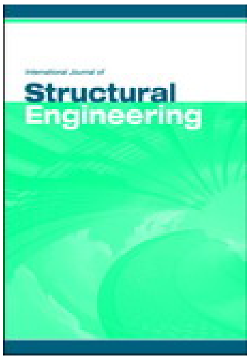

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Said Hicham Boukhalkhal, Mohamed Badaoui, Abdallah Yacine Rahmani

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Seismic assessment of base-isolated reinforced concrete moment-resisting frames

Said Hicham Boukhalkhal*

Built Environment Research Laboratory,
Faculty of Civil Engineering,
University of Sciences and Technology
Houari Boumediene of Algiers (USTHB),
BP.32 El-Alia, Bab Ezzouar 16111 Algiers, Algeria
Email: saidhichamboukhalkhal@yahoo.fr
*Corresponding author

Mohamed Badaoui

Department of Civil Engineering,
Laboratory of Mechanics and Materials Development,
University of Djelfa, Djelfa 17000,
P.O.B. 3117, Algeria
Email: badaoui.mohamed@yahoo.fr

Abdallah Yacine Rahmani

Department of Civil Engineering,
Seismic Engineering and Structural Dynamics Laboratory,
National Polytechnic School, Algiers, Algeria
University of M'sila, M'sila, Algeria
Email: abdallahyacine.rahmani@univ-msila.dz

Abstract: Until now, the Algerian seismic code has provided no guidance on how to design base-isolated structures. This work was done in order to propose including this technology in future versions of the seismic code. The present paper assesses the seismic performance of two types of buildings, conventional (fixed-base) and base-isolated, designed according to the Algerian seismic code RPA99/2003 using the capacity spectrum method (CSM). Herein, the influence of seismic isolators on the seismic behaviour of buildings is estimated. The nonlinear constitutive laws of the structural components and seismic isolators were derived and incorporated into the analysis. The comparative study carried out on the structure with and without the base-isolation, system highlighted the effect of seismic isolators on the reduction of seismic demands such as the base shear forces and the story drifts. The results also show that the use of seismic isolators is disadvantageous for tall buildings.

Keywords: pushover analysis; lead rubber bearings; LRB; seismic base isolation; capacity spectrum method; seismic performance.

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Biographical notes: Said Hicham Boukhalkhal is an Associate Professor at the Faculty of Civil Engineering, University of Sciences and Technology Houari Boumediene (USTHB) in Algiers, Algeria. He earned his Bachelor's in Civil and Industrial Construction from Djelfa University in 2010. In 2019, he completed his PhD in Civil Engineering from USTHB. During this time, he actively contributed to the academic community by reviewing articles for various national and international journals and by publishing numerous works in the field of earthquake engineering. Additionally, he holds the distinguished position of President at the 'Mohamed Sayhi' Association of Civil Engineering (AIC).

Mohamed Badaoui is an Associate Professor at Zian Ashour University in Djelfa, currently holds the position of Director at the School of Professions for Qualifying Engineers, affiliated with the Ministry of Public Works. His extensive body of work includes numerous publications and research contributions in the field of earthquake engineering.

Abdallah Yacine Rahmani is an Associate Professor at the University of M'sila in Algeria. He earned his Bachelor's and Master's in Civil and Industrial Construction from Djelfa University in 2010 and 2013, respectively. In 2014, he achieved a Magister degree in Seismic Risk and Earthquake Engineering from the University of Tlemcen, followed by a PhD in Civil Engineering from the University of Blida 1 in 2018. Over the past decade, he has delivered numerous presentations at national and international conferences. He is an active member of the international network of Algerian scientists and a founding member of the 'Mohamed Sayhi' Association of Civil Engineering (AIC). Furthermore, he serves as a reviewer for various national and international journals and has authored several publications in the field of earthquake engineering.

1 Introduction

During the last decades, several earthquakes of different intensities have occurred in several countries, Algeria being one of them, and caused considerable loss of life and material damage. These levels of damage have prompted researchers in the field to develop solutions to reduce the seismic risk (Kasimzade et al., 2018; Akhaveissy et al., 2023; Mehta and Purohit, 2022; Hashemi et al., 2021). The main objective of designers is to provide an acceptable level of safety (Gong et al., 2023; Chen et al., 2023; Yakut, 2004) to reduce the risk of failure, damage, and loss of life.

In the current practice of calculation, design, and dimensioning to earthquakes of structural elements in reinforced concrete, the Algerian seismic rules RPA99/2003 (CGS, 2003) attempt, through the objectives assigned, to provide buildings with sufficient strength to avoid total collapse and adequate ductility to absorb seismic energy by post-elastic deformations and then accept a level of damage to non-structural elements. These objectives can be achieved by ensuring proper implementation and execution and improving the quality control of materials. However, the fact remains that the damage and loss of life caused by recent earthquakes confirm each time the inadequacy of our practices and the inadequacy of our control process (Boukhalkhal et al., 2019).

One of the recent approaches to better protecting buildings, which tends to be generalised in countries with high seismic risk and particularly in Japan, the USA, Italy, and China, is the use of seismic isolation techniques at the base of buildings (Martelli et al., 2012). This method involves controlling the displacements and accelerations induced in structures and, as a result, reducing stresses in structural elements by keeping them in the elastic domain (De Domenico and Ricciardi, 2018; Bhandari et al., 2018).

Seismic isolation at the base consists in decoupling the ground movement from the movement of the structure to reduce the forces transmitted to the latter. In addition, the displacements imposed on the structure by the ground movements are concentrated at the level of the supports, designed to support them without damage. Due to the low horizontal stiffness of these supports, the natural period of the construction is prolonged and the oscillation speed is lower, as well as the accelerations transmitted to the superstructure (Kasimzade et al., 2018; Akhare, 2023).

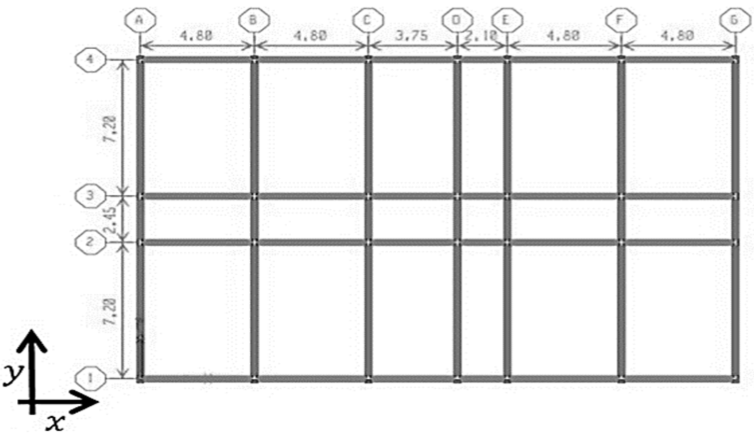
For base-isolated structures, the research on evaluating responses at performance points in contrast to nonlinear time history analysis (NTHA) is quite limited (Bhandari et al., 2018; Boukhalkhal et al., 2020). While existing fixed-base frame design practice allows for adequate inelastic deformation in the structure, available base-isolated structure design guidelines, such as Eurocode 8 (European Commitee for Standardization, 2004), propose that the superstructure should remain in the elastic range. Under earthquakes, both types of frames experience inelastic behaviour, while it is widely considered that base-isolated frames respond elastically at design-level earthquakes. However, several studies have shown that depending on the nature and intensity of the earthquake, base-isolated buildings can exhibit different levels of inelastic behaviour (Baker, 2007; Kikuchi et al., 2008; Kilar and Koren, 2009; Bhandari et al., 2017; Mazza and Vulcano, 2012). This has resulted in the performance evaluation of base-isolated buildings using simplified nonlinear static analyses (NSPs) (Boukhalkhal et al., 2020; Rahmani et al., 2022). Extensive research has been conducted over the last few decades in an attempt to enhance the NSPs methods. (Chopra and Goel, 2004; Rahmani et al., 2018, 2022; Rahmani et al., 2019; Poursha et al., 2011). Unfortunately, the new procedures made the pushover analysis more complex and difficult to apply in practice.

At the international level, many studies on the performance evaluation of base-isolated buildings have been done in recent years (Doudoumis et al., 2006; Providakis, 2008; Kilar and Koren, 2008; Koren and Kilar, 2011). However, in Algeria, only two buildings were designed based on isolated bases, and the Grand Mosque of Algiers is one of them (Constantinescu and Köber, 2013). In effect, this technology has not found its way into the Algerian seismic bases until now.

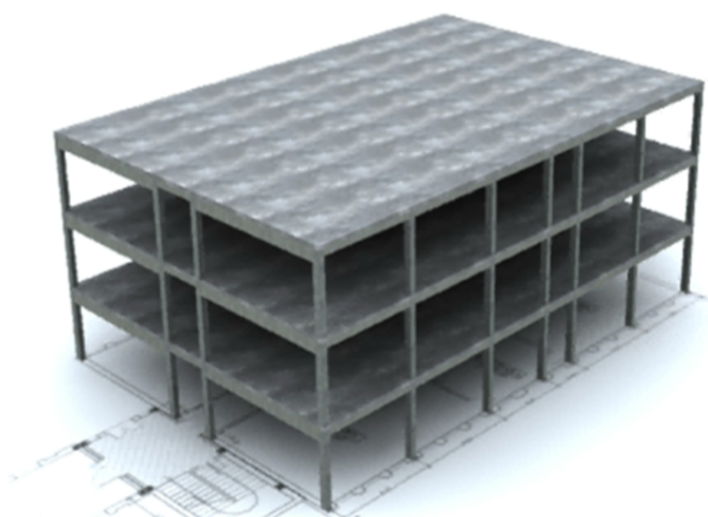
This research is motivated by some concerns about the use of seismic isolators in the construction of reinforced concrete moment-resisting frames RC-MRF in medium and high seismicity zones according to Algerian seismic rules, RPA 99/2003 (CGS, 2003). As a result, the main assignments are summarised as follows: The limitation on the number of levels or heights of structures for systems 1.a and 1.b in a way that is stipulated in paragraph 3.4 of RPA 99/2003(CGS, 2003) and the level of seismic performance achieved using this technique.

To achieve the objectives of this study, a series of numerical simulations were performed on two types of structures: conventional (fixed-base) and isolated-base, using nonlinear analysis methods. The dimensioning of the structural elements was done based on the rules of RPA 1999 (Version 2003) (CGS, 2003) and CBA 1993 (CBA, 1993). The nonlinear constitutive laws of the structural elements and the seismic isolators were calculated and inserted as given in the calculation program ETABS software (2015). The capacity spectrum method (CSM) (ATC-19, 1995) has been used in the analysis of conventional and base-isolated frames.

Figure 1 Details of 3-story test frames (a) plan view, (b) 3D view of the building



(a)



(b)

2 Description of the studied building

The structure studied is a high school with 600 students, built in the region of Djelfa (Algeria). The resistance of the building is ensured in both horizontal directions by reinforced concrete moment-resisting frames (RC-MRF): seven RC-MRF in the longitudinal direction and four RC-MRF in the transversal direction [Figure 1(a)]. The dimensions of the structure in plan are LX = 25.05 m, LY = 16.85 m and the overall height is (3.74 m × 3) = 11.22 m. The plan, and 3D views are shown in Figures 1(a) and 1(b).

The two Algerian codes, CBA 93 (CBA, 1993) and RPA 99/2003 (CGS, 2003) are used to design structural and non-structural elements. The two Tables 1 and 2 summarise the adopted dimensions. Aside from the weight of the concrete slab and the structural components, each level of the structure faces a set of distributed loads, as indicated in Table 3. The characteristic values of the dead loads are denoted by Gj, whereas the live load is denoted by Qj.

Table 1 Sizing of structural elements

Story	*Slab (cm)*	*Columns (cm)*	*Beams (cm)*
3rd floor	Hollow core slab (16 + 4)	(30 × 40)	Principal (30 × 60)
			Secondary (30 × 35)
2nd floor	Hollow core slab (16 + 4)	(30 × 40)	Principal (30 × 60)
			Secondary (30 × 35)
1st floor	Hollow core slab (16 + 4)	(30 × 40)	Principal (30 × 60)
			Secondary (30 × 35)

Table 2 Cross-section and reinforcement details of the beams and columns

Story	*Beams*			*Columns*		*Mechanical properties*
	b x h cm²	*Steel bars*		*a x a cm²*	*Steel bars*	
		Top layer	*Bottom layer*			
1	30 × 60 30 × 35	3Φ12 + 3Φ12	3Φ12 + 3Φ12	30 × 40	12Φ14	f_{c28} = 25 *MPa*
2						f_y = 500 *MPa*
3						E_c = 32.16 *GPa*
						E_S = 210 *GPa*

Table 3 Distributed loads per unit area at each level of the building

Story	*G_j (kN/m²)*	*Q_j (kN/m²)*
3rd floor	6.47	1.00
2nd floor	5.15	4.00
1st floor	5.15	4.00
Exterior walls	2.90	-
Acroterion	2.25	-

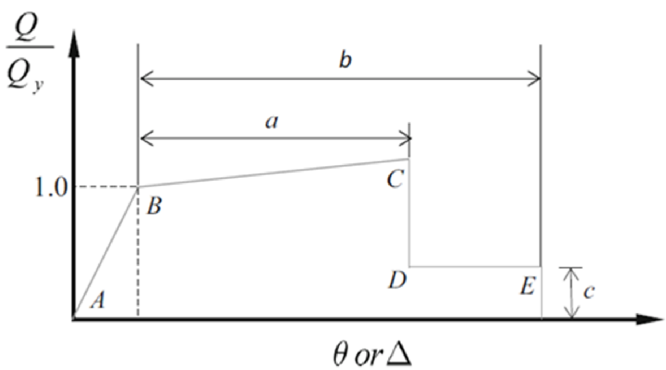
ETABS (2015) is professional software adapted to reinforced concrete, steel, or mixed constructions. Several types of analysis are available in this software, which makes it one of the most powerful in its category. The analysis types available in ETABS include modal analysis, response spectrum analysis, linear and nonlinear time history analyses, and the nonlinear static or pushover analysis for both conventional and base-isolated structures. In this study, the nonlinear static pushover analysis is used.

3 Static nonlinear analysis

3.1 Constitutive law of elements

Figure 2 depicts the nonlinear behaviour of a structural element (column or beam). This curve explains the behaviour of the development of plastic hinges in the elements extremities. The ETABS program uses constitutive laws called rigid-plastic by default for all the elements; the software determines their properties when giving the geometry of the elements as well as the section of the steel bars based on the FEMA-356 guidelines (FEMA, 2000).

Figure 2 Generalised force deformation relationship for plastic hinges



Source: FEMA (2000)

3.2 Design and constitutive law of seismic isolators

In this study, a lead rubber bearing (LRB) isolator is used. The system consists of 28 isolators placed concentrically under each column; the most stressed isolator has been calculated from the maximum vertical load that falls on the most stressed column, and the dimensions have been generalised to all the other bearings. The design of the seismic isolator is done according to UBC 97 [36]. Figure 3 and Table 4 show the geometric dimensions and mechanical characteristics of the seismic isolators used.

Figure 3 Lead rubber bearings (LRB) (see online version for colours)

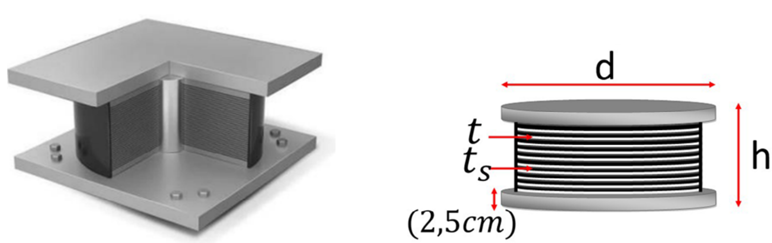


Table 4 Geometric dimensions and mechanical characteristics of the seismic isolator

Geometric dimensions of the seismic isolator	Diameter of the bearing, d = 40.00 *cm* total height of the bearing, h = 10.00 *cm* number of rubber layers, n_C = 04 thickness of a single layer of rubber, t = 10.00 *mm* number of steel layers, n_S = 05 thickness of a single steel layer, t_S = 2.00 *mm* Mounting plate thickness = 2.50 *cm*
Mechanical characteristics of the seismic isolator	Effective stiffness k_{eff} = 596 kN/m^2 Effective damping ratio ξ_{eff} = 20%

Figure 4 depicts the seismic isolator's constitutive law. The bilinear approximation parameters representing the behaviour curve are as follows (UBC-97, 1997):

$$K_u = \alpha K_d \tag{1}$$

$$K_d = \left(K_{eff} \frac{Q_d}{D} \right) \tag{2}$$

$$Q_d = \frac{\pi}{2} K_{eff} \xi_{eff} D \tag{3}$$

$$D_y = \frac{Q_d}{K_u K_d} \tag{4}$$

$$F_y = \frac{K_u}{D_y} \tag{5}$$

K_u linear stiffness

K_d nonlinear stiffness

K_{eff} effective stiffness

ξ_{eff} effective damping ratio

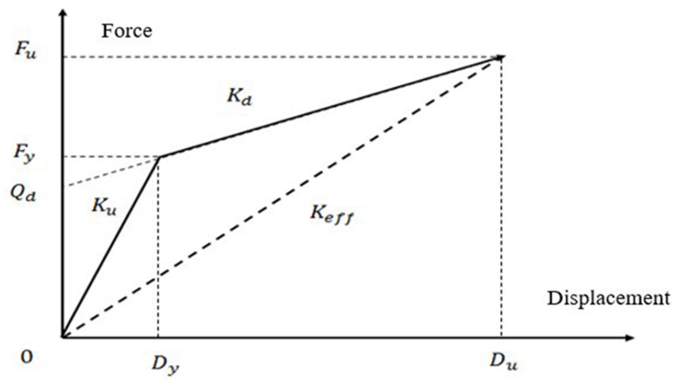
Q_d short-term elasticity force

$D = \dfrac{\left(\dfrac{g}{4\pi^2}\right) S_D T_D}{B_D}$ with S_D = 0.4 and B_D = 1.5: Design displacement (for more details see UBC 97 [36])

D_y yield displacement

F_y yield force.

Figure 4 Bilinear seismic isolator's constitutive law



4 Computation results and interpretations

4.1 Dynamic characteristics of the studied structures

The modal results obtained for the two types of structures are summarised in Table 5. The results demonstrate that the isolation system is intended to soften the building by increasing the fundamental period of the structure to a value greater than the value obtained for fixed-base structures ($T_{isolated} = 3 \cdot T_{Fixed}$). The period shift is the primary reason for the effectiveness of the isolation system.

Table 5 The modal characteristics of the studied structures

	Fixed-base structure	*Base-isolated structure*
Fundamental period T (s)	0.886	2.735
Modal participation factor of the first mode (Γ)	1.25	1.04
The first modal participating mass ratios (α)	87.46%	99.61%

According to article 4.3.4 of the RPA 99/2003 (CGS, 2003), the number of modes to be considered is such that the sum of the effective modal masses for the selected modes is at least equal to 90% of the total seismic mass of the structure. From Table 5, it can be seen that the cumulative modal mass contribution of the base-isolated structure exceeds 95% in the first vibration mode. On the other hand, for fixed-base frames, the mass contribution is 90%. Therefore, the domination of the first mode is observed for the base-isolated structures; in other words, the contribution of higher modes is negligible.

4.2 Capacity curves (pushover)

Figures 5 and 6 show the capacity curves for the fixed-base and isolated-base structures in both longitudinal and transversal directions. The curves are obtained by applying an inverted triangular load pattern (Fajfar and Gaspersic, 1996). The response of the fixed-base structure is characterised initially by an elastic phase, then it becomes inclined, describing the behaviour of the structure in its inelastic phase, and at the end, it notes a significant degradation of the lateral stiffness of the frame until the failure that caused by the formation of a ruin mechanism. In contrast, the response of the base-isolated structure shows little change between the elastic and plastic phases.

These curves show the influence of seismic isolation systems on the capacity of structures. Fixed-base structures have an initial stiffness superior to that of base-isolated structures, but with a maximum displacement less than that of the base-isolated structure.

Figure 5 Capacity curve in x-direction

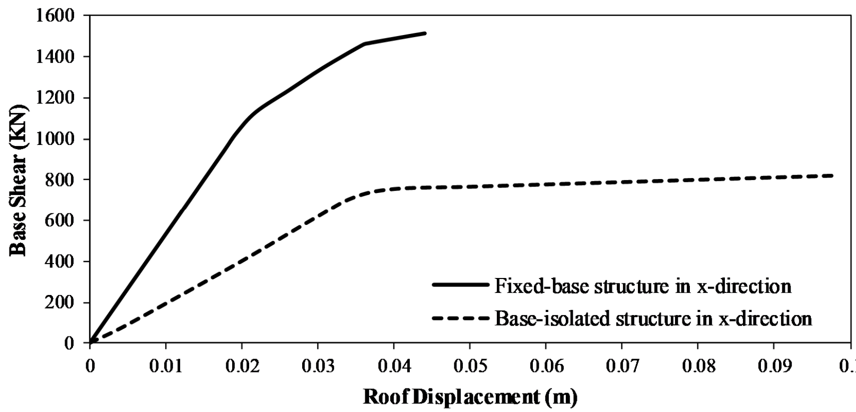
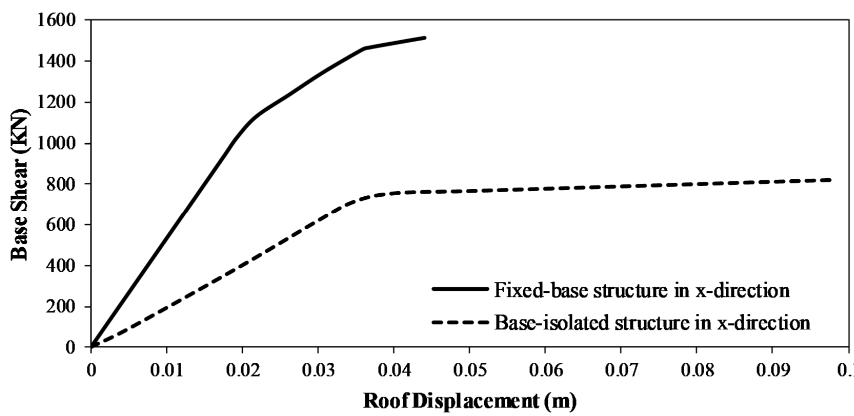


Figure 6 Capacity curve in y-direction



4.3 Seismic demand assessment

The response spectrum according to the Algerian seismic code RPA99/2003 (CGS, 2003) was used in this analysis (Figure 7). After that, the elastic response spectrum (Sa-T) is converted into the acceleration-displacement response spectrum ADRS format (Sa-Sd). Figure 8 depicts the ADRS format. After that, CSM (ATC-19, 1995; ATC-40, 1996) is used to evaluate the performance point (target displacement), the calculation steps are summarised as follows:

- Conversion of the demand spectrum to ADRS format
- Evaluation of the performance point.

Figure 7 RRPA 99/2003 elastic response spectrum (see online version for colours)

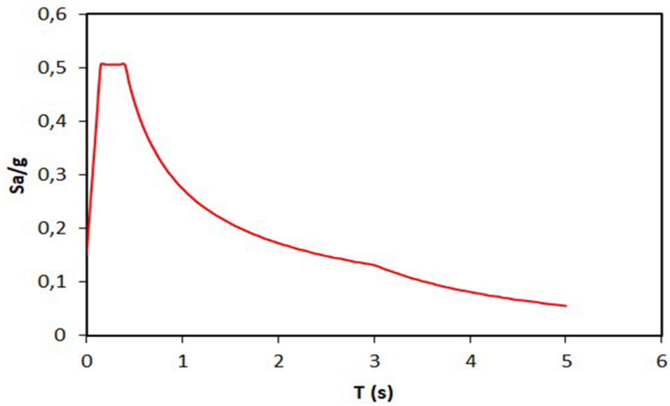
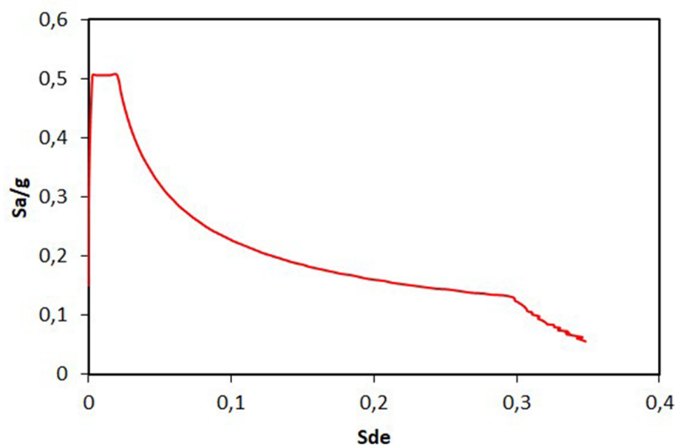


Figure 8 Elastic response spectrum in ADRS format (see online version for colours)



4.4 Performance point assessment

To determine the performance point, procedure A (the damping approach) is used (ATC-40, 1996; Lagaros and Fragiadakis, 2011). It compares the structure's capacity curve (capacity to dissipate energy) with the demand (energy demand to be dissipated) in the form of an inelastic spectrum (for more details, see ATC-19 ((1995)). The inelastic spectrum is established by reducing the elastic design spectrum by factors related to damping and period. Figures 9 and 10 illustrate the performance points for both fixed-base and base-isolated structures.

The determination of the performance point for each structure shows an increase in spectral displacement, which represents the displacement of the isolation system, and a decrease in spectral acceleration (in the order of 49% in the x-direction and 41% in the y-direction of building), which represents the reduction in demand in terms of loads brought by the earthquake.

Table 6 shows the different response characteristics for both fixed-base and base-isolated structures. The seismic isolators decreased the shear force at the base by around 51% and consequently increased the target displacement and the ductility of the structures by approximately 95% and 35%, respectively. This is due to the increase in the period and the influence of the base isolation system on the frequency content of the structures.

The energy dissipation capacity is a critical feature in seismic design. The flexibility of the base-isolated frame under excessive deformation leads to the formation of a less important mechanism of failure than that of a fixed-base structure.

Figure 9 Performance point of fixed-base structure (see online version for colours)

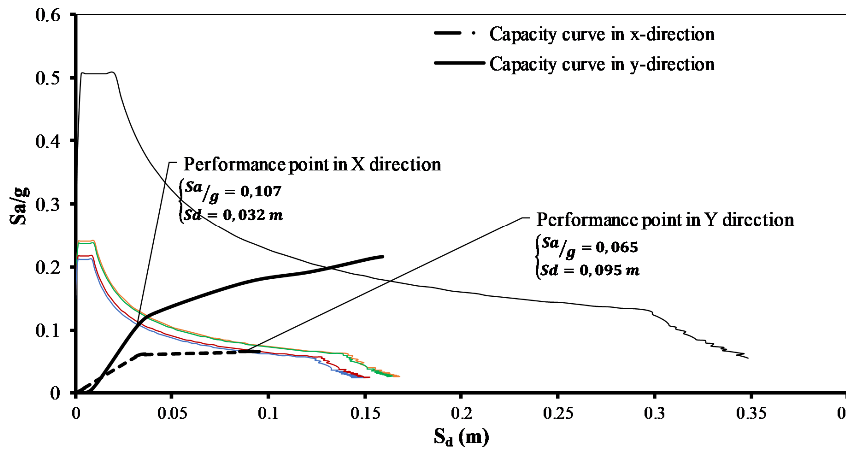


Figure 10 Performance point of base-isolated structure (see online version for colours)

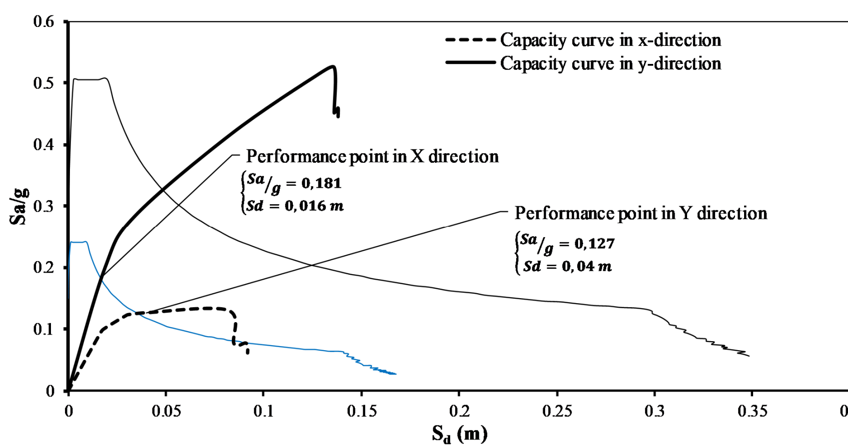


Table 6 Response characteristics for studied building

Results	*Fixed-base structure*		*Base-isolated structure*	
	x-direction	*y-direction*	*x-direction*	*y-direction*
Target displacement $\Delta_{x,y}$ (m)	0.05	0.024	0.098	0.046
Base shear force $V_{x,y}$ (KN)	52.79	87.70	26.83	55.80
Ductility factor (μ)	2.27	1.09	3.06	1.27

Figure 11 Inter-story drifts ratio in x-direction (see online version for colours)

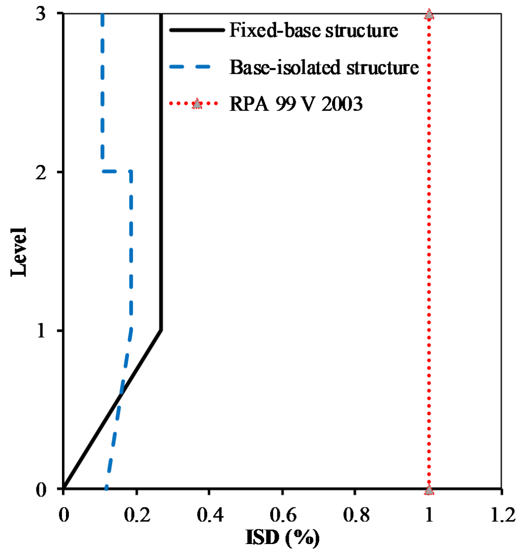
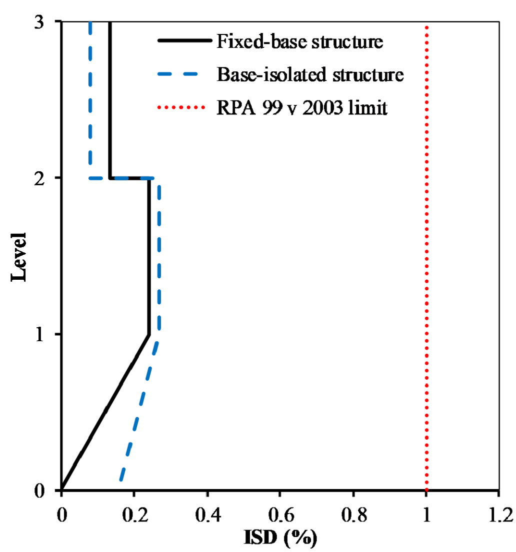


Figure 12 Inter-story drifts ratio in y-direction (see online version for colours)



4.5 Inter-story drift ratio

The determination of the inter-story drift ratio (ISD) is essential for the seismic evaluation of buildings because structural damage is directly related to this parameter. The results of ISD are shown in Figures 11 and 12. The inter-story drifts of the base-isolated structure are lower than those of the fixed-base structures. This difference is explained by the contribution of the seismic isolators, which makes these structures deform almost like rigid bodies. It should be noted here, however, that the ISD ratios obtained for both cases remain less than the upper limit recommended by RPA 99 v 2003 (1%) (CGS, 2003).

4.6 Failure mechanisms

The redistribution of loads in the various parts of the structure is caused by cracking of the concrete in the structures and increasing loading. Certain zones enter the post-elastic field, where the appearance of the plastic hinges contributes to the formation of a mechanism of failure that must be statically stable to be retained as representative of the bearing capacity of the studied system.

The ultimate failure mechanisms for fixed-base and base-isolated buildings are depicted in Figures 13 and 14, respectively. The results demonstrate that the seismic isolators reduce the plastic zones by 63% and then improving the structure's resistance to seismic loads.

5 Parametric study

The findings in the preceding sections of this study prompted us to look into the effect of the seismic isolation system on muti-storys buildings. Then, three, five, and ten-story buildings are selected to investigate the influence of the structure height on the nonlinear behaviour of base-isolated structures. All structures in plan have the following dimensions: L_X = 25.05 m, L_Y = 16.85 m, and a storey height of 3.74 m. Figure 15 depicts the 3D perspectives.

Figure 13 Plastic hinges distribution of the fixed-base structure (see online version for colours)

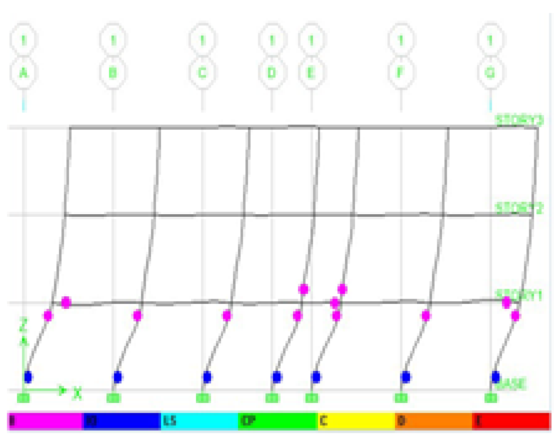
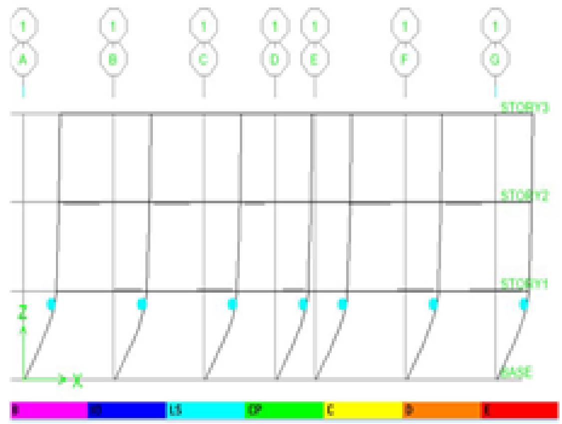


Figure 14 Plastic hinges distribution of the base-isolated structure (see online version for colours)



The two Algerian codes, CBA 93 and RPA 99/2003 (CGS, 2003; CBA, 1993) are used to design structural and non-structural elements. A Table 7 summarise the adopted cross-section and reinforcement details of the beams and columns. The adopted values of dead and live loads are shown in the Table 3.

5.1 Constitutive law of elements

Figure 2 depicts the nonlinear behaviour of a structural element (column, beam). This curve explains the development of plastic hinges in the elements.

5.2 Constitutive law of seismic isolators

The bilinear constitutive law (force – displacement) of the isolator for the studied structures is shown in Figure 16.

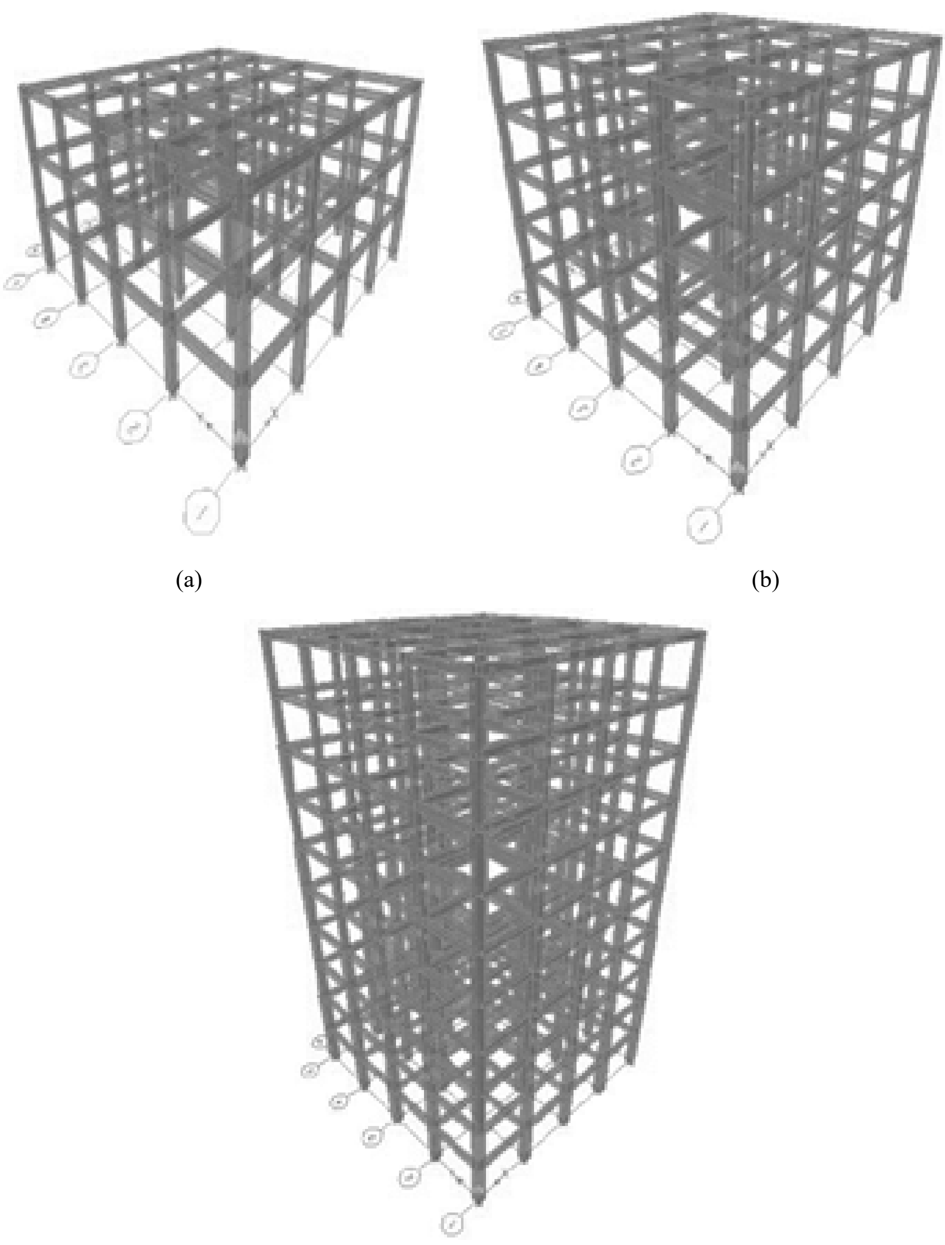
5.3 Dynamic characteristics of the studied structures

The modal results obtained for the studied structures are summarised in Figure 17. An increase in the base-isolated structure's fundamental periods of about 60% and 27% for the frames of 3 and 5-story buildings, respectively, is observed. On the other hand, the order is 1% for the structure of a 10-story frame. Furthermore, there is no change in the mass participation factor for the 10-story structure, and a slight variation is observed for the 5-story structure.

5.4 Performance point assessment

In this part of the study, the same elastic response spectrum of the seismic demand is used with the same characteristics (Figure 8). Figure 18 shows the performance characteristics for the fixed-base and base-isolated 3, 5, and 10-story structures. A significant increase in the target displacement of the base-isolated structures (about 50%) is detected. Concerning the base shear forces, the seismic isolation system increases these forces in an unexpected manner (particularly for the 10-story building), which explains why the effect of seismic isolators is unfavourable for tall buildings.

Figure 15 3D view of the building, (a) 3-story building, (b) 5-story building, (c) 10-story building (see online version for colours)



(a) (b) (c)

Figure 16 Bilinear constitutive law of the seismic isolator

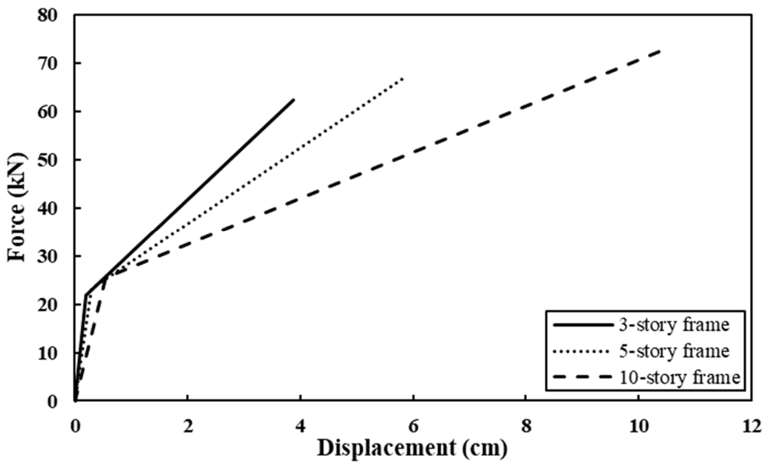


Table 7 Cross-section and reinforcement details of the beams and columns

Structure		*Beams*		*Columns*		*Mechanical properties*
		b × h cm²	*Steel bars*	*a × a cm²*	*Steel bars*	
3-story	1	30 × 40	3Φ12+3Φ12	40 × 40	12Φ14	f_{c28} = 25 *MPa* f_y = 500 *MPa* E_c = 32.16 *GPa* E_S = 210 *GPa*
	2			35 × 35	8Φ14	
	3			35 × 35	8Φ14	
5-story	1	30 × 40	3Φ12+3Φ12	45 × 45	12Φ14	
	2			40 × 40	12Φ14	
	3			40 × 40	12Φ14	
	4			35 × 35	8Φ14	
	5			35 × 35	8Φ14	
10-story	1	30 × 40	3Φ12+3Φ12	55 × 55	16Φ16	
	2			55 × 55	16Φ16	
	3			50 × 50	16Φ14	
	4			50 × 50	16Φ14	
	5			45 × 45	12Φ14	
	6			45 × 45	12Φ14	
	7			40 × 40	12Φ14	
	8			40 ×40	12Φ14	
	9			35 × 35	8Φ14	
	10			35 × 35	8Φ14	

Figure 17 Dynamic characteristics of the studied structures, (a) fundamental period T, (b) the first modal participating mass ratios (α) (see online version for colours)

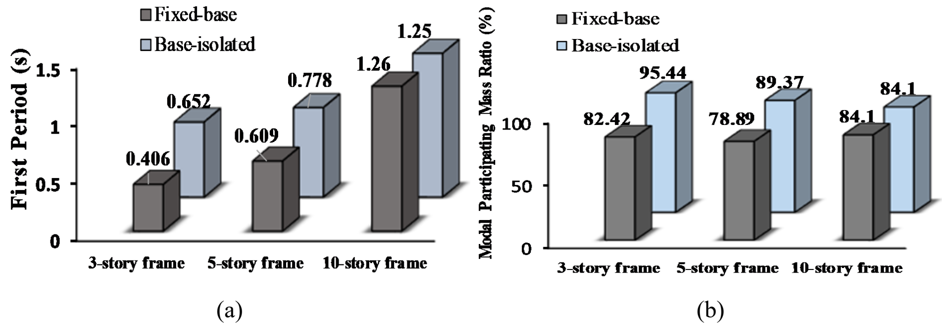
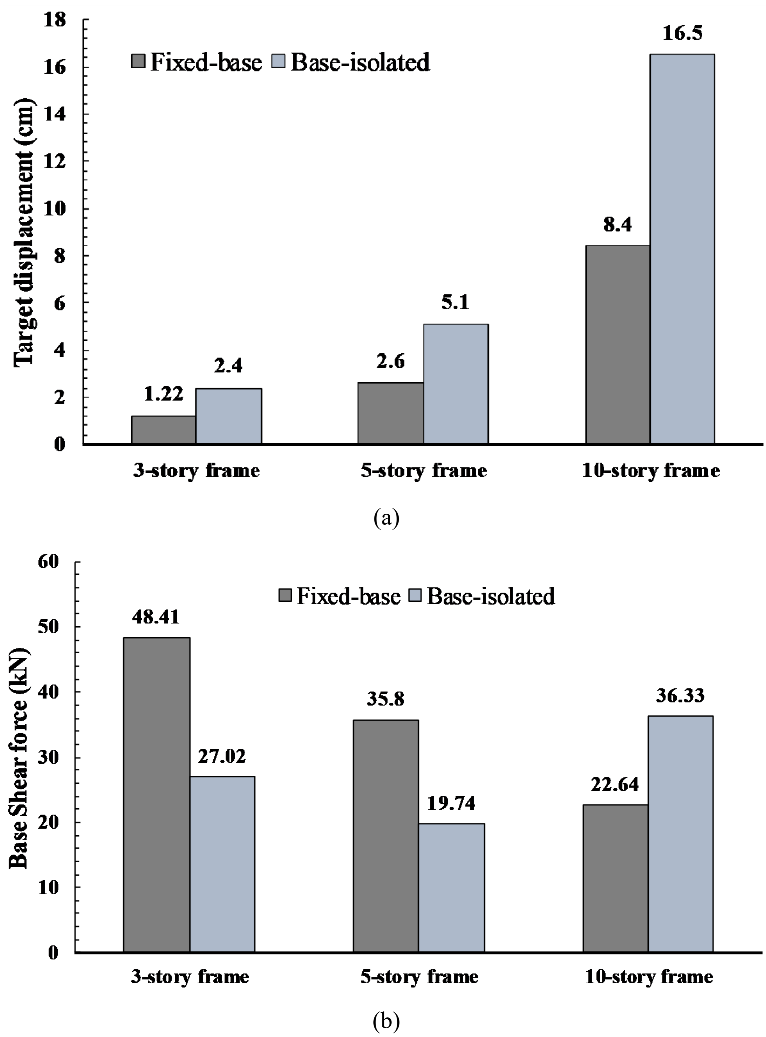


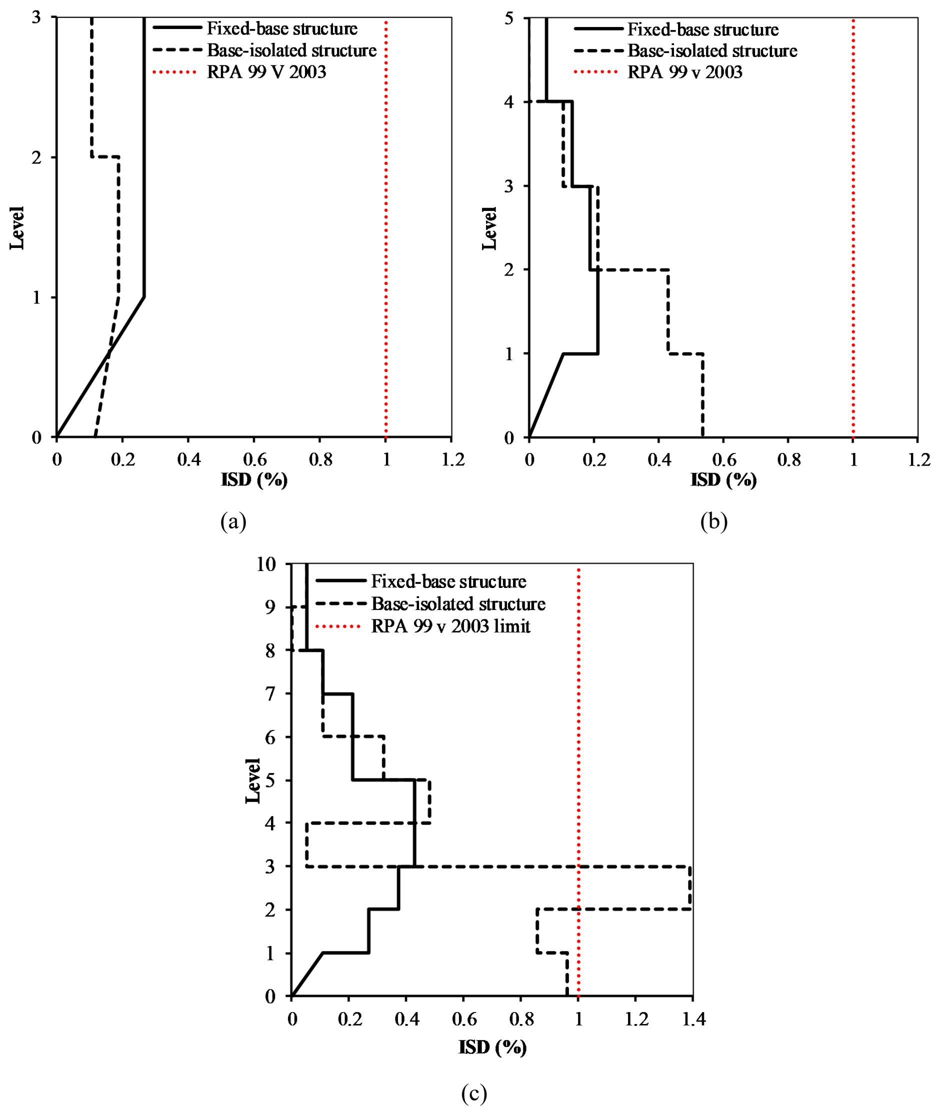
Figure 18 Performance characteristics for the (a) fixed-base and (b) base-isolated 3, 5, and 10-story structures (see online version for colours)



5.5 Inter-story drift ratio

The ISDR profiles of the studied structures are shown in Figure 19. The ISD ratio of the base-isolated 5-story structure is relatively large; therefore, the seismic isolators are less effective in the case of tall structures (> 5 stories). For the 10-story building, the ISD ratio exceeds the RPA 99 v 2003 limit (1%).

Figure 19 Inter-story drifts ratio (ISD) of studied structures, (a) 3-story structure, (b) 5-story structure, (c) 10-story structure (see online version for colours)



6 Conclusions

The main objective of this paper is to highlight the role of seismic isolators in the reduction of seismic effects on the RC-MRF designed according to the Algerian Seismic Rules RPA99/2003. In the current study, the performance-based design method called the CSM is used. Its principle consists in superimposing a curve representing the structure capacity resulting from a nonlinear static analysis (pushover) with a curve representing the seismic demand. The intersection of these two curves represents the point of performance.

An application of the pushover analysis was performed for four structures with and without the seismic isolation system, and a seismic demand evaluation study was carried out using the ATC-40 procedure A (damping approach). The main results can be listed as follows:

- The periods of the base-isolated structures are longer than those of the fixed-base structures
- The impact of seismic isolators is unfavourable for tall structures
- Inter-story displacement of base-isolated structures is almost negligible (except tall buildings)
- The seismic isolation system reduces the base shear forces.

This study has limitations, notably the use of only a few building models, requiring a more extensive and varied selection. Additionally, the employed analyses are simplistic, and more sophisticated techniques like nonlinear dynamic analysis could offer greater insights. Furthermore, the study's scope could be broadened by considering different types of isolation systems for a more comprehensive perspective.

In general, the results obtained show the influence of the seismic isolation system at the base on the seismic demand reduction. Furthermore, for better performance, it must limit the building height. Authors recommend including this technique in future versions of the Algerien seismic codes.

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