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Article of investigation

Influence of seismic isolation on the seismic design of buildings with reinforced concrete wall structure

Influencia del aislamiento sísmico en el diseño sismorresistente de edificios con estructura de muros de concreto reforzado

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Abstract

The use of reinforced concrete walls has become popular in Latin America as a structural system for the construction of residential buildings. However, this system is characterized by a low ductility capacity, compromising its seismic performance during the last strong earthquakes. This study uses three real buildings composed of reinforced concrete walls located in a high seismic region and soil type D, designed based on the Colombian building code. Nonlinear models of these three buildings were generated to evaluate the seismic response under actual ground motions. The three buildings were then redesigned using seismic isolation and the same analysis procedure was carried out to obtain the seismic response of the isolated buildings, comparing the results with those of the fixed base. The results show that the seismically isolated buildings exhibited a higher seismic performance, moving from a life safety performance level of the fixed-base buildings to an immediate occupancy performance level. In addition, the isolated buildings required up to 50% less reinforced steel and up to 100% fewer boundary elements compared to the fixed-base buildings, while keeping the architectural and building advantages of the wall structural system.

Resumen

En América Latina se ha popularizado el uso de muros de concreto reforzado como sistema estructural para la construcción de edificaciones; sin embargo, este sistema se caracteriza por ser de baja ductilidad por lo cual su desempeño se ha visto comprometido durante diferentes sismos ocurridos en los últimos años. Esta investigación toma tres edificios reales con estructuras de muros en concreto reforzado, localizados en zonas de sismicidad alta y en un suelo tipo D, los cuales se diseñan según la normativa colombiana. Adicionalmente, se crean modelos numéricos no lineales para evaluar el comportamiento sísmico de los edificios ante sismos reales. Este mismo procedimiento es repetido para los tres edificios dotándolos con aisladores sísmicos y comparando su desempeño sísmico con el obtenido de los análisis de los edificios de base fija. Los resultados muestran que se mejora el desempeño de la estructura aislada ante la ocurrencia de los sismos pasando de un nivel de desempeño de protección de la vida a uno de ocupación inmediata, mientras se obtiene una reducción de hasta un 50% del acero de refuerzo y de hasta un 100% del uso de elementos de borde comparado con los edificios diseñados con base fija, conservando las ventajas constructivas y arquitectónicas del sistema de muros.

Keywords: reinforced concrete walls, seismic isolation, seismic performance, boundary elements, steel reinforcement.

Palabras clave: : muros de concreto, aislamiento sísmico, desempeño sísmico, elementos de borde, acero de refuerzo.

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Why was it done?

The low ductility that characterizes structures composed of reinforced concrete walls has severely penalized their seismic performance in recent seismic events. Therefore, the implementation of seismic protection systems becomes necessary, allowing for an increase in the capacity and final seismic performance of reinforced concrete wall structural systems while maintaining the benefits of such structural systems, such as construction speed, low cost, and maximum utilization of areas. This study evaluates the implementation of seismic isolation in different buildings composed of reinforced concrete walls, analyzing not only their expected seismic performance but also the reductions in the reinforcing steel quantities required to achieve a seismic-resistant design that complies with new regulatory trends worldwide.

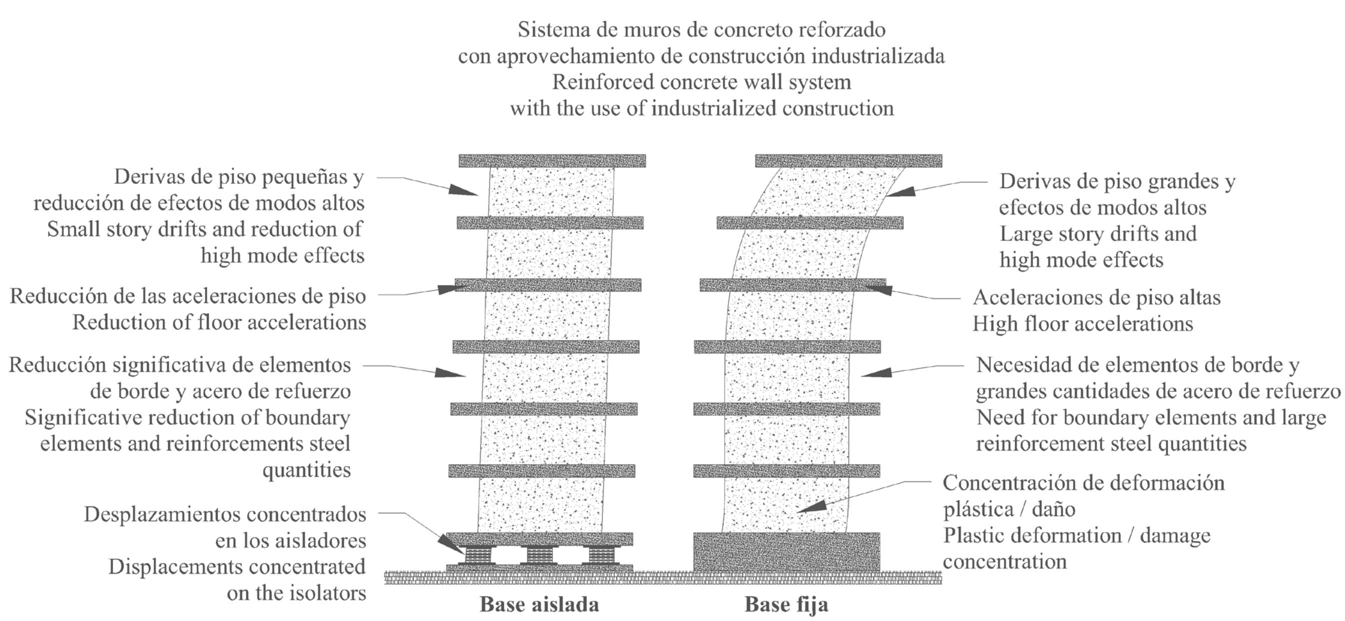
What were the most relevant results?

The results of the seismic design comparison among the different case study buildings with and without the implementation of seismic isolation demonstrate that the use of base isolation allows for an average reduction of 50% in the total reinforcing steel required to meet building code requirements. Additionally, with the implementation of seismic isolation, there was a reduction of up to 100% in the need for boundary elements in the walls. Regarding seismic performance, it was observed that the isolated case study buildings, despite requiring less reinforcing steel than the fixed-base buildings, exhibited higher seismic performance in terms of story drifts and floor accelerations, with average reductions of 85% and 54% for story drifts and peak floor accelerations, respectively.

What do these results provide?

The results of this study help demonstrate the advantages of combining a well-known construction system, such as reinforced concrete walls, prevalent in the Latin American context and especially in Colombia, with the use of seismic protection technologies such as base isolation. Additionally, it is shown that due to the reduction in reinforcement steel quantities, an isolated building will not necessarily be much more expensive than its counterpart with a fixed base, thus promoting the research and implementation of seismic isolation in reinforced concrete walls as a solution to reduce construction costs and increase the seismic performance of common structures.

Graphical Abstract



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Introduction

In Latin America, the use of reinforced concrete walls has become popular as a structural system for high-rise housing construction due to its cost-effectiveness, construction speed, and optimal space use. However, this structural system is characterized by low ductility capacity due to the high rigidity and slenderness of the walls, exhibiting low seismic performance during recent seismic events. To enhance the seismic performance of reinforced concrete wall structures, building codes have augmented the design requirements, leading to an increment in construction costs without a real guarantee of achieving better performance with the implementation of these measures.

Based on the aforementioned limitations and considering the construction and architectural advantages of reinforced concrete wall structures as an industrialized system, there is a need to assess the feasibility of improving and continuing to use this structural system without penalizing its implementation. It is commonly believed that improving the seismic performance of a building composed of shear walls involves increasing reinforcement steel ratios, use of boundary elements, larger cross sections, or using alternative materials to replace steel or concrete. Nevertheless, few studies have investigated the alternative of controlling seismic demand on this type of structure through the use of seismic isolation at the building's base. This is particularly relevant as buildings composed of reinforced concrete walls are very rigid, making the use of seismic isolation systems more effective compared to their implementation in more flexible structural systems. Seismic isolation decouples the building from the ground, allowing a reduction in seismic demand on the structure. This study aims to assess the influence of implementing seismic isolation on the structural design, detailing, and seismic performance of reinforced concrete wall structures.

The requirements for the seismic design of reinforced concrete walls and the implementation of seismic isolation have been developed based on the results of different research campaigns. Initially, studies on shear forces in concrete walls (1, 2) laid the foundation for the ACI-318 building code (3), which serves as a reference for the structural design in Colombia. Building codes have been continuously modified based on the findings of new studies, incorporating new requirements for the design and construction of structural systems with reinforced concrete walls [4-13]. Regarding seismic isolation, it was initially described in various documents explaining its use, dating back to 1970 [14-16]. The development of these systems has led to improvements in their application and construction [17-19], as well as regional guidelines for their implementation [20-22]. The premise of the implementation of seismic isolation is that it significantly improves the seismic performance of the building. However, the effectiveness of its implementation is influenced by the difference between the isolated period and the original period of the structure or other factors that may interfere with the dynamic response of the structure, such as the presence of soft soils.

This study explores the implementation of seismic isolation in buildings with a reinforced concrete wall structure and investigates its influence on their structural design and detailing. For this purpose, three actual buildings of different heights were selected and were originally designed according to the Colombian building code NSR-10 [23]. These buildings were redesigned considering the use of seismic isolation, and the differences in the total quantity of reinforcement steel and boundary elements were compared. Additionally, both configurations of buildings (i.e., with and without seismic isolation) were numerically modeled and subjected to nonlinear time-history analyses using real ground motion records to compare their seismic performance.

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Methodology

Case Study Buildings, Structural Design, and Numerical Analyses

Case study buildings

The case study buildings are composed of 8, 12, and 16 stories, with built areas of 2982.00 m^2, 4472.80 m^2, and 8385.60 m^2, and total heights of 19.60 m, 31.70 m, and 39.58 m, respectively. These buildings are part of residential projects, either already constructed or currently under construction. The case study buildings are characterized by the following translational periods: 0.39 s and 0.36 s for the 8-story building, 0.70 s and 0.59 s for the 12-story building, and 0.64 s and 1.21 s for the 16-story building. Figures 1 to 3 depict an isometric projection and the typical floor plan for each of the case study buildings.

The gravity loads assigned to the case study buildings include the self-weight of structural elements, dead loads, floor live loads, roof live loads, and hail loads, as described in Table 1. Additionally, a linear load of 2.60 kN/m was applied at the locations of attics and parapets.

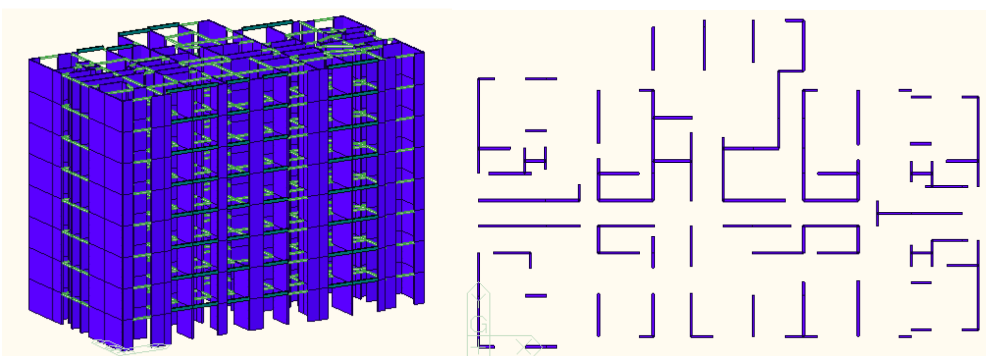

Figure 1 8-story case study building.

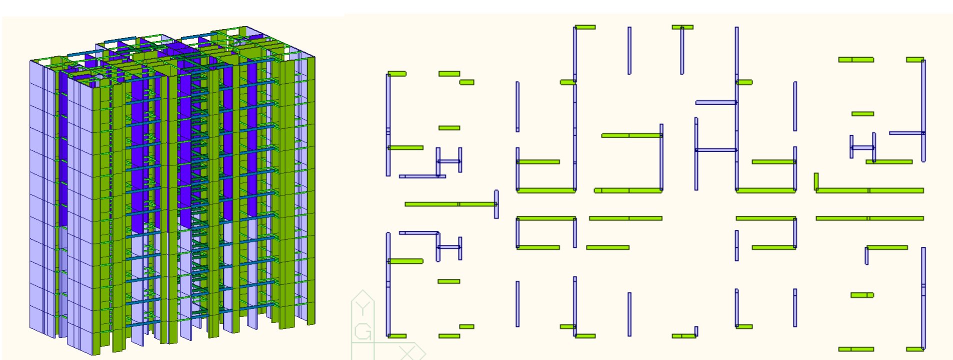

Figure 2 12-story case study building.

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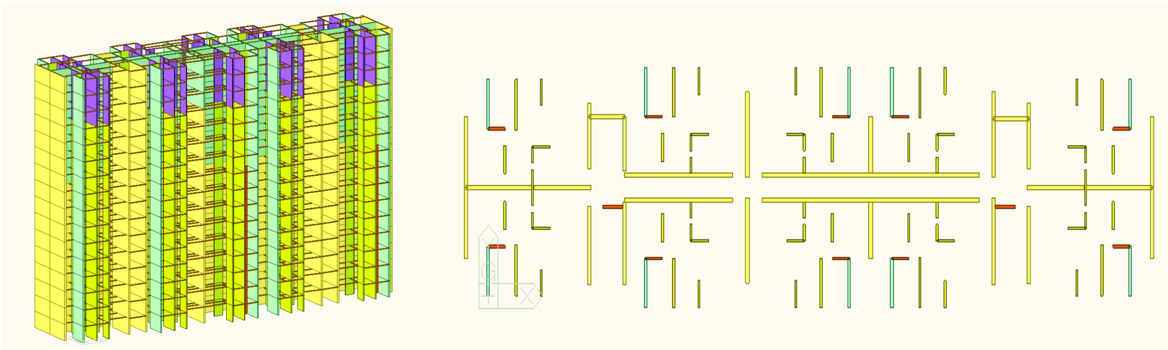

Figure 3 16-story case study building.

Table 1 Typical gravity loads applied to the case study buildings

	Dead load (D) kN/m²	Live load (L) kN/m²	Roof live load (L_r) kN/m²	Hail load (S) kN/m²
Floor load	4.16	1.80		
Roof loads	1.00		0.50	1.00
Stairs	7.64	3.0		
Elevator Shaft Roof	4.80		1.80	1.00

Numerical Modeling

The three case study buildings were modeled using the MIDAS Gen software [24], which enables the execution of modal analysis as well as nonlinear time-history analysis. The initial conditions for the execution of different analyses begin with the definition of a load combination equal to 1.0 (D) + 0.25 (L), the inclusion of P-Delta effects, and the characterization of the walls' plastic hinges. These plastic hinges were characterized by inelastic material hysteresis models, assigning the Japanese standard concrete specification model [25], with a compressive strength, f'_c, equal to 21 MPa for the 8-story building, between 21 and 35 MPa for the 12-story building, and 35 MPa for the 16-story building. Additionally, a peak concrete strain of 0.002, as recommended by the ACI 318 [3], was assigned for the nonlinear analysis. Regarding the reinforcing steel, the Park & Paulay model [26] was assigned, with a yield strength, f_y, of 420 MPa, ultimate strength, f_y, of 550 MPa, an elasticity modulus, E, of 200 GPa, and yield strain, ε_y, equal to 0.0021, hardening strain, ε_{sh}, equal to 10 times ε_y, and ultimate strain, ε_u, equal to 0.09 (27).

Seismic Hazard

The seismic loads applied to the case study buildings, with and without seismic isolation, were calculated following the criteria of the NSR-10 building code [23]. According to this code, the design spectrum was generated assuming the following site characteristics: 1) the buildings are located in a high seismic hazard zone, 2) the occupancy group is I with an importance factor of 1.0, 3) the soil is type D, 4) the effective peak acceleration, A_a, and the effective peak velocity, A_v, are both equal to 0.25, 5) the amplification coefficients F_a and F_a are equal to 1.30 and 1.90, respectively, and 6) the inherent damping of the structure

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is assumed as 5% of the critical damping. Additionally, 11 pairs of earthquakes were selected from the far-field ground motion set proposed by the FEMA P695 (28) (see Table 2) to assess the seismic behavior of the structure through nonlinear dynamic time-history analysis. These earthquakes were scaled according to the guidelines of Chapter 16 of ASCE 7-16 (29) for an intensity corresponding to the Maximum Considered Earthquake (MCE), equivalent to 1.5 times the Design Basis Earthquake (DBE). More information about the selection and scaling of seismic records can be found in Niño Castaño (2023) (22). Figure 4 shows the design spectrum and acceleration spectra of the 11 selected ground motions along with their median spectrum.

Table 2 selected pairs of ground motions from the FEMA P695 far-field ground motion set [28].

FEMA pair	Magnitude	Year	Event	Station	Source
3-4	6.7	1994	Northridge, US	Canyon Country-WLC	USC
5-6	7.1	1999	Duzce, Turkey	Bolu	ERD
7-8	7.1	1999	Hector Mine, US	Hector	SCSN
13-14	6.9	1995	Kobe, Japan	Nishi-Akashi	CUE
15-16	6.9	1995	Kobe, Japan	Shin-Osaka	CUE
23-24	7.3	1992	Landers, US	Coolwater	SCE
27-28	6.9	1989	Loma Prieta, US	Gilroy Array #3	CDMG
29-30	7.4	1990	Manjil, Iran	Abbar	BHRC
35-36	7.0	1992	Cape Mendocino, US	Rio Dell Overpass	CDMG
41-42	6.6	1971	San Fernando, US	–A - Hollywood Stor	CDMG
43-44	6.5	1976	Friuli, Italy	Tolmezzo	--

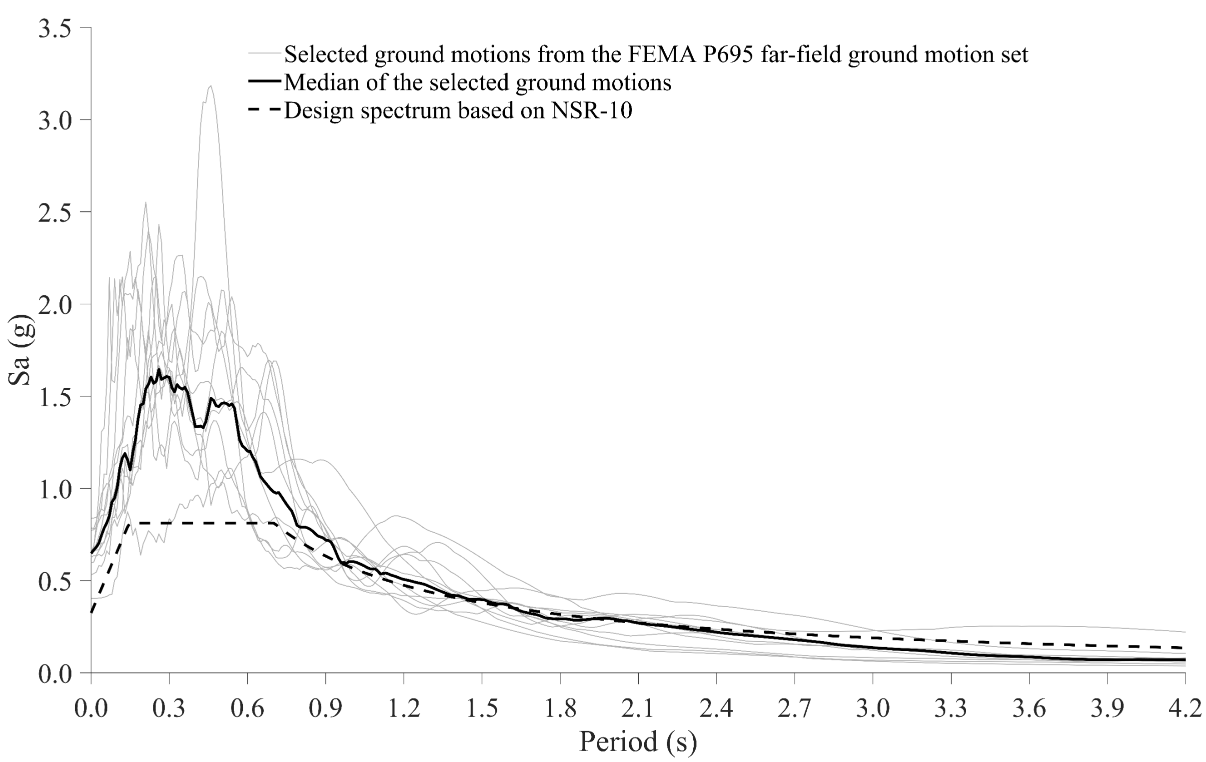

Figure 4 Design spectrum and spectra of the selected records from the FEMA P695 far-field set [28].

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Seismic design of the structural and isolation systems

The seismic design of the case study fixed-base buildings was conducted based on the results of spectral analysis and the structural detailing (steel reinforcement) corresponding to a system with special energy dissipation capacity for high seismic demand. On the other hand, the design of the case study buildings equipped with the seismic isolation system followed the requirements outlined in Chapter 17 of the ASCE 7-16[29], summarized as follows:

1. Assumption of the isolation activation/yield displacement, D_Y.
2. Assumption of the maximum displacement at the center of stiffness of the isolation system, D_M.
3. Assumption of the activation force of the activation system, F_Y, between 5 and 10% of the total building's weight.
4. Calculation of initial stiffness, k_1, and post-yield stiffness, k_2, as follows:
   $$k_1 = \frac{F_Y}{D_Y};\ k_2 = k_1/10 \qquad (2.1)$$
5. Calculation of the maximum force, F_D, on the isolators for a displacement D_M as:
   $$F_D = F_Y + k_2 * (D_M - D_Y) \qquad (2.2)$$
   and the isolator's characteristic strength (i.e., force-intercept at the zero displacements), Q_M, as:
   $$Q_M = D_Y * (k_1 - k_2) \qquad (2.3)$$

With the above information, the following data was obtained:

6. The effective horizontal stiffness of the isolation system, k_M, defined as:

$$k_M = \frac{F_D}{D_M} \qquad (2.4)$$

7. Moreover, the value of effective horizontal stiffness, the energy dissipated by the isolation system over a complete hysteresis loop, E_M, and the effective damping, β_M, and effective period, T_M, of the isolation system, for a displacement D_M can be determined as:

$$E_M = 4Q_M * (D_M - D_Y) \qquad (2.5)$$

$$\beta_M = \frac{E_M}{2\pi * k_M * D_M^2} \qquad (2.6)$$

$$T_M = 2\pi \sqrt[2]{\frac{W}{k_M g}} \qquad (2.7)$$

where W is the weight of the superstructure considering the diaphragm at the isolation level and g is the gravitational constant.

8. The value of T_M is used to enter the design displacement spectrum and verify that the displacement D_M matches the value assumed for the effective damping, β_M, calculated in step 7. If this value does not coincide, return to step 2 to iterate until there is no significant difference in the value of the effective damping between iterations. The value of the effective horizontal stiffness of the isolation system from the last iteration

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should be taken as the needed stiffness to reach the target displacement (D_M). Figure 5 illustrates the hysteresis cycles of the isolation systems of the three case study buildings.

9. A base shear correction is made following the requirements of ASCE 7-16 [29] with the 90% of $V_b = k_M * D_M$, using the 5% damped design spectrum.

Finally, for the detailing of reinforced concrete walls, a reduction factor, R_I, equal to three-eighths of the value of R used in the fixed-base structures is used. This reduction factor should be larger than unity and smaller than two. For instance, $R_I = \left(\frac{3}{8}\right)5 = 1.875$, fulfilling this requirement.

For the seismic isolation system design, an activation displacement of 30 mm was used for all three cases, while the target displacements were established as 195 mm, 280 mm, and 300 mm for the 8-, 12-, and 16-story buildings, respectively. With these values, the effective stiffness and effective damping values were obtained as: 14.38 kN/mm and 31.3% for the 8-story building, 15.54 kN/mm and 27.9% for the 12-story building, and 32.53 kN/mm and 26.9% for the 16-story building. Furthermore, the isolated periods of the case study buildings were computed as 3.17 s, 3.57 s, and 3.61 s for the 8-, 12-, and 16-story buildings, respectively.

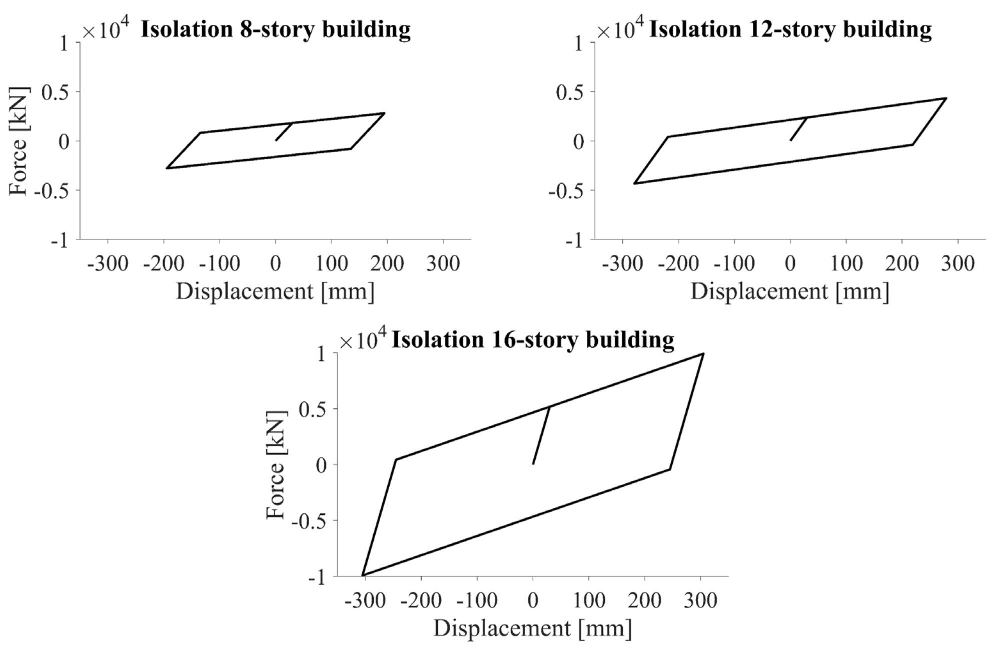

Figure 5 Hysteresis loops of the seismic isolation systems of the three case study buildings

Results and discussion

The case study buildings were designed and detailed considering both a traditional fixed base and the implementation of a seismic isolation system. It is important to emphasize that, to facilitate result comparison, identical wall distributions (i.e., same architecture) and concrete specifications were used for both building configurations (i.e., isolated base and fixed base). Consequently, at the detailing level, only the quantities of vertical and horizontal reinforcing steel varied, and the respective boundary elements, if necessary. Regarding concrete, the case study buildings required concrete volumes equal to 396.1, 811.4, and 2092.2 m³ for the walls of the 8-, 12-, and 16-story buildings, respectively.

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Boundary elements and reinforcement steel

For reinforced concrete wall structures, structural design codes stipulate reinforcement steel ratios that vary based on the computed shear force demand for each wall. Additionally, under certain conditions, the inclusion of boundary elements is required to increase the ductility capacity of the structural system. Boundary elements consist of longitudinal and transverse steel reinforcements located at the ends of the wall, supplementing the reinforcement required in the detailing of the wall's core. These boundary elements enhance the ductility of the reinforced concrete walls, thereby increasing the collapse capacity during seismic events.

Since the implementation of seismic isolation reduces the seismic demand on the structure, the number of walls requiring boundary elements is significantly reduced. Figure 6 illustrates a comparison of the number of wall sections requiring boundary elements for each case study building configuration. In the case of the 8-story building, 258 wall sections required boundary elements when the building was designed with a fixed base, whereas only 7 wall sections required boundary elements when the building was designed with base isolation. A similar trend was observed for the 12-story building, where 301 wall sections required boundary elements in the fixed-base structure, while they were not needed at all in the isolated structure. Finally, for the 16-story building with a fixed base, 382 walls required boundary elements, whereas the isolated-base configuration only required 16 wall sections to have boundary elements. In other words, the reduction in the need for boundary elements ranges from 98% to 100% with the implementation of seismic isolation. This reduction in the required number of boundary elements is one of the primary factors contributing to the overall decrease in the total quantity of reinforcement steel for the reinforced concrete walls.

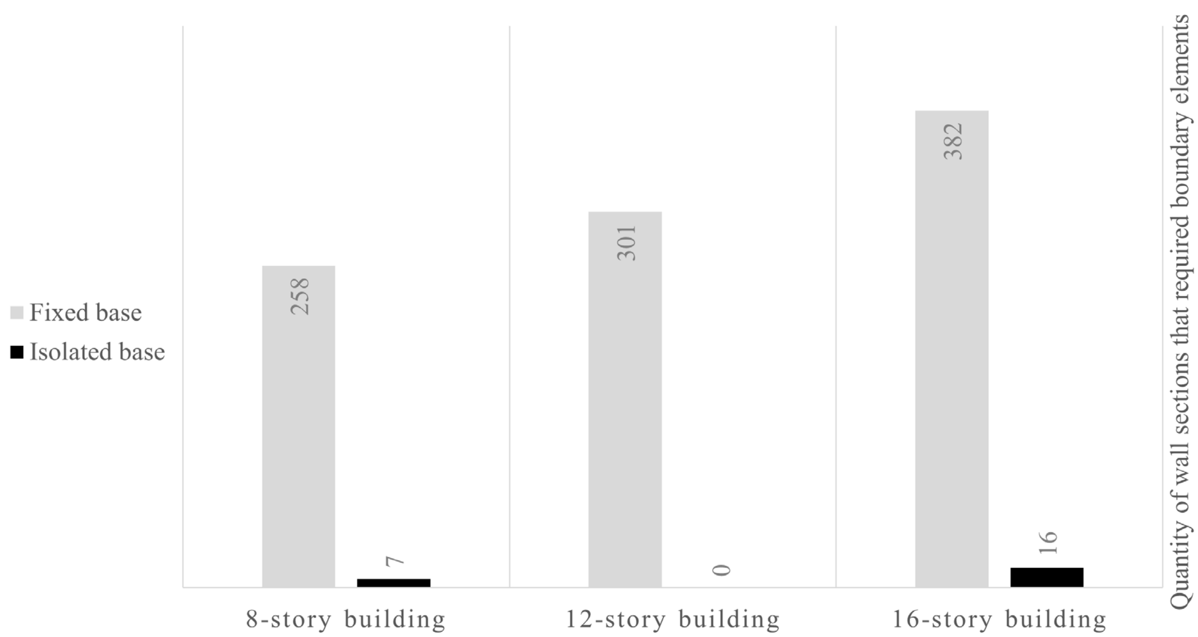

Figure 6 Quantity of wall sections with boundary elements for the fixed-base and isolated-based buildings.

To assess the influence of seismic isolation on the structural design and detailing of the selected buildings, particularly the reduction in the required reinforcement steel for boundary elements, the resulting reinforcement steel ratios from both configurations are

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compared in terms of reinforcement steel total weight and volumetric ratio (i.e., the ratio of the total weight of reinforcement steel to the volume of concrete in the walls). Table 3 reports the calculated reinforcement steel ratios for both configurations of the 8-, 12-, and 16-story case study buildings. It is important to highlight that in the 16-story building, it is possible to have a lower volumetric ratio of reinforcement steel compared to those obtained in the other two buildings, as in the latter, the minimum reinforcement steel ratios required by the building code govern the steel detailing, increasing thus the volumetric ratios, whereas in the former, the use of reinforcement steel can be optimized further in the final detailing, thus reducing the volumetric ratio. The final detailing shows that the reinforcement steel quantities of the reinforced concrete walls of the case study buildings equipped with seismic isolation were reduced by 45.30% for the 8-story building, 59.06% for the 12-story building, and 47.93% for the 16-story building, compared to the reinforcement steel quantities obtained for the fixed-base case study buildings, resulting in an average reduction of approximately 50% in the required reinforcement steel in the walls.

Table 3 Total reinforcement steel quantities for both configurations of the case study buildings.

	8-story building		**12-story building**		**16-story building**	
	Fixed base	**Isolated base**	**Fixed base**	**Isolated base**	**Fixed base**	**Isolated base**
Total weight of the reinforcement steel of the structural walls [kg]	71749	39245	110493	45237	198641	103441
Reinforcement steel volumetric ratio [kg/m^3]	181.11	99.06	136.18	55.75	94.94	49.44
Reduction	-45.30%		-59.06%		-47.93%	

Comparison of Reinforcement Steel Detailing

A different approach to assess the influence of seismic isolation on the design and structural detailing of reinforced concrete wall structures is by comparing the final design of the ten most stressed walls in each of the case study buildings. This selection was made based on the ratio of the shear force of each wall on the first floor to the total base shear. Tables 4 to 6 report the comparison of the distribution of reinforcement steel for the 8-, 12-, and 16-story case study buildings, respectively. The floor plan of the 8-story building is characterized by a large number of slender walls characterized by minimum required quantities of reinforcement steel. The average reinforcement steel ratios, both vertical and horizontal, were 0.48% for both configurations (i.e., fixed base and isolated base). The difference between these lay in the fact that, in the ten most stressed walls on the first floor, the use of boundary elements was generally not necessary in the isolated-base configuration, while in the fixed-base configuration, it was required to add boundary elements with an average reinforcement steel ratio equivalent to 2.0%. For the detailing of walls with steel bars, it was considered a maximum vertical and horizontal spacing of 250 mm. This explains the matching reinforcement steel ratios for both base configurations, as the maximum spacing between steel bars was limited by code requirements. In the case of the 12-story building, the average vertical reinforcement steel ratio for the most stressed

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walls on the first floor was 0.71% for the fixed-base configuration, compared to 0.28% for the same walls when designed considering the implementation of seismic isolation, representing a reduction in reinforcement steel ratios of approximately 61%. Regarding the horizontal reinforcement steel, the difference between the reinforcement steel ratio obtained for the structure with a fixed base and the isolated base is approximately 16%. Finally, in the 16-story building, a reduction of approximately 60% for the vertical reinforcement steel ratio and 15% for the horizontal reinforcement steel ratio were observed between the fixed-base and isolated-base configurations for the ten most stressed walls. It is noteworthy that the detailing of the reinforced concrete walls was carried out following the requirements of the NSR-10 [23], which requires that the reinforcement steel ratios of the structural elements cannot be lower than the minimum allowed, causing similarities in the final reinforcement steel ratios for both base configurations. Additionally, both configurations of the case study buildings must withstand the same gravitational loads, which contribute to similar reinforcement steel ratios for both cases.

Table 4 Mean reinforcement steel ratios of the ten more stressed walls of the 8-story building.

	Number of reinforcement layers	**Mean vertical reinforcement steel ratio ρ_v [%]**	**Mean horizontal reinforcement steel ratio ρ_h [%]**	**Total boundary elements length [m]**	**Mean boundary element reinforcement steel ratio [%]**
Fixed base	2	0.48	0.48	5.67	2.00
Isolated base	2	0.48	0.48	-	-
Reduction	0.00%	-61.38%	-16.20%	-100.00%	-100.00%

Table 5 Mean reinforcement steel ratios of the ten more stressed walls of the 12-story building.

	Number of reinforcement layers	**Mean vertical reinforcement steel ratio ρ_v [%]**	**Mean horizontal reinforcement steel ratio ρ_h [%]**	**Total boundary elements length [m]**	**Mean boundary element reinforcement steel ratio [%]**
Fixed base	2	0.71	0.33	6.34	1.81
Isolated base	2	0.28	0.28	-	-
Reduction	-0.00%	-61.38%	-16.20%	-100.00%	-100.00%

Table 6 Mean reinforcement steel ratios of the ten more stressed walls of the 16-story building.

	Number of reinforcement layers	**Mean vertical reinforcement steel ratio ρ_v [%]**	**Mean horizontal reinforcement steel ratio ρ_h [%]**	**Total boundary elements length [m]**	**Mean boundary element reinforcement steel ratio [%]**
Fixed base	2	0.52	0.25	7.63	1.47
Isolated base	2	0.21	0.21	-	-
Reduction	-0.00%	-59.51%	-15.02%	-100.00%	-100.00%

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Seismic response

In Section 3.2, it was demonstrated how the implementation of seismic isolation allows for a significant reduction in the number of boundary elements and the reinforcement steel ratios required for the design and detailing of buildings composed of reinforced concrete walls. These reductions compensate for the higher construction costs associated with the use of seismic isolation. However, it is important to compare the seismic response of both configurations to verify whether the implementation of seismic isolation also contributes to a better seismic response, or conversely, due to the reduction in reinforcement steel, the seismic response is similar to that obtained in the fixed-base case study buildings. To carry out this comparison, nonlinear dynamic time-history analyses were performed using 11 pairs of ground motion records scaled to match the MCE intensity level as explained in section 2.3. From these analyses, the median peak story drifts and median peak floor accelerations were computed and retained for each pair of ground motions in each configuration of the case study buildings. Subsequently, the median seismic response values were calculated and compared to evaluate the seismic response of the case study buildings. Additionally, the level of seismic performance was evaluated according to life safety or immediate occupancy limit states based on the values suggested by the Vision 2000 report [30].

The median peak story drifts, median peak floor accelerations, and median peak floor shear forces are shown in Figures 7, 8, and 9, respectively. The results showed that the case study buildings equipped with the seismic isolation system showed an average reduction of 85% of the median peak story drifts, exhibiting also a more uniform drift profile compared to those observed in the fixed-base case study buildings, in which median peak story drifts tend to increase at the top floors. The seismic performance of the fixed-base case study building was equivalent to the life safety level, while isolated-base case study buildings exhibited an immediate occupancy performance level. Regarding median peak floor accelerations, two important trends are observed; on the one hand, the implementation of seismic isolation generally led to a reduction in peak floor accelerations compared to the case study buildings with fixed base. Additionally, the case study buildings equipped with seismic isolation showed a more uniform peak floor acceleration profile, reducing the effects of geometric irregularities and higher modes in the seismic response. It is important to highlight the positive influence of seismic isolation on floor acceleration response, which represents the seismic demand on non-structural elements and contents sensitive to accelerations. Protection of non-structural elements is important since they can account for up to 90% of the total cost of a building [31]. The reduction in the seismic demand on non-structural elements generated by seismic isolation allows for higher seismic performance, ensuring and protecting the lives and integrity of occupants, and their belongings, and promoting earthquake-resilient communities. Lastly, as illustrated in Figure 9, equipping buildings with seismic isolation led to an average reduction in median peak floor shear forces of approximately 60%, demonstrating a significant drop in the structural seismic demand by increasing the fundamental period and the inherent damping of the structure.

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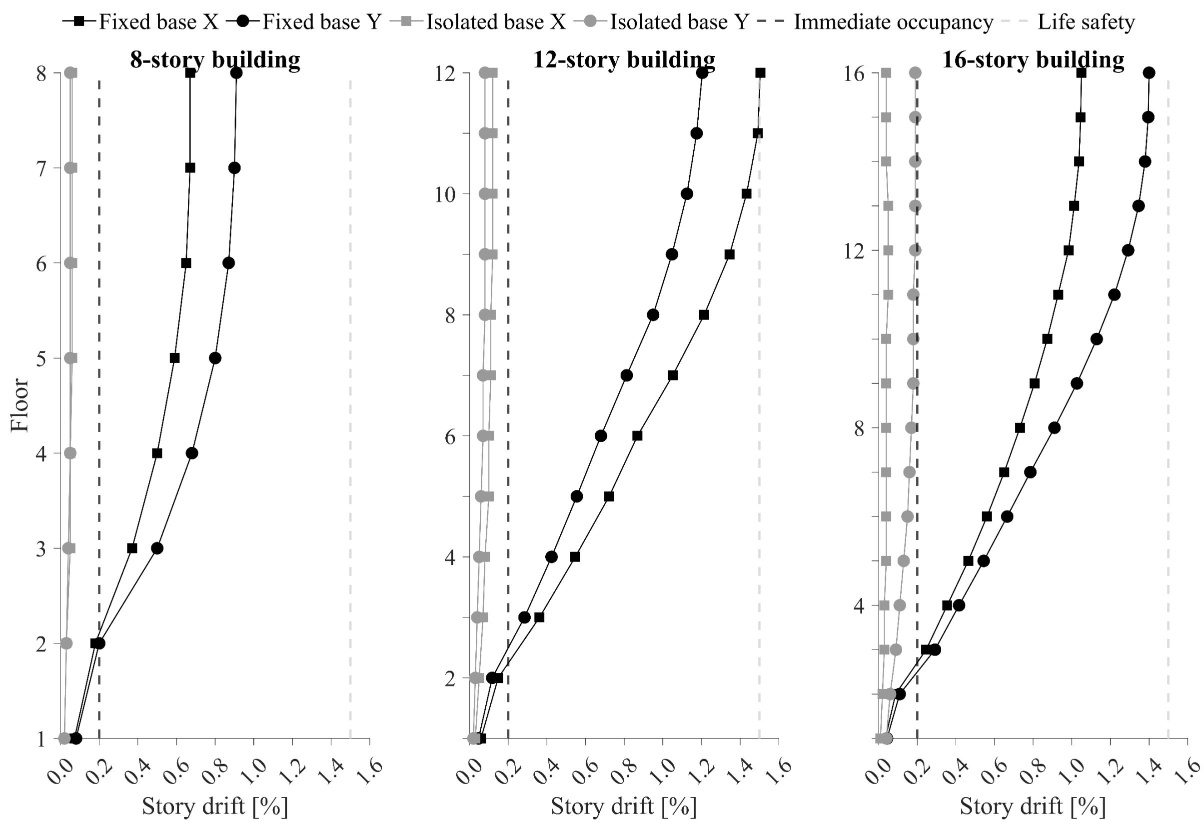

Figure 7 Median peak story drifts at MCE intensity level

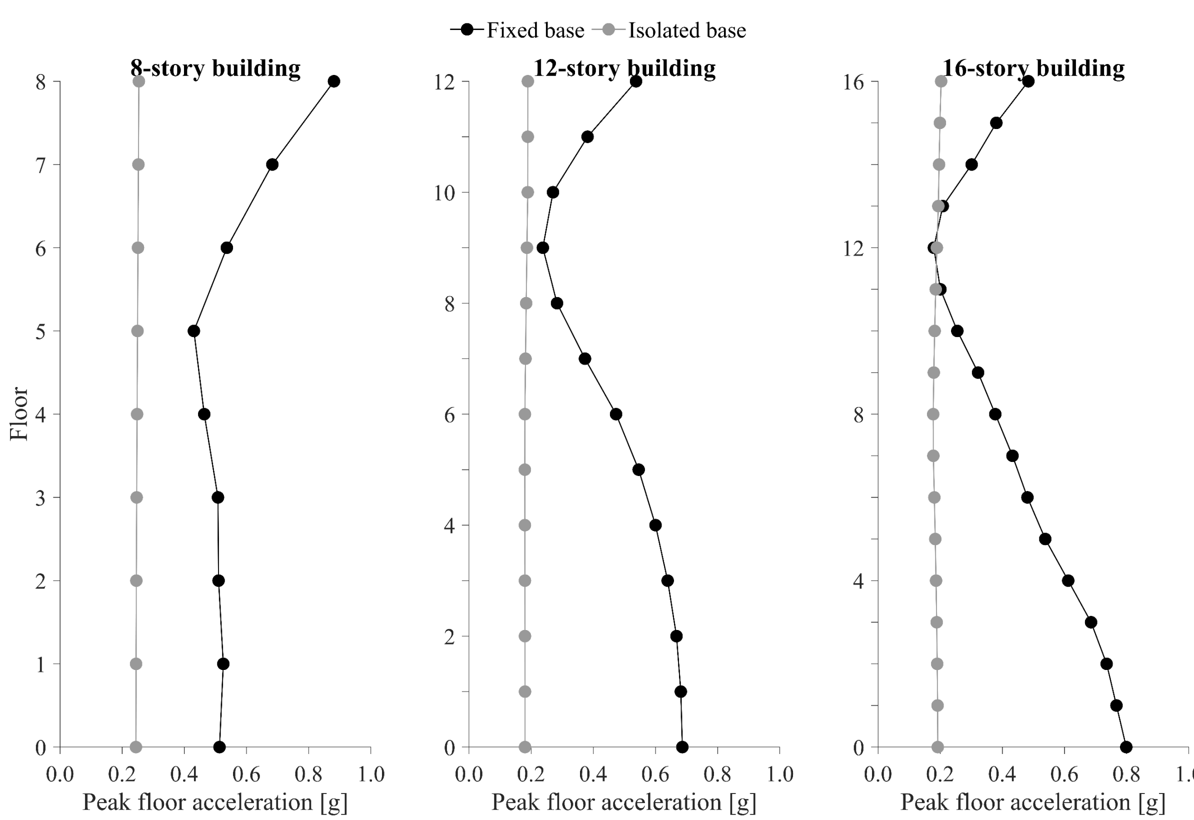

Figure 8 Median peak floor accelerations at MCE intensity level.

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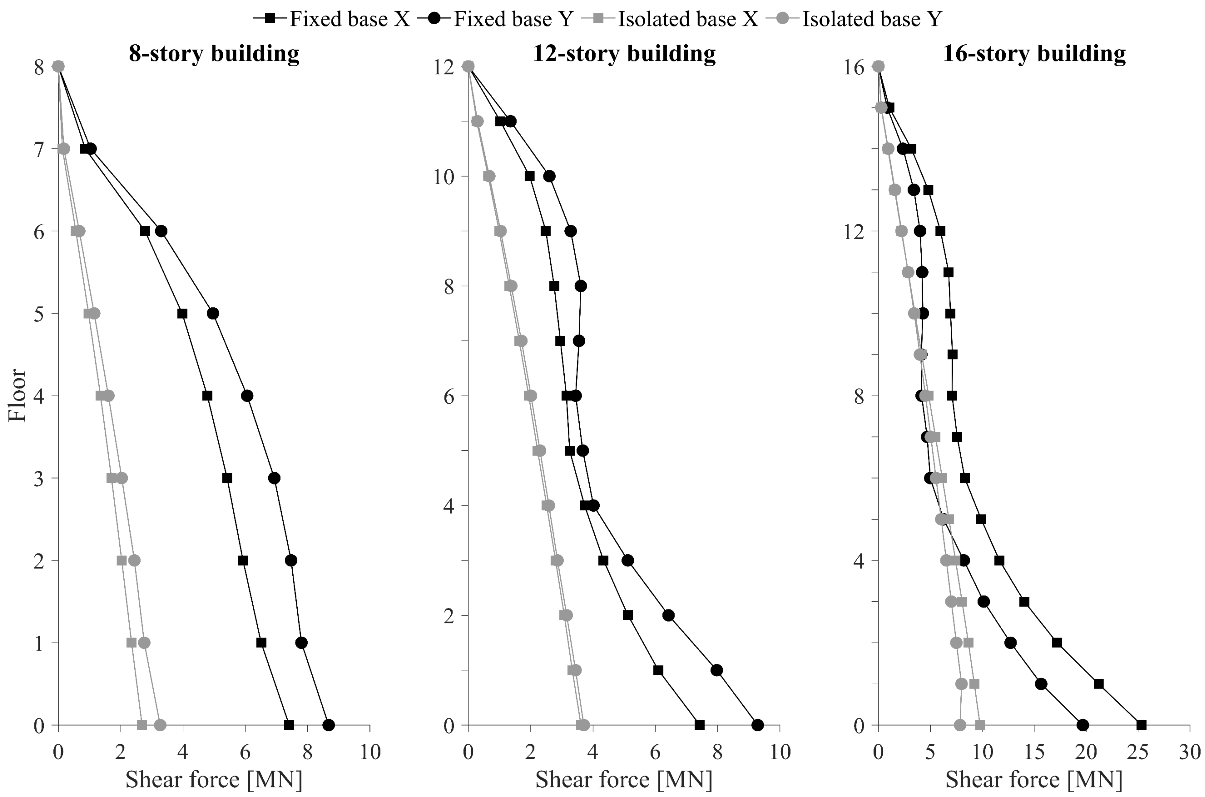

Figure 9 Median peak floor shear forces at MCE intensity level.

Conclusions

Several studies and building codes have proposed new ways to improve the seismic performance of buildings composed of reinforced concrete walls, resulting in increased minimum wall sections, larger amounts of reinforcement steel, and the addition of boundary elements with different layouts. Additionally, there have been proposals to use novel materials and technologies to replace conventional wall reinforcement, such as prestressed concrete systems. However, few studies have focused on reducing the seismic demand on reinforced concrete walls, which, due to their structural rigidity, tends to be larger compared to other structural systems. Conventionally, the ductility capacity of reinforced concrete walls is provided by adding boundary elements, leading to an increment in the amount of reinforcement steel and, consequently, in the construction costs.

The implementation of seismic isolation allows for reducing the seismic demand on the building by partially decoupling the structure from the ground. However, their use has been focused on framed structures, high-performance buildings, and heritage buildings, where their effectiveness and benefits have been proven. However, few studies have been conducted on their implementation in reinforced concrete wall structures, especially those with limited ductility. This study investigated the influence of seismic isolation on the seismic design, detailing, and seismic response of three real case study buildings composed of reinforced concrete walls. These buildings were structurally designed and detailed considering a fixed base, as well as an isolated base. In order to measure the influence of seismic isolation on structural detailing, both configurations were compared considering the number of wall sections that required boundary elements, as well as the total amount of reinforcement steel. Additionally, the different reinforcement steel ratios of the ten most stressed walls in each building were also compared. Finally, nonlinear time history analyses

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were carried out using 11 pairs of ground motion records from real events and scaled according to regulatory requirements. From these analyses, the median peak story drifts, median peak floor accelerations and median peak floor shear forces were computed, as well as the structural seismic performance.

The results showed a reduction of 45%, 59%, and 48% in the required reinforcement steel with the implementation of seismic isolation on the 8-, 12-, and 16-story case study buildings, respectively. In other words, on average, an approximate 50% reduction in reinforcement steel can be expected with the implementation of seismic isolation. This decrement of the required reinforcement steel is mainly due to the reduction of the need for boundary elements on the buildings characterized by an isolated base. This reduction varies between 98% and 100% of walls needing such elements. Additionally, the reinforcement steel required for wall core reinforcement is reduced by approximately 60% for vertical steel and 16% for horizontal steel due to the reduction in seismic-induced shear forces acting on the isolated buildings. On the other hand, despite the significant reduction in reinforcement steel quantities, the case study buildings equipped with seismic isolation showed better seismic performance at an equivalent intensity to the maximum considered earthquake, exhibiting lower story drifts and floor accelerations than those observed in the fixed-base case study buildings. These reductions were on average 85% and 54% for median peak story drifts and median peak floor accelerations, respectively. This behavior also led to a better structural seismic performance of the isolated buildings, obtaining an immediate occupancy performance level instead of a life safety performance level obtained by the fixed-base case study buildings. It is important to highlight that, although the use of seismic isolation reduces the relative displacements among the different stories, the absolute displacement is increased and concentrated at the level of the isolation system. This characteristic is of utmost importance for the calculation of the isolation system to avoid interactions with neighboring structures, as well as for the design and construction of complementary building systems, such as public utility connections, accesses, stairs, elevators, etc. Finally, it is necessary to emphasize that this study does not present the final design and detailing of the seismic isolation system, such as the design of the rigid diaphragm, isolator layout, and individual design of each isolator and/or slider. It is important to clarify that, for this process, the requirements regarding the local and global stability of the building and the isolation system must be met.

The results of this study validate the feasibility of using seismic isolation systems in buildings composed of reinforced concrete walls, especially in those built using the industrialized system that tends to generate limited ductility walls, allowing for a reduction in reinforcement steel ratios while preserving the constructive and architectural advantages of the system. A new seismic design approach for reinforced concrete wall buildings using base isolation could ensure and protect the lives and integrity of exposed communities.

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