

Research Article

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Advancing seismic performance: Isolators, TMDs, and multi-level strategies in reinforced concrete buildings

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Abstract: This study evaluates seismic mitigation methods, including high damping rubber bearing, lead rubber bearing, double sliding pendulum (DSP), and tuned mass damper (TMD), considering earthquake intensity, building height, and isolation level. Moreover, the study delves into a novel approach that incorporates multi-level isolation and multi-level TMD. Reinforced concrete buildings, ranging in height from 4 to 40 storeys, were analysed and analysed using SAP2000 under the seismic influence of the Badra, El Centro, and Northridge earthquakes. The study reveals a significant rise in the fundamental period (T) with base isolation systems, reaching 378% of the fixed base value for a six-storey building. Building height directly affects T values, with simplified equations introduced for calculation. DSP proves 5% more efficient in reducing base shear (BS), while TMD is effective in weaker earthquakes for minimizing lateral displacement. Base isolators outperform mid-level isolation and TMD at the top storey. Combining base isolators with TMD at the top storey is deemed impractical and uneconomical. The study recommends multilevel isolation or multilevel TMD for enhanced seismic isolation efficiency, with four-level isolation achieving an 80% reduction in BS for 12-storey buildings. In addition, four-level TMD outperforms TMD at the top storey with a 44.5% reduction in BS, surpassing the 26.6% reduction achieved with TMD at the top storey only.

Keywords: base isolation, multi-level isolation, seismic isolation, tuned mass damper, seismic response

1 Introduction

Generally, the earth structure consists of inner core, outer core, mantle, and crust. The crust and the upper part of the mantle layer form the tectonic plates. There are seven large and several smaller plates [1]. The boundaries between these plates are named faults. These plates move relatively to each other [2]. As tectonic plates move, they can get stuck at their edges due to friction. Stress builds up in these areas, and when it exceeds the rocks' strength, a sudden release of energy causes an earthquake or seismic wave. The size and severity of an earthquake are estimated by intensity and magnitude [3,4].

Earthquakes can be destructive to people and economy as well. It is found that around 10,000 people die every year due to earthquakes. Also, many towns and villages were destroyed around the world [5].

Since earthquake events cannot be predicted or avoided, implementing measures to minimize damage and protect communities becomes crucial. Many seismic construction design and technology have been developed to reduce the effect of earthquakes on the structures. In traditional methods, the building's resistance to earthquakes is provided by either high strength and rigidity or high ductility of the structure. Increasing the structure's stiffness reduces the vibration period, causing a rise in acceleration and amplified seismic loads. Concurrently, higher ductility contributes to an increase in interstory drift demands [6,7]. The negative side of this method is that the building has to absorb all the lateral forces induced by the seismic ground motion. A modern method was developed to overcome the disadvantage of the traditional method by isolating the structure from the earthquake effect by using flexible material at the horizontal level called isolators (Figure 1) [3]. Base isolators come primarily in two major types: elastomeric

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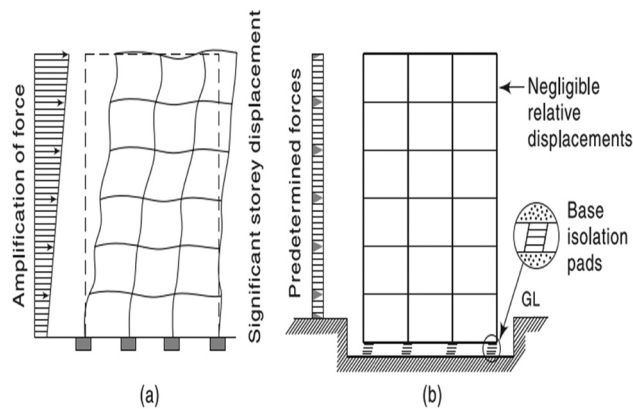


Figure 1: Fixed and base isolated structures [3]. (a) Conventional earthquake-resistant building. (b) Building with base isolation pads.

bearings and friction pendulum systems (Figure 2) [8]. Using the isolation systems increases the superstructure's period much longer than its fixed-base natural period. This can reduce the pseudo-acceleration and the induced forces in the structure, but at the same time, the deformation may be increased. This deformation is concentrated in the isolation system; therefore, only small deformations in the structure occur [9–11].

Base isolation has gained popularity due to advancements in isolator production. Various types of isolators and techniques are now available for consideration during the building design stage [12,13].

Many previous studies investigated the efficiency of different base isolation systems. The seismic behaviour of a low-rise base isolated building in Italy was explored by Braga and Laterza [14]. The isolators were high damping

rubber bearing (HDRB). The study proved the efficiency of these isolators in reducing the seismic response of the studied buildings. Symmetrical and horizontally and vertically irregular reinforced concrete buildings with fixed and base isolated were studied by Al-Jubair and Majeed [15] to show the efficiency of base isolated technique. The isolators were HDRB and friction pendulum (FP) having the same fundamental period and design displacement. It was found that both HDRB and FP isolators can be used with high efficiency. The effect of isolator location on 10-storey reinforced concrete buildings was studied by Seranaj and Garevski [16]. It was found that the base isolation gave better performance than middle storey isolation. The study conducted by Komur [17] demonstrated that the fundamental period was increased due to using lead rubber bearing (LRB) as a base isolator for reinforced concrete building. Also, the storey drift was minimized. Abed *et al.* [18] showed that the behaviour of friction isolator is related to the low value of peak ground acceleration-to-peak ground velocity ratio. Momeni and Bagchi [19] developed seismic control devices to enhance the performance of the structure. On the other hand, using the tuned mass damper (TMD) at the top of six-storey reinforced concrete building reduced the seismic response of the building. The base shear (BS) was reduced by about 10–30% [21].

This study aims to investigate the optimal isolator type for enhancing the fundamental period and reducing BS, top storey displacement (TSD), storey drifts and top story acceleration. It conducts a thorough comparison of isolator efficiency with TMD. In addition, the study evaluates the effectiveness of a recently developed system that integrates both base isolators and TMD. The impact of varying

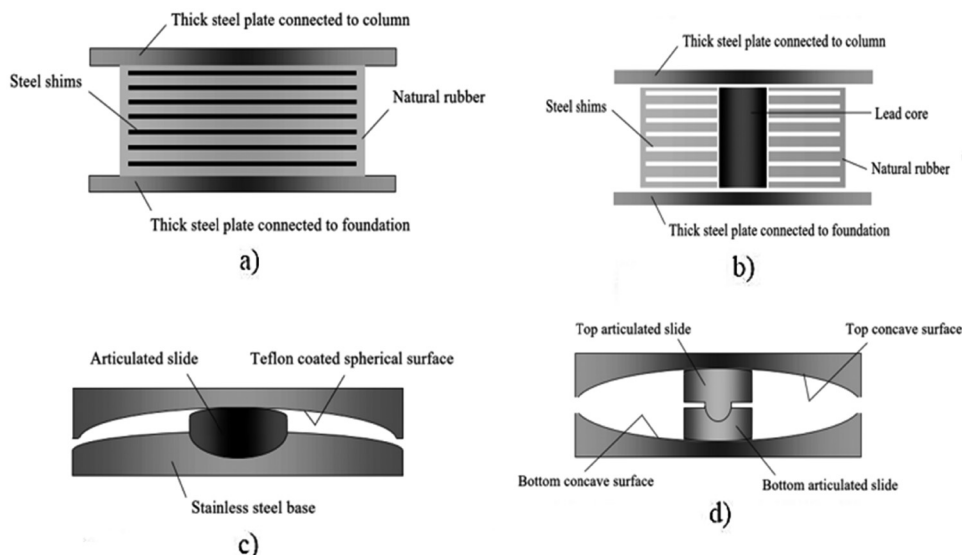


Figure 2: Common base isolators [8]. (a) Elastomeric bearing with steel shims. (b) Lead-plug bearing. (c) Friction pendulum bearing. (d) Friction pendulum bearing with double concave surface.

building heights and earthquake intensities on the efficiency of base isolators and TMD is thoroughly investigated. Simultaneously, the study delves into the efficiency of multilevel isolation and multilevel TMD configurations.

2 Building description

To demonstrate the effectiveness of the isolators and mass dampers, multistorey reinforced concrete office buildings

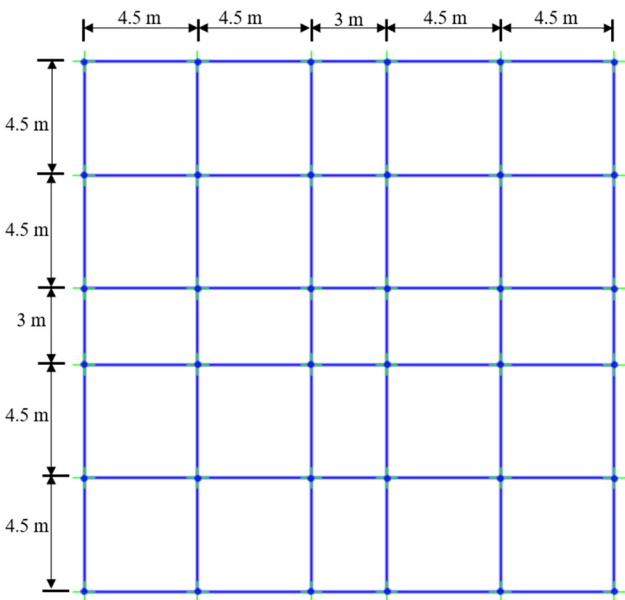


Figure 3: Plan of the building.

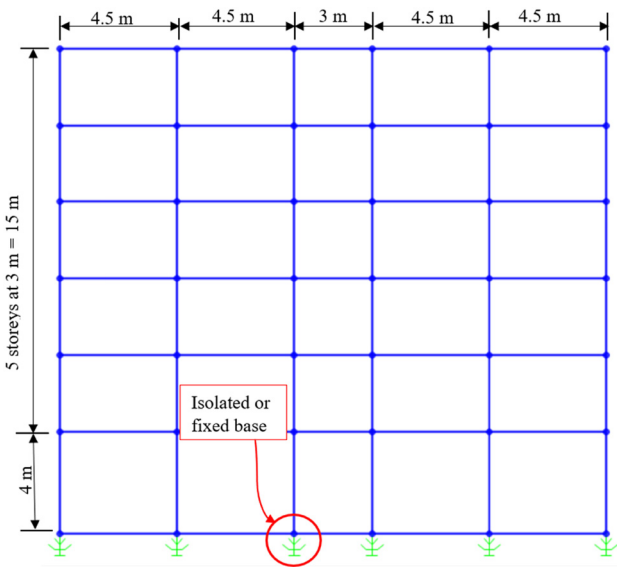


Figure 4: Elevation view of six-storey building.

Table 1: Geometry of building

Element	Dimensions (mm)	Reinforcement	Storey range*
Column (C1)	400 × 300	10 Ø 25	1st 5 storeys
Column (C2)	500 × 300	12 Ø 25	2nd 5 storeys
Column (C3)	600 × 300	14 Ø 25	3rd 5 storeys
Column (C4)	600 × 400	16 Ø 25	4th 5 storeys
Column (C5)	600 × 500	16 Ø 25	5th 5 storeys
Column (C6)	700 × 500	20 Ø 25	6th 5 storeys
Column (C7)	800 × 500	20 Ø 25	7th 5 storeys
Column (C8)	800 × 600	24 Ø 25	8th 5 storeys
Beams	200 × 500	4 Ø 20 T&B	All storeys

*Storeys range measured from the top storey.

with a range of 4–40 storeys are considered in this study. The plan for the studied symmetric office building is shown in Figure 3, and the elevation view of six-storey building is shown in Figure 4. The reinforced concrete building cross-sections details are presented in Table 1. The reinforced concrete slab has a thickness of 150 mm. The base of the building is either fixed or isolated by using the isolators. The soil structure interaction is not considered.

3 Applied loads and ground motions

The applied loads are defined in according to the International Building Code 2021 (IBC 2021) [22]. In addition to the self-weight, 2 kN/m² is applied to each floor surface as a dead load resulting from the finishing materials. The roof live load is taken as 1.5 kN/m², and the floor live load is taken as 2.5 kN/m² for offices and 4 kN/m² for corridors. The outside walls are made from thermiston bricks. The partition load is 0.72 kN/m², considered a uniform distributed live load. All dead load and only 25% of the live load are considered in the seismic analysis.

Three earthquakes are considered in this study. They are Badra (Iraq-Iran boundaries, 2009), El Centro (Los Angeles USA, 1940), and Northridge (California USA, 1994). The time history data of these earthquakes are shown in Figures 5–7 [23,24].

4 Base isolation systems

The HDRB, LRB, and double sliding pendulum (DSP) isolators are used to isolate the building from seismic effect. The

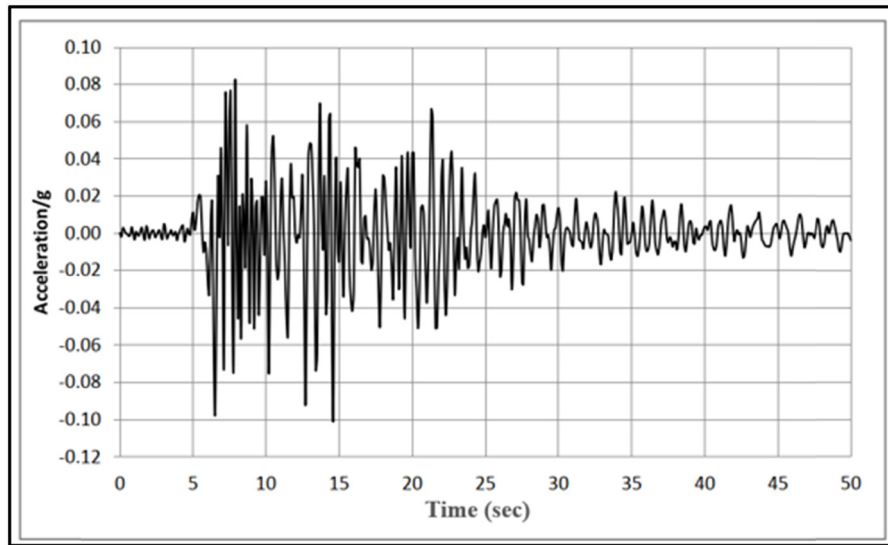


Figure 5: Badra (Iraq-Iran border) earthquake [23].

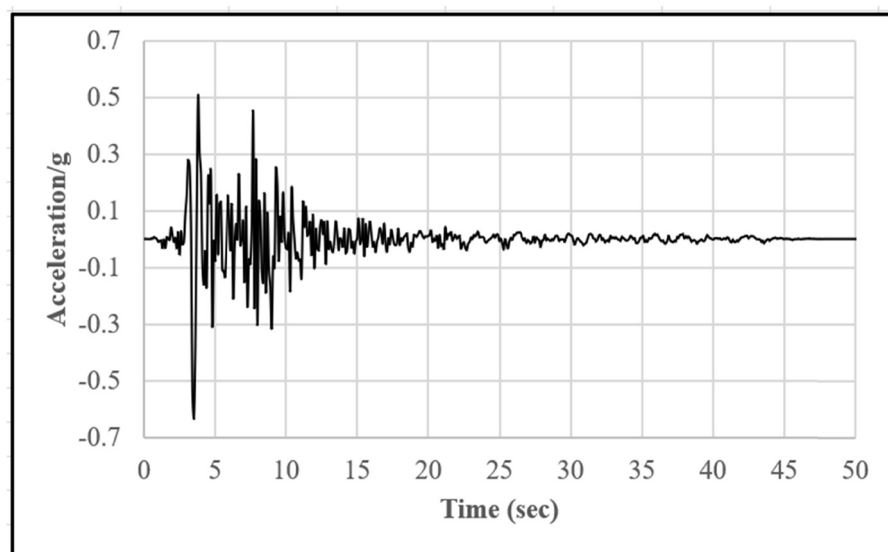


Figure 6: Northridge earthquake (Sepulveda VA Hospital, $R_{rup} = 8.44$ km) [24].

three used isolators in this study are designed to provide adequate damping to dissipate the energy during an earthquake with a practical displacement (Appendix). Also, they should have high vertical stiffness to support the vertical loads and sufficient horizontal stiffness to make the building stable under service lateral loads.

The input and output parameters used to isolate six-storey building are given in Table 2 and defined as follows:

T_D , design period; D , design displacement; K_v , vertical stiffness; K_{eff} , effective horizontal stiffness; Q , characteristic strength or yield strength; K_2 , inelastic stiffness or

post-yield stiffness; β , effective damping; K_1 , elastic stiffness or initial stiffness; D_y , yield displacement; R , radius of curvature of the sliding surface.

5 TMD

It is a well-known type of active seismic isolation system. A typical application of a tuned mass damper consists of a heavy mass installed near a building's top in such a way that it tends to remain still while the building moves

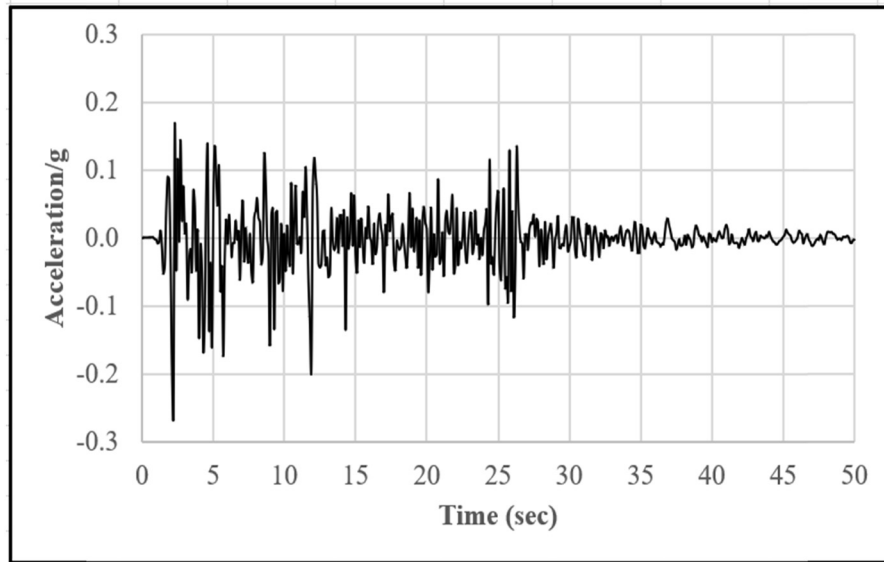


Figure 7: El Centro earthquake (El Centro Array #9, $R_{rup} = 6.09$ km) [24].

beneath it. This strategy allows the mass at the top to transmit its inertial force to the building in a direction opposite to the motions of the building itself, thereby reducing the building's oscillations [25].

The pendulum TMD system can be represented by a mass supported by cables, which allow the system to behave as a pendulum. Figure 8 shows a simple pendulum attached to a floor. The properties of the system are defined as follows: L is the cable or spring length, u is the displacement, K_H is the equivalent stiffness of the cable, and m_d is the mass of damper [26].

Different values for m_d and L are investigated to select the best m_d and L , which give the minimum BS and TSD. The considered TMD properties in this study are listed in Table 3.

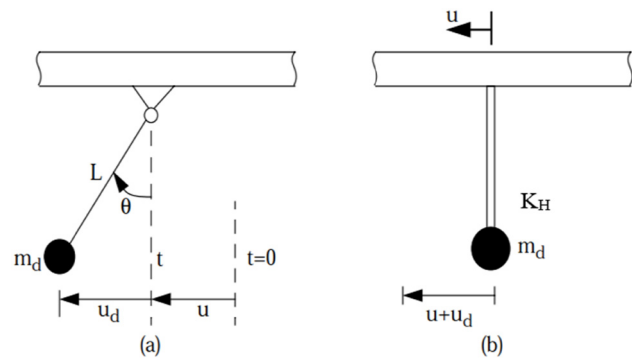


Figure 8: Simple pendulum tuned mass damper [26]; (a) actual system and (b) equivalent system.

Table 2: Properties of base isolators (six-storey building)

Property	HDRB	LRB	DSP
T_D (s)	2.5	2.5	2.5
D (mm)	200	200	200
K_v (kN/m)	4,300,000	1,970,000	1,360,000
K_{eff} (kN/m)	1,400	1,370	1,360
Q (kN)	113	141	47
K_2 (kN/m)	829	663	1,125
D_y (mm)	15.1	17.7	0.42
β (%)	24	30	23
r	0.1	0.077	0.1
R (m)			2

Table 3: Properties of the used TMD

Property	Value
Spring length (L)	1 m
Vertical stiffness (K_v)	490,000 kN/m
Damping constant (C)	0.07
Damper weight/total building weight% (W_d/W_t %)	1.3
Horizontal stiffness (K_H)	366 kN/m

6 Numerical modelling

In this study, SAP2000-V24 is used to model and analyse all the studied cases. Frame elements are used to define the

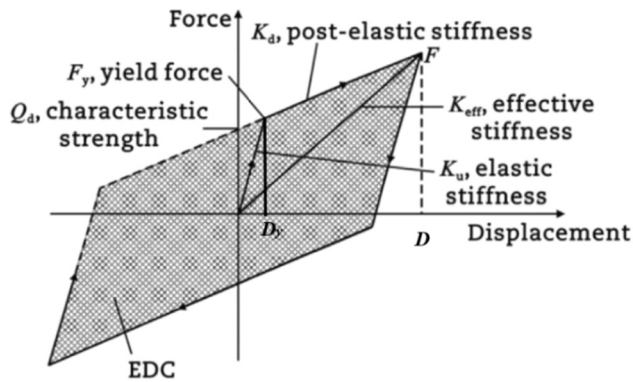


Figure 9: Characteristics of bilinear seismic isolation [27].

beams and columns. Shell elements are used to model the slabs. Link/support elements are used to model the isolators. The optimum mesh size is found to be $0.25 \text{ m} \times 0.25 \text{ m}$ for slabs and 0.25 m length for all beams and columns.

The nonlinear properties of the isolation systems are represented by the bilinear hysteretic model as shown in Figure 9. These properties are defined in SAP2000 as shown in Figure 10.

The configuration of the studied building with TMD is shown in Figure 11. The mass damper is modelled as a linear link with one end fixed at the top storey and the other end free. The mass weight is assigned at the free end.

Link/Support Properties

Link/Support Type: Rubber Isolator

Property Name: HDRB

Property Notes:

Total Mass and Weight

Mass: 0.

Weight: 0.

Factors For Line, Area and Solid Springs

Property is Defined for This Length In a Line Spring

Property is Defined for This Area In Area and Solid Springs

Directional Properties

Direction	Fixed	NonLinear	Properties
☒ U1	☐	☐	Modify/Show for U1...
☒ U2	☐	☒	Modify/Show for U2...
☒ U3	☐	☒	Modify/Show for U3...

Fix All

Stiffness Options

Stiffness Used for Linear and Modal Load Cases

Stiffness Used for Stiffness-proportional Viscous Damping

Stiffness-proportional Viscous Damping Coefficient Modification Factor

Link/Support Directional Properties

Identification

Property Name: HDRB

Direction: U2

Type: Rubber Isolator

NonLinear: Yes

Properties Used For Linear Analysis Cases

Effective Stiffness: 1400.

Effective Damping: 0.24

Shear Deformation Location

Distance from End-J: 0.

Properties Used For Nonlinear Analysis Cases

Stiffness: 829.

Yield Strength: 113.

Post Yield Stiffness Ratio: 0.1

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Figure 10: Isolator properties.

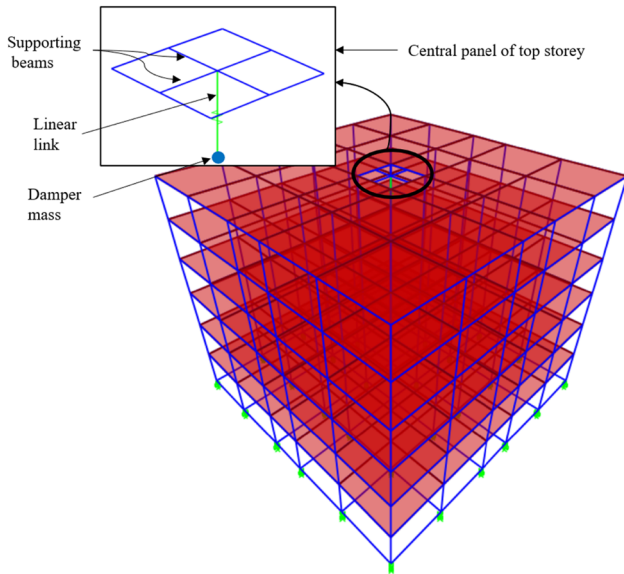


Figure 11: Building with TMD.

7 Results and discussion

7.1 Efficiency of base isolation systems and TMD

The nonlinear modal time history analysis method is used to analyse the fixed base (FB) and isolated base (IB) buildings with and without TMD at the top storey. Three systems of isolators (HDRB, LRB, and DSP) located at the base of ground floor columns are studied. A six-storey reinforced concrete building subjected to the N–S component of El Centro earthquake is considered to investigate the efficiency of the isolation systems. The results of fundamental period (T), BS, base shear reduction (BSR), TSD, base displacement (BD), and top storey acceleration (TSA) are presented in Table 4.

It is found that using all the base isolation systems leads to an increase in T by around 378%. Also, HDRB

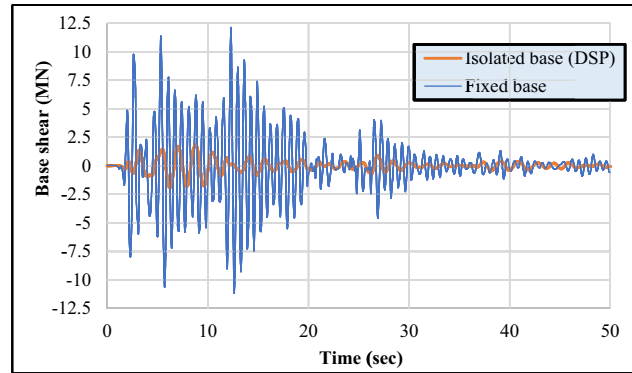


Figure 12: BS for FB and DSP IB buildings (El Centro).

and LRB reduce the BS by about 73%, while the DSP reduces the BS by 84.5%. Figure 12 depicts the time variation of BS for fixed-base and DSP IB buildings. Hence, using DSP isolators is preferred over HDRB and LRB.

The investigated isolation systems remain unaffected by earthquake intensity, consistently achieving BSR within the range of 70–90%. Consequently, base isolation techniques prove effective in safeguarding buildings from any earthquake event (Figure 13). Using TMD reduces BS of FB building by 38% when the building is subjected to weak earthquake (Badra), while the BSR is around 9% only when the building is subjected to strong earthquake such as Northridge. This indicates that TMD is less efficient than base isolation systems, as illustrated in Figure 14. It might be considered to enhance the seismic response of buildings exposed to weaker earthquakes.

The TSA can be reduced by about 66% when using base isolators (Figure 15). show that the TSD for the isolated buildings is increased as compared with FB buildings but this increase in TSD is mainly concentrated in the isolator's level. On the other hand, it is found that modeling the TMD at the top of six-storey building with FB reduces the TSD or total building drift (TBD) from 112.3 to 54.2 mm, but this reduction is still low compared to that obtained in the case of using base isolators. Therefore, TMD may serve as

Table 4: Efficiency of base isolation systems and TMD

Isolation system	T (s)	BS (kN)	BSR%	TSD (mm)	BD (mm)	TBD (mm)	TSA (m/s^2)
FB	0.52	12069		112.3		112.3	8.3
IB (HDRB)	2.475	3248	73	146	129.5	16.5	2.91
IB (LRB)	2.477	3314	72.5	166	149	17	2.96
IB (DSP)	2.488	1865	84.5	140.3	127.8	12.5	2.83
FB + TMD	1.052	8931	26	54.2	0	54.2	5.67
IB (HDRB) + TMD	2.461	2925	76	117	103.6	13.4	3.51
IB (LRB) + TMD	2.46	3020	75	141.5	126.2	15.3	3.57
IB (DSP) + TMD	2.464	1419	88	102	93.5	8.5	3.04

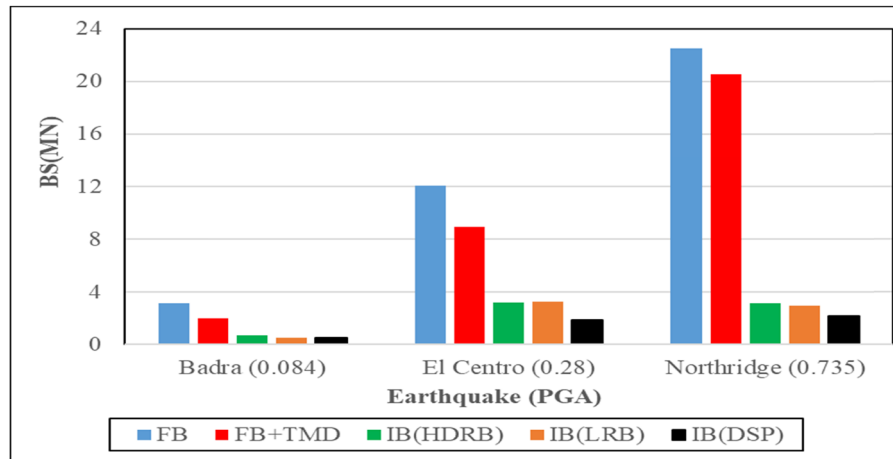


Figure 13: BS values for different earthquakes.

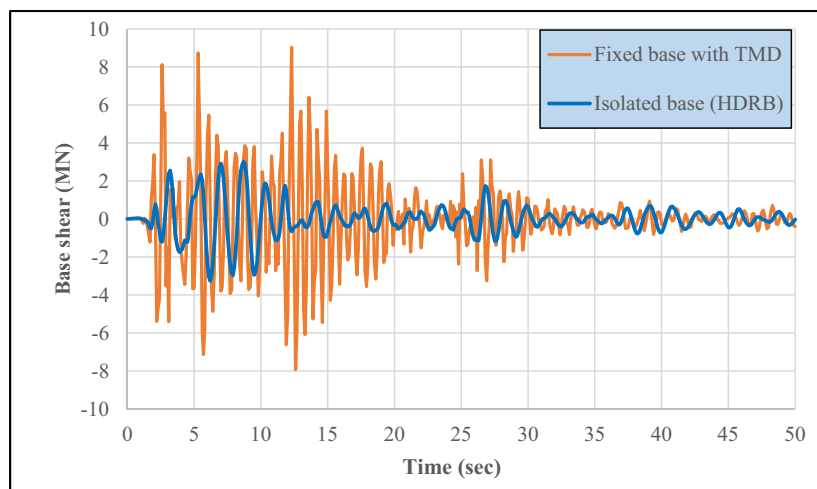


Figure 14: BS for HDRB IB building and FB building with TMD (El Centro).

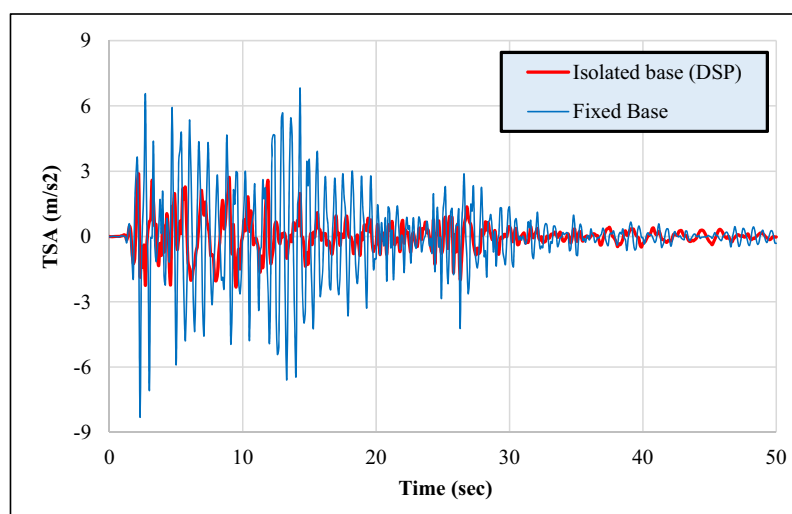


Figure 15: TSA for FB and DSP IB buildings (El Centro).

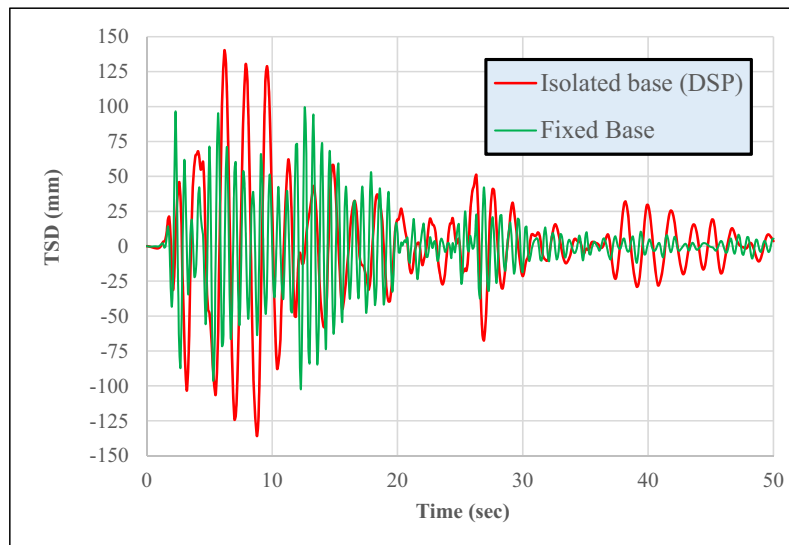


Figure 16: TSD for FB and DSP IB buildings (El Centro).

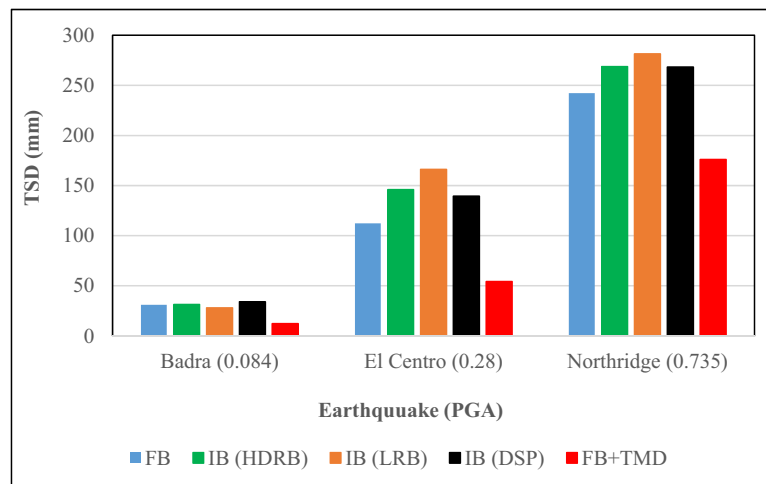


Figure 17: TSD for different earthquakes.

a practical choice for buildings with limited lateral movement space.

Also, it is detected that the building moves as a rigid body where the storey drift (TSD – BD) is very small as compared with the FB case (Figures 18–20).

Conversely, the results shown in Table 4 indicate that the utilization of a novel system incorporating both base isolation and TMD at the top storey leads to a mere 3% increase in BSR. Furthermore, BD and TSD exhibit a reduction of 20–27% compared to values obtained from base isolation systems. Thus, this system combines the advantages of base isolation systems and TMD, rendering it a practical choice for buildings with restricted lateral space necessary for the movement of base-isolated structures.

7.2 Effect of building height

To study the relationship between building height and seismic response of FB and IB buildings, 11 buildings subjected to El Centro earthquake were modelled. The buildings have the same slabs and beam sizes, while the columns sections are changed depending on the building height as presented in Table 1. The buildings height varies from 4 storeys (13 m) to 40 storeys (121 m).

It is clearly found that the natural vibration period (T) of FB and base isolated buildings has a direct relationship with the number of storeys or building height (Figure 21).

New formulas have been proposed to calculate the fundamental period (T) values for diverse building heights

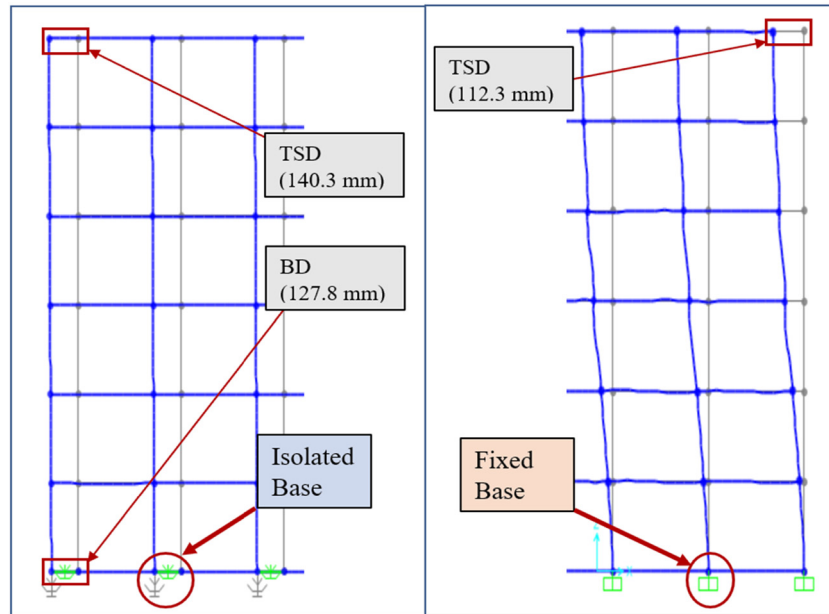


Figure 18: Deformation model of FB and DSP isolated buildings (El Centro).

and under various base conditions. They are based on the building height (H) or the number of storeys (N), given as follows:

$$T(\text{FB}) = 0.18N^{3/4} \text{ for } N < 10 \text{ storey, Else } = 0.21N^{3/4}, \quad (1)$$

$$T(\text{FB}) = 0.075H^{3/4} \text{ for } H < 31 \text{ m, Else } = 0.09H^{3/4}, \quad (2)$$

$$T(\text{IB}) = (T_D - 0.5) + 0.075N, \quad (3)$$

$$T(\text{IB}) = (T_D - 0.5) + 0.025H. \quad (4)$$

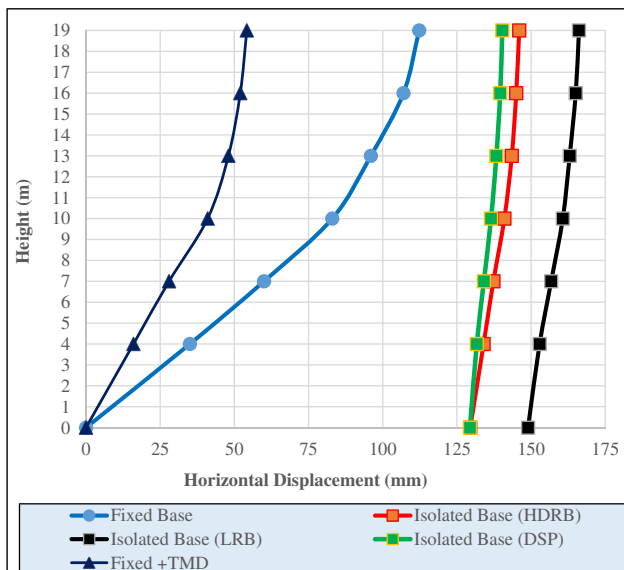


Figure 19: Lateral displacement for FB and isolated buildings (El Centro).

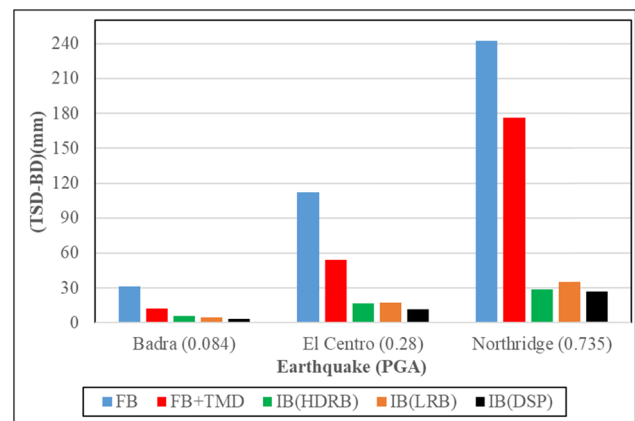


Figure 20: TBD for different earthquakes.

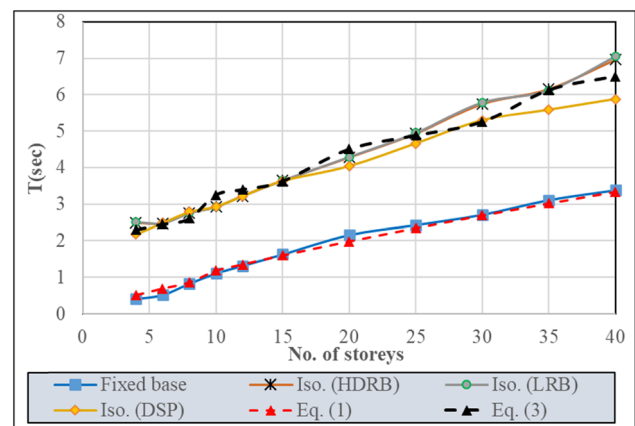


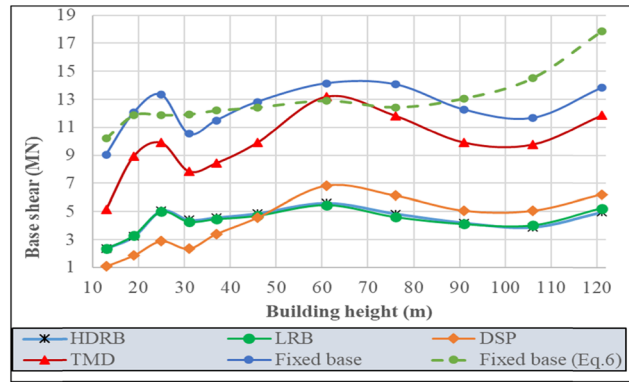
Figure 21: Relationship between the number of storeys and T .

Table 5: Fundamental period of FB buildings

No. of storeys	T (s)				
	FE	Equation (1)	Previous studies [Ref.]		
4	0.41	0.51	0.39 [28]	0.562 [30]	0.4 [37]
5	0.57	0.60	0.641 [33]		
6	0.52	0.69	0.57 [28]	0.625 [29]	0.6 [37]
7	0.78	0.77	0.829 [33]		
8	0.83	0.86	0.81 [28]	1.083 [30]	0.8 [37]
9	0.95	0.94	0.997 [33]		
10	1.11	1.18	1.14 [32]	1.16 [35]	
12	1.32	1.35	1.159 [33]		
15	1.63	1.60	1.426 [29]		
20	2.16	1.99	1.71 [36]	1.887 [31]	1.96 [35]
25	2.43	2.35	2.22 [36]		
30	2.71	2.69	2.58 [35]		
35	3.11	3.02	3.37 [36]	3.323 [34]	
40	3.38	3.34	3.721 [34]		

These equations are verified against previous studied, and the results are presented in Tables 5 and 6.

It is noticed that the BS values fluctuate with changing of building height (Figure 22). The increase in BS is associated with a low value for seismic response coefficient (C_s), which is defined as total seismic BS value (BS)/total effective seismic weight (W). Therefore, any increase in BS

**Figure 22:** Relationship between building height and BS.

for tall building is mainly related to (W). The relationship between building height (number of storeys) and C_s is shown in Figure 23.

Simple formulas are suggested to calculate the (C_s) and BS for FB buildings depending on the number of storeys and building height. These equations provide a practical means to reduce both effort and time in the analysis process, given as follows:

$$C_s = \frac{2.5}{N} = \frac{8}{H}, \quad (5)$$

$$BS = C_s \times W. \quad (6)$$

Table 6: Fundamental period of IB buildings

No. of storeys	T_D (s)	T (s)		
		FE	Equation (3)	Previous studies [Ref.]
3	4		3.755	4.007 [38]
4	1.5		1.3	1.523 [29]
	2		1.8	2.05 [39]
	2.5	2.15	2.3	2.23 [30]
6	2		1.95	2.15 [12]
	2.5	2.48	2.45	2.455 [30]
8	2	2.75	2.1	2.35 [39]
	2.5		2.6	2.78 [39]
9	4		4.175	4.07 [38]
	3		3.175	3.09 [38]
10	3	2.92	3.25	2.97 [12]
	2.5		2.75	2.67 [12]
	2		2.25	2.65 [32]
12	3	3.22	3.4	
15	3	3.64	3.625	3.501 [29]
20	3.5	4.27	4.5	4.05 [30]
	3		4	3.493 [31]
25	3.5	4.93	4.875	
30	3.5	5.75	5.25	
35	4	6.16	6.125	
40	4	6.96	6.5	

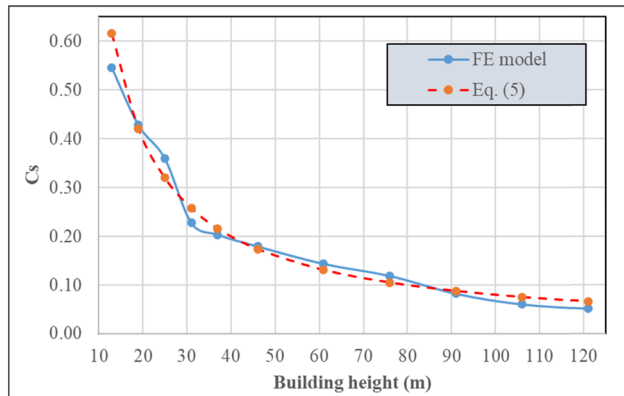


Figure 23: Relationship between C_s and building height.

Also, it is found that base isolation systems are efficient in reducing BS for all the studied earthquakes and building heights (Figure 24).

It is found that TSD is greater in tall FB buildings than in low-rise structures. The application of base isolation leads to an increase in TSD for low- and medium-rise buildings, while for tall buildings, it decreases compared to FB buildings (Figure 25). The TSD in base-isolated tall buildings is due to the higher horizontal stiffness of the utilized base isolators.

Generally, this increase in TSD is concentrated at isolator level where the total building drift (TBD = TSD – BD) is much lower than that found in the case of FB buildings (Figure 26).

The following equation is suggested to calculate the TBD for base isolated building:

$$\text{TBD} = \text{TSD} - \text{BD} = 6N^{0.7}. \quad (7)$$

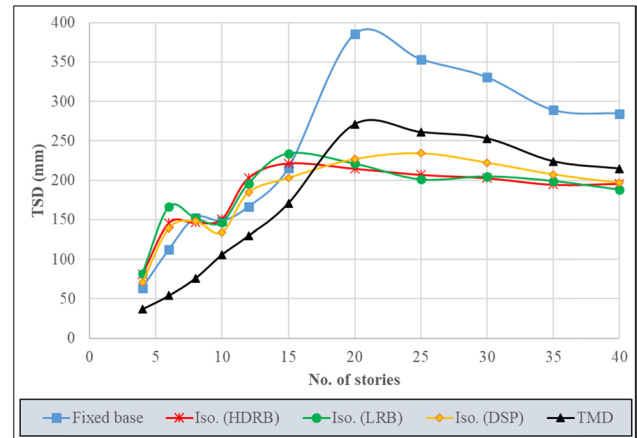


Figure 25: TSD and number of storey relationship.

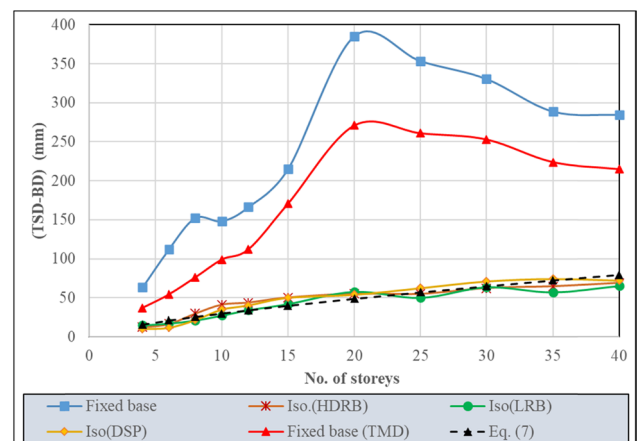


Figure 26: Relationship between number of storeys and TBD.

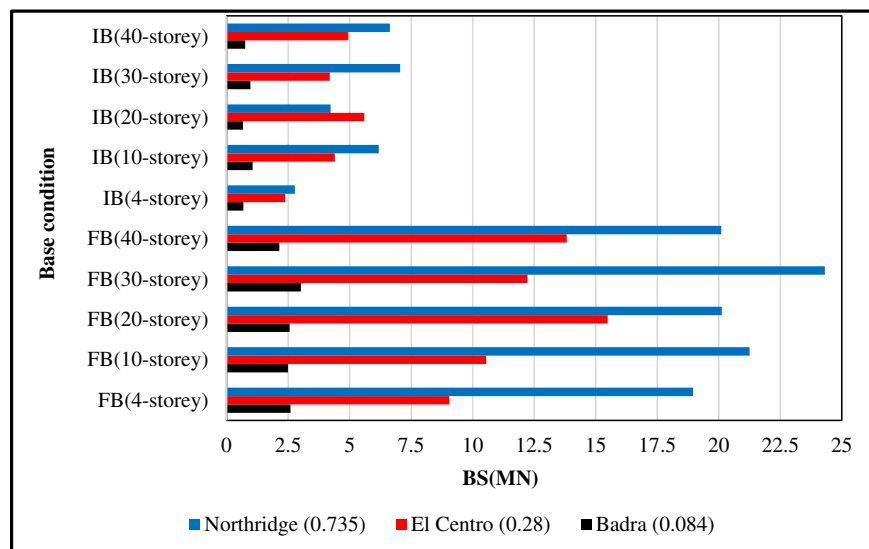


Figure 24: BS for different earthquakes and the number of storeys.

Table 7: TBD of base isolated buildings

No. of storeys	TBD (mm)		
	FE	Equation (7)	Previous studies [Ref.]
4	12.25	15.83	13.2 [30], 16 [43]
6	16.38	21.03	24 [31], 26 [40]
8	29.74	25.72	28.6 [30]
10	41.2	30.07	36 [32]
12	43.85	34.16	47 [40]
15	50.32	39.94	
20	55.21	48.85	54 [31], 53 [32], 58 [41]
25	55	57.11	
30	62.37	64.88	
35	64.6	72.28	
40	68.78	79.36	

The aforementioned equation is verified by using some previous studies as given in Table 7.

7.3 Multilevel isolation systems and TMD

The efficiency of one, two, three, and four isolation levels along a building height is investigated. A 12-storey building is considered to be subjected to El Centro earthquake in the N–S direction. The 11 cases studied are described in Table 8. The results of these cases are presented in Table 9.

It is noticed that using multilevel isolation gives higher values to the natural vibration period (T). Also, it is identified that using TMD at multilevels has a negligible effect on (T).

On the other hand, it is observed that using the isolators in the middle of building with FB reduces the BS about

Table 8: Case studies of multilevel isolation and TMD

Case study	Description
Case 1	FB building without isolation and TMD
Case 2	Base isolated (HDRB)
Case 3	FB with isolator at middle (6th) storey (HDRB).
Case 4	Two-level isolated building (base (HDRB) + middle (6th) storey (HDRB))
Case 5	Three level isolated building (base (HDRB) + 4th storey (HDRB) + 8th storey (HDRB))
Case 6	Four levels isolated building (base (HDRB) + 3rd (HDRB) + 6th storey (HDRB) + 9th storey (HDRB))
Case 7	FB with TMD at top storey
Case 8	FB with TMD at middle (6th) storey
Case 9	FB with TMD at top storey and middle (6th) storey
Case 10	FB with TMD at top storey + 4th storey + 8th storey
Case 11	FB with TMD at (top storey + 3th storey + 6th storey + 9th storey)

Table 9: Results of multilevels isolation and TMD

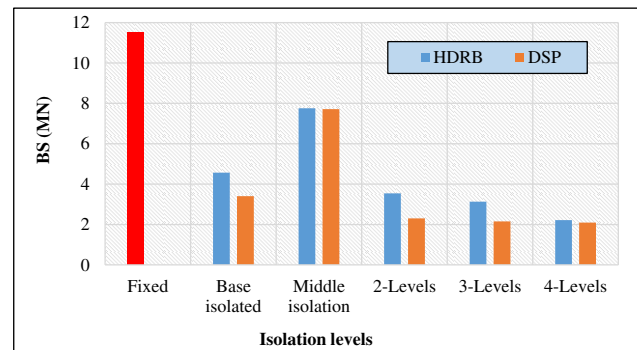
Case no.	T (s)	BS (kN)	BSR %	TSD (mm)	CDI* (mm)	TSD-ID (mm)	TSA (m/s)
1	1.52	11,495	0	166.4	0	166.4	5.78
2	3.22	4568.9	60.3	202.8	161.7	41.1	2.9
3	3.21	7756.3	32.5	234.4	151	83.4	3.14
4	3.02	3543.8	69.2	231.6	172.7	58.9	2.74
5	4.14	3130.2	72.8	230	183.4	46.6	2.36
6	4.28	2220.2	80.7	230.1	195	35.1	2.41
7	2.18	8442	26.6	112	0	112	5.55
8	2.18	8219	28.5	104.04	0	104.04	5.04
9	2.18	7785.6	32.3	90.9	0	90.9	4.84
10	2.18	6,687	41.8	81.9	0	81.9	4.67
11	2.18	6,381	44.5	76.6	0	76.6	4.64

CDI*: Summation of the lateral displacements of isolators occurred at all levels.

33%, while the base isolation with the isolators in the middle of building reduces the BS by around 70%. Also, it is found that using multilevel isolation reduces the BS more than using base isolation alone (Figure 27). The four-level isolation reduces the BS up to 81% (Figure 28). Consequently, employing a base isolation system demonstrates high efficiency, practicality, and economic feasibility compared to mid-level isolation systems.

Using TMD at middle of the building height with FB gives almost the same performance as that obtained from using TMD at the top storey. However, using TMD at multilevels leads to a decrease in the BS of the building (Figure 29). The BS is reduced by 44.5% in the case of using four levels of TMD, while it is reduced by 26.6% when only one TMD is used at the top storey of the building.

The multilevel isolation gives TSD values little higher than those obtained using base isolation only. This increase in TSD values is related to the displacement of the isolators at the different levels as shown in Figure 30.

**Figure 27:** Effect of multilevel isolation on (BS).

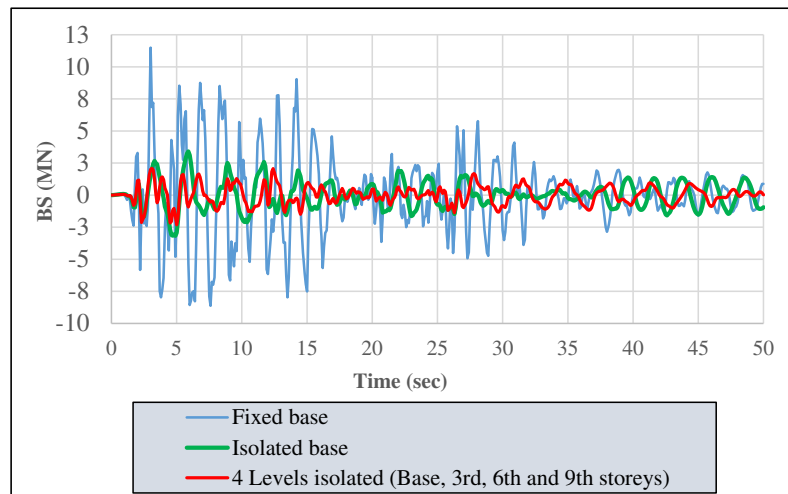


Figure 28: BS for fixed and IB and four-level isolation.

Using TMD at multilevel leads to a decrease in the TSD as well as the storey drift as depicted in Figure 31. Generally, the storey drift values in cases of using TMD are higher than the values resulting from using an isolator at base only or at multilevels.

8 Conclusions

The study explores the effectiveness of three commonly used seismic isolators and TMD in reducing BS, lateral displacement, and top storey acceleration for low, medium, and tall buildings. In addition, a newly suggested system that combines base isolators and TMD as well as a

multilevel isolation system are examined. The following conclusions can be drawn from this study:

- The use of base isolation systems increases the fundamental vibration period by over 378% for six-storey buildings.
- HDRB and LRB base isolation systems are equally effective in reducing seismic response, with the DSP system showing a slightly higher efficiency in minimizing BS. Hence, it is advisable to prioritize DSP during the design stage of base isolators.
- The TBD is highly reduced by using base isolation system although the TSD may be increased, but this increase is concentrated at the isolation level.

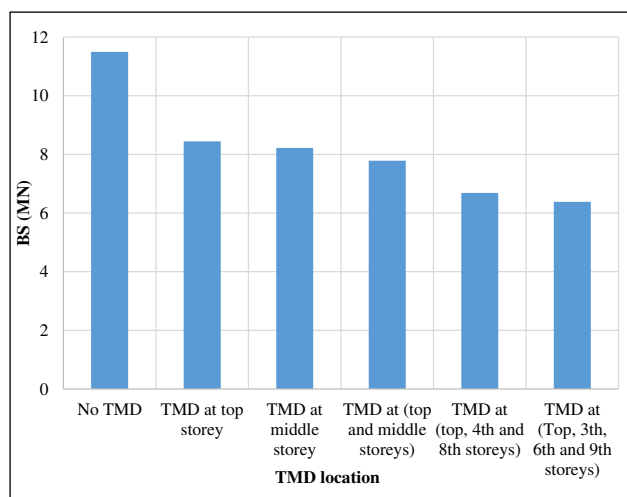


Figure 29: BS values for TMD at multilevels.

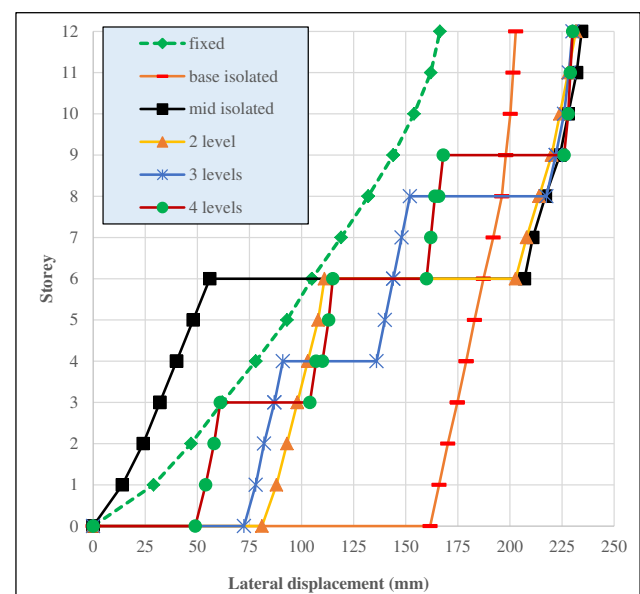


Figure 30: Storey displacement and isolation levels.

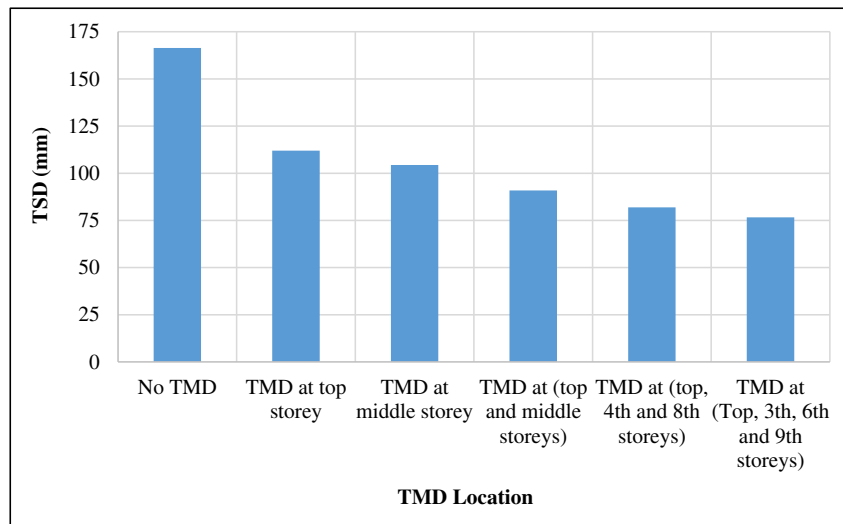


Figure 31: TSD of multilevel TMD.

- The TMD shows a small efficiency in reducing the BS, top storey acceleration, and TBD as compared with the base isolation systems. It reduces the TSD more effectively than base isolators.
- TMD demonstrates suitable efficiency in reducing BS resulting from weak earthquakes compared to strong earthquakes. Therefore, TMD and the system combines the base isolation and TMD are a practical choice for buildings with restricted lateral space and may be subjected to weak earthquakes.
- A slight improvement is achieved by adding a TMD at the top storey of the base isolated buildings. Hence, employing a combined system of base isolators and TMD is neither practical nor economical.
- The fundamental period of a building is directly related to its height. This relationship can be presented by simplified equations (equation (1)–(4)).
- Employing a base isolation system demonstrates high efficiency, practicality, and economic feasibility compared to midlevel isolation systems.
- Using base isolation increases the TSD of low- and medium-rise buildings and decrease the TSD in high-rise buildings as compared with FB buildings.
- The TBD for all heights of base isolated building is very small compared with FB buildings and can be calculated by using the proposed formula, equation (7), with error percentage less than 30%.
- The BS can be reduced by 81% using a four-level isolation system, surpassing the 60% reduction achieved with a base isolation system alone.
- The BS can be reduced by 44.5% in the case of using four levels of TMD, while it was reduced by 26.6% in the case of using one TMD at top storey.

The presented results and equations are specific to reinforced concrete buildings. Further studies should explore other types of buildings and structures. In addition, investigating a combined active and passive system of seismic isolation could be considered.

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Appendix

A1 Design of isolators

For the six-storey building, the maximum vertical load in service condition including seismic action (P_v) is 2,250 kN, T_D was assumed 2.5 s, and D was assumed 200 mm. The effective damping (β) for HDRB is taken 24%.

The horizontal or effective stiffness of the isolator is given by [1] and [3]:

$$K_{\text{eff}} = \frac{W \left(\frac{2\pi}{T_D} \right)^2}{g} = \frac{2,250 \left(\frac{2\pi}{2.5} \right)^2}{9.81} = 1,447 \text{ kN/m}.$$

Then, the energy dissipation per one cycle is calculated as follows [1,3]:

$$\text{EDC} = 2\pi K_{\text{eff}} D^2 \beta_{\text{eff}} = 2\pi \times 1,447 \times 0.2^2 \times 0.24 = 87.23 \text{ kN m}.$$

By neglecting the yield displacement (D_y), the characteristic strength is calculated as follows [1,3]:

$$Q = \frac{\text{EDC}}{4D} = \frac{87.23}{4 \times 0.2} = 109 \text{ kN}.$$

The value for post yield stiffness is calculated as follows [1,3]:

$$K_2 = K_{\text{eff}} - \frac{Q_d}{D} = 1,447 - \frac{109}{0.2} = 902 \text{ kN/m}.$$

Then, by assuming ($K_1 = 10K_2$) [1,3]:

$$K_1 = 9,020 \text{ kN/m}.$$

The yield displacement (D_y) is calculated as follows [1,3]:

$$D_y = \frac{Q}{K_1 - K_2} = \frac{109}{9,020 - 902} = 0.0134 \text{ m} = 13.4 \text{ mm}.$$

By considering the isolator catalogues, HDRB isolator is used with the following properties:

$$K_{\text{eff}} = 1,400 \text{ kN/m}, K_2 = 829 \text{ kN/m}, D_y = 15.1 \text{ mm}, \text{ and } \beta = 24\%.$$