptation, 41(4), 767-788.

[29]. Antoniou, S. (2023). Seismic retrofit of existing reinforced concrete buildings. John Wiley & Sons.

[30]. Al-Sakkaf, A., & Ahmed, R. (2019). Applicability of BIM in heritage buildings: a critical review. International Journal of Digital Innovation in the Built Environment (IJDIBE), 8(2), 20-37.

[31]. Shendkar, M. R., Tantri, A., & Rao, A. U. (2025). Seismic evaluation and retrofit of reinforced concrete structures. Journal of Infrastructure Preservation and Resilience, 6(1), 2.

[32]. Jung, J. S., & Lee, K. S. (2025). Seismic Safety Evaluation of a Full-Size Reinforced Concrete Frame Infilled with Precast Modular Reinforced Blocks Using Pseudo-Dynamic Testing and Nonlinear Dynamic Finite Element Analysis. Earthquake Engineering & Structural Dynamics, 54(2), 724-746.