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Structural Influence Due to the Elevator Shaft under the Response Spectrum Analysis

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Abstract

Elevators are essential in urban infrastructure, not only providing a critical means of vertical transportation in high-rise buildings but also ensuring accessibility for individuals with disabilities. In typical office buildings, elevator shafts are commonly integrated into a single core, where their associated shear walls play a key role in enhancing the structural seismic resistance. Conversely, many modern public buildings, such as shopping malls and conference centers, adopt multi-core designs with distributed elevator shafts, offering improved convenience and spatial flexibility. This research analyzes a real construction project, the public commercial hub in Astana, Republic of Kazakhstan, by utilizing response spectrum analysis based on actual testing data from Almaty. By comparing two configurations of the RC (Reinforced Concrete) structure (CASE-1 without elevator shafts and CASE-2 with elevator shafts) through SAP 2000, this research examines a range of critical parameters, including base reaction, structural period, frequency, acceleration, layer displacement, layer radians, and drift ratio. The comprehensive evaluation reveals the structural benefits of incorporating elevator shafts, as well as potential challenges, thereby providing valuable insights and design references for optimizing multi-core, multi-elevator systems in RC structures to achieve enhanced seismic performance and overall safety.

Keywords

Elevator Shaft, RC Structure, Response Spectrum Analysis, Seismic Resistance, SAP 2000

1. Introduction

For the past few decades, earthquakes have posed significant challenges to structural engineering, primarily due to the devastating damage they cause to buildings and infrastructure. The frequency and intensity of seismic events have increased concerns about the resilience of structures, as seen in past catastrophic earthquakes such as the 1994 Northridge earthquake in the United States [1], the 1995 Kobe earthquake in Japan [2], the 1999 Chi-Chi earthquake in Taiwan region [3], and the 2008 Wenchuan earthquake in China mainland [4]. More recently, seismic events such as the 2021 Alaska Peninsula earthquake [5], the 2022 Morobe earthquake in Papua New Guinea [6], the 2023 Southeastern Anatolia earthquake in Turkey [7], and the 2024 Ishikawa earthquake in Japan [8] have further underscored the persistent threat. Research indicates that earthquake-induced structural failures result in substantial economic losses and human casualties, highlighting the urgent need for improved seismic design and reinforcement strategies.

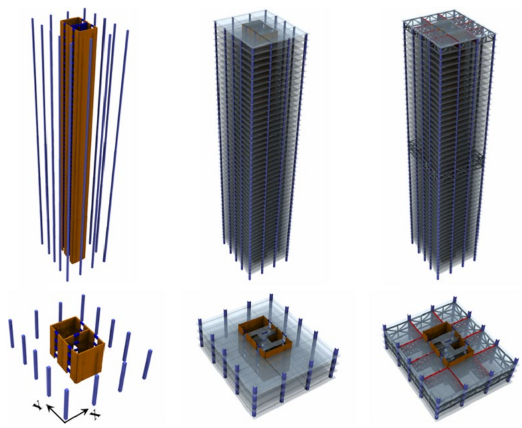


Figure 1. Typical one-core office building design.

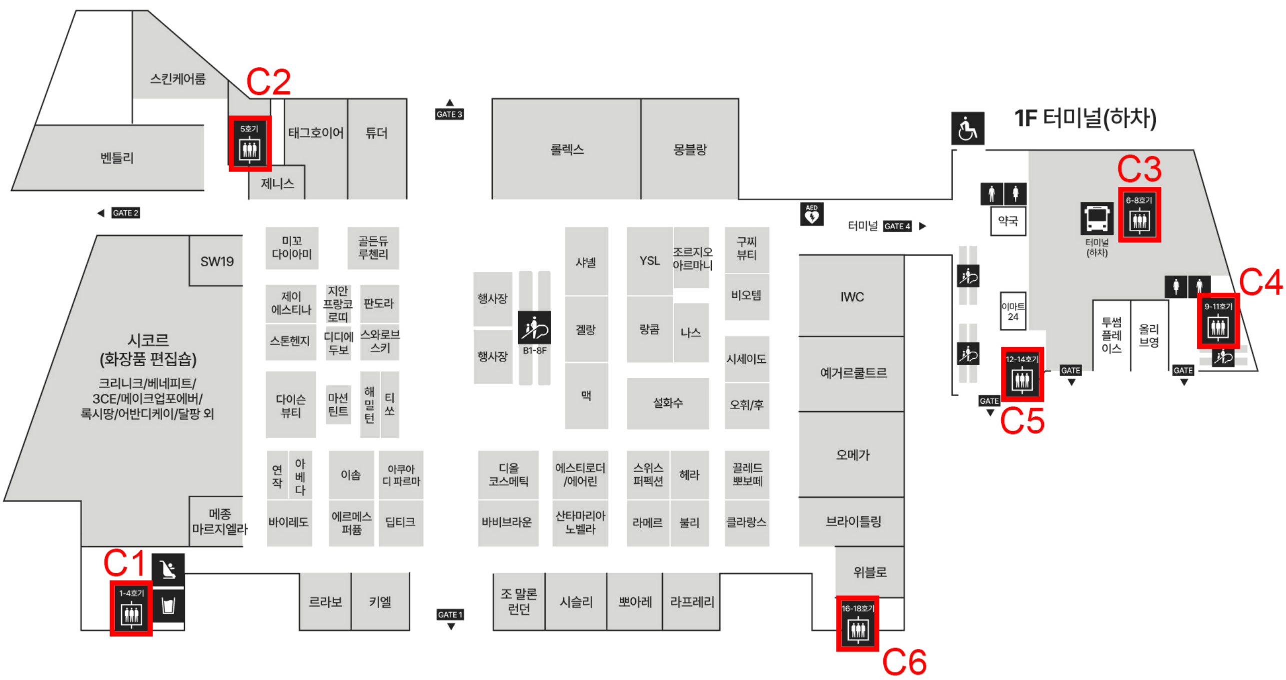


Figure 2. Typical multi-core shopping mall design.

In modern public RC frame structures such as shopping malls and conference buildings, elevators play a crucial role in providing accessibility and convenience. Unlike typical RC office buildings, where the elevator shaft is commonly integrated into the core of the structure to serve as a centralized load-bearing element as Murat Melek *et al.* [9] indicate in **Figure 1**, the design approach in shopping malls and conference buildings tends to differ as **Figure 2** illustrates the guide map of Daegu Shinsegae, the Republic of Korea with six different elevator placement that are spread into the whole shopping mall space. Due to the widespread layout of these structures, elevator shafts are often distributed across various locations rather than being concentrated at the center. This distinction significantly affects the structural behavior of the building, particularly in terms of seismic resistance. In office buildings, the core zone (including the elevator shaft) primarily absorbs and resists seismic forces, enhancing the overall stability of the structure. Conversely, multiple elevator shafts in shopping malls and conference buildings are also expected to contribute to seismic resistance. This is achieved through the incorporation of shear walls within the elevator shafts, which assist in distributing lateral loads and improving the overall structural integrity of the building during seismic events [10]-[12]. Consequently, the placement and design of elevator shafts play a crucial role in determining the seismic performance of different types of RC frame structures.

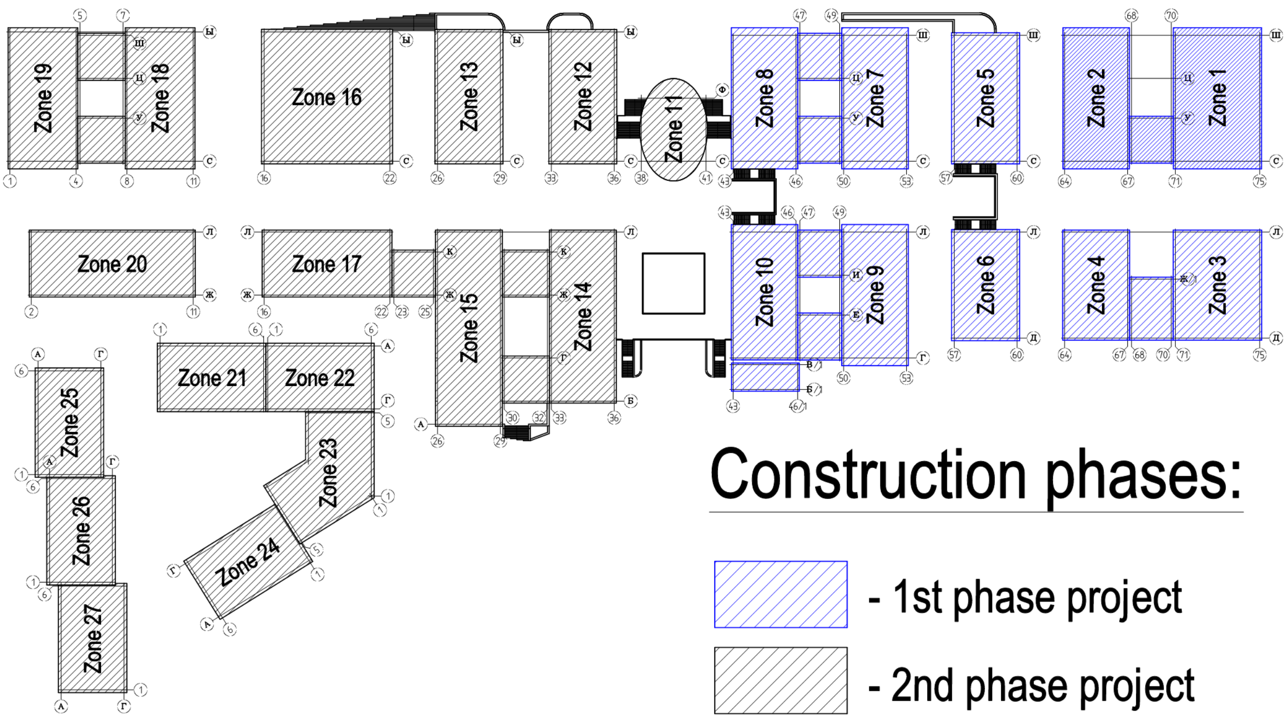


Figure 3. Schematization of the construction project.

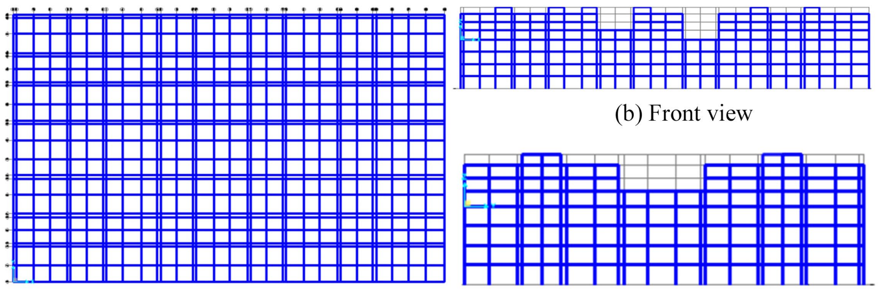
Based on a comprehensive evaluation of diverse earthquake records, it is evident that while nonlinear time history analysis provides a detailed and robust assessment of seismic performance, particularly for complex structures with accurately capturing material plasticity and energy dissipation mechanisms, it also demands significant computational resources and storage capacity [13]-[15]. In contrast, the response spectrum analysis has emerged as a practical and widely adopted method in many engineering practices, as its analytical results correlate strongly with those obtained from nonlinear time history approaches, as numerous researches indicate [16]-[20]. Due to this, to achieve an efficient yet reliable evaluation for a large-scale structure, this research employs the method of response spectrum analysis to conduct an in-depth analysis of a public commercial hub in Astana, Republic of Kazakhstan. As depicted in **Figure 3**, the project is divided into two phases, with the current investigation focusing exclusively on the first phase. The first phase of the construction project features an RC structural design that incorporates eleven elevator shafts distributed throughout the RC structure to serve not only as vertical transportation systems but also as integral seismic resistance components.

To evaluate the structural influences of these shafts on the structural dynamic performance, this research undertakes a comparative analysis by modeling two cases: one where all eleven elevator shafts are omitted (CASE-1) and another where the elevator shafts are included (CASE-2). This research aims to clarify how distributed elevator shafts influence the overall stability and lateral force resistance of large public RC structures under seismic activities. By examining parameters such as base reaction, structural period, frequency, and various deformation metrics, this research seeks to demonstrate that the inclusion of the elevator shafts contributes positive structural influences to enhance the structural seismic resistance performance under the seismic activities. The anticipated findings are expected to offer valuable insights into the structural significance of incorporating multiple elevator shafts, serving as a critical reference for future research and providing practical guidance for engineers involved in the planning and construction of large-scale public RC structures.

2. Description of the Research

2.1. RC Structure

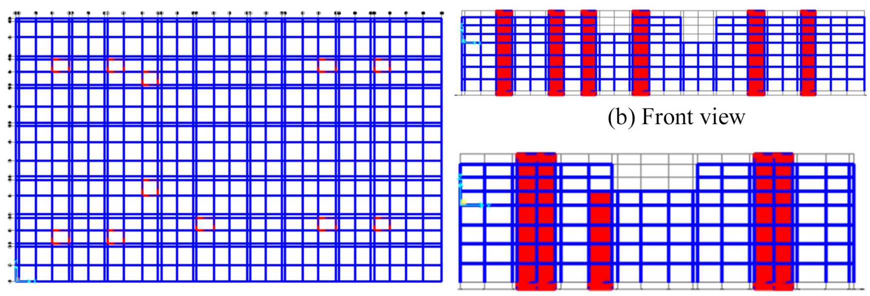
In this research, the structural design of the public commercial hub in Astana serves as the basis for a comparative response spectrum analysis, where two different cases of the RC structure (one with elevator shafts and one without) are simulated. As illustrated in **Figure 4** and **Figure 5**, these two structural models are analyzed to evaluate the impact of elevator shafts on the overall seismic response of the building. **Figure 4** presents the structural configuration without elevator shafts, providing a baseline for understanding the behavior of the building under seismic forces when relying solely on other structural elements for stability. In contrast, **Figure 5** displays the structure with elevator shafts incorporated, allowing for an assessment of how these elements influence the overall stiffness, load distribution, and seismic performance. By comparing these two cases, this research aims to identify how elevator shafts contribute to structural integrity, particularly in large public buildings where they are widely distributed.



(b) Front view

(a) Floor plan (c) Side view

Figure 4. Structural design of CASE-1.



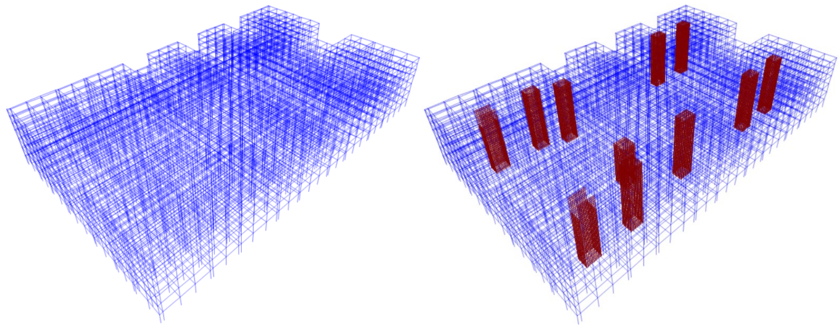
(b) Front view

(a) Floor plan (c) Side view

Figure 5. Structure design of CASE-2.

The structural design of the public commercial hub in Astana encompasses a total area of 15,773.52 m^2 as represented in Figure 4 and Figure 5, with both aboveground and underground sections carefully planned for functional and structural efficiency. The aboveground portion consists of three floors, each with varying heights to accommodate different architectural and operational needs. Specifically, the first floor is designed with a height of 3.6 m, while the second and third floors each have a height of 3.3 m. Additionally, the MR (Machine Room) for the elevators is given special consideration, featuring a dedicated height of 2.45 m to house essential elevator components. Regarding the negative floors, the structure extends into four underground levels, all uniformly designed with a height of 4.8 m per floor, ensuring ample space for basement functions such as parking, storage, or mechanical systems. Furthermore, the elevator pit, an essential component for elevator operation and stability, is constructed with a height of 1.5 m. These detailed design specifications highlight the structural complexity of the building and ensure that both spatial efficiency and structural stability are optimized, particularly in relation to the role of elevator shafts in the overall seismic performance of the RC structure.

Based on the detailed building design of the public commercial hub in Astana, Republic of Kazakhstan, two distinct RC structural models have been developed to evaluate the influence of elevator shafts on the overall RC structure. As illustrated in Figure 6, the research presents a comparative visualization where Figure 6(a)



(a) CASE-1 (b) CASE-2

Figure 6. Structural models of the two cases.

shows the RC structure without the elevator shafts, and **Figure 6(b)** shows the structure with the elevator shafts incorporated. The utilization of 3D modeling techniques in this analysis enhances clarity by providing a comprehensive view of the specific RC structure layout and the strategic placement of the elevator shafts. The visual approach not only aids in understanding the architectural and engineering nuances of the public commercial hub but also facilitates a deeper insight into how the inclusion or exclusion of elevator shafts can affect the structural behavior and seismic performance of the building.

2.2. Material Property and Section Designs

The material properties of concrete and rebar are critical factors in the performance and safety of the RC structure of the public commercial hub in Astana, Republic of Kazakhstan. To provide a clear and comprehensive understanding, **Table 1** and **Table 2** in this research detail the specific properties of the concrete and rebar used respectively. These tables are grounded in extensive previous research [21]-[24] and closely aligned with the unique structural design requirements of the public commercial hub in this research. In establishing the material specifications, this research adheres to the guidelines of SNiP 2.03.01-84, a standard that has been widely recognized and applied in Kazakhstan, as corroborated by the research of Muhammad Sajjad Rashid *et al.* [25]. By utilizing SNiP 2.03.01-84, the research not only ensures consistency with the latest Kazakhstan design codes but also reinforces the reliability and relevance of the material properties chosen for this project.

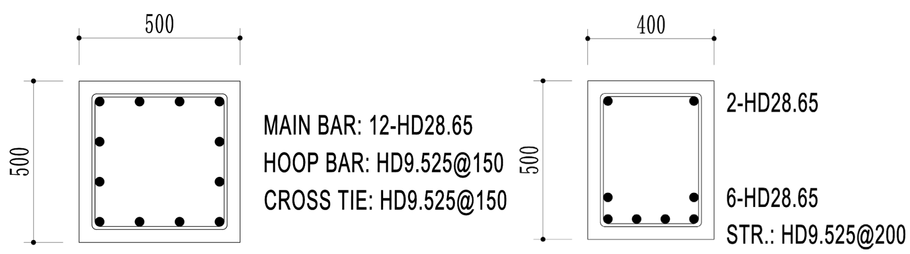
Table 1. Concrete property.

Weight per unit volume	25,000 N/m^3
Mass per unit volume	2550 kg/m^3
Modulus of Elasticity (E)	30,000 MPa
Poisson (U)	0.2
Coefficient of Thermal Expansion (A)	1.000E-05
Shear Modulus (G)	12,500 MPa
Specified Compressive Strength (F_{ck})	20 MPa
Expected Compressive Strength (F_{ek})	25 MPa

Table 2. Rebar property.

Weight per unit volume	77,000 N/m^3
Mass per unit volume	7850 kg/m^3
Modulus of Elasticity (E)	210,000 MPa
Poisson (U)	0.3
Coefficient of Thermal Expansion (A)	1.170E-05
Minimum Yield Stress (F_y)	300 MPa
Minimum Tensile Stress (F_u)	420 MPa
Expected Yield Stress (F_{ey})	330 MPa
Expected Tensile Stress (F_{eu})	460 MPa

According to the specific structural design of the public commercial hub in Astana, the RC structure is developed through a focus on the main section designs of the columns and beams, as detailed in Figure 7(a) and Figure 7(b). The section designs for columns and beams illustrate the fundamental load-bearing elements that serve as the backbone of the building, ensuring that the structure can safely distribute and resist various loads. Moreover, regarding CASE-2 which includes the integration of elevator shafts, the design incorporates a specialized shear wall around the elevator shaft as shown in Figure 8.



(a) Column (b) Beam

Figure 7. Section design of the column and beam.

Referring to the SNiP 2.03.01-84 standard, which is recognized as the latest design code for RC structures in Kazakhstan, the structural elements of the public commercial hub are designed to ensure both safety and performance. For specifics, the column is designed with a cross-sectional area of 250,000 mm^2, achieved with a dimension of 500 mm × 500 mm and a concrete cover depth of 40 mm, while the beam is similarly specified with a section area of 200,000 mm^2 using dimensions of 500 mm × 400 mm and an identical cover depth of 40 mm, as clearly illustrated in Figures 7(a) and Figure 7(b). In terms of reinforcement, the column is equipped with 12 main bars designated as #9, each having a diameter of 28.65 mm, which are essential for providing the primary load-bearing capacity. Additionally, the lateral reinforcement of the column is secured with hoop bars and cross ties made from #3 rebar, with a diameter of 9.525 mm, arranged at an interval of 150 mm to enhance its shear resistance and overall stability, as depicted in Figure 7(a). Conversely, the beam is reinforced with 8 main bars, also designated as #9 and having a diameter of 28.68 mm, and incorporates #3 cross ties with a diameter of 9.525 mm, spaced at wider intervals of 200 mm, as shown in **Figure 7(b)**.

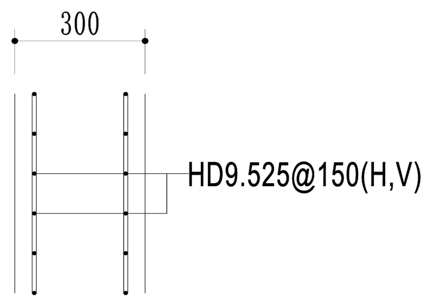


Figure 8. Design of the shear wall.

For the RC structure of the public commercial hub in Astana, specifically in CASE-2 where elevator shafts are integrated, a dedicated shear wall is designed for elevator utilization as detailed in **Figure 8**. This shear wall features a thickness of 300 mm while maintaining a concrete cover depth of 40 mm to protect the reinforcement. The design incorporates #3 rebar with a diameter of 9.525 mm, which serves as the primary reinforcement within the wall. Referring to the methodology established by Mo Shi *et al.* [26], the reinforcement is arranged in a grid pattern that consists of two layers, both at the top and bottom of the shear wall, oriented at 0˚ and 90˚. This configuration not only ensures uniform distribution of stresses across the wall but also maximizes its structural capacity by providing consistent rebar spacing of 150 mm as **Figure 8** illustrates.

2.3. Response Spectrum Analysis

The seismic zoning of the Republic of Kazakhstan is a crucial consideration for the response spectrum analysis conducted in this research. Seismic zoning defines the expected levels of ground motion and potential earthquake forces in different areas, ensuring that structures are designed to withstand regional seismic hazards. In this study, incorporating seismic zoning data allows for a more accurate and reliable structural performance analysis during seismic events. Notably, the research of N.V. Silacheva *et al.* [27] provides a comprehensive illustration of the seismic zoning across Kazakhstan, using PGA (Peak Ground Acceleration) as a primary metric as depicted in **Figure 9**.

According to the seismic zoning maps of the Republic of Kazakhstan, as **Figure 9** shows, Astana is not located within the region of highest seismic risk. However, to ensure that the public commercial hub is designed with sufficient seismic resistance, this research adopts a conservative approach by basing its response spectrum analysis on the actual seismic activity observed in Almaty, as the largest metropolis and an area subject to more significant seismic events. **Figure 10(a)** illustrates the earthquakes that occurred near Almaty from 2014 to 2016, providing a showcasing of all seismic events [27]. Complementing this, **Figure 10(b)** presents seismic hazard maps of Almaty with the observation point from the CSO (Central

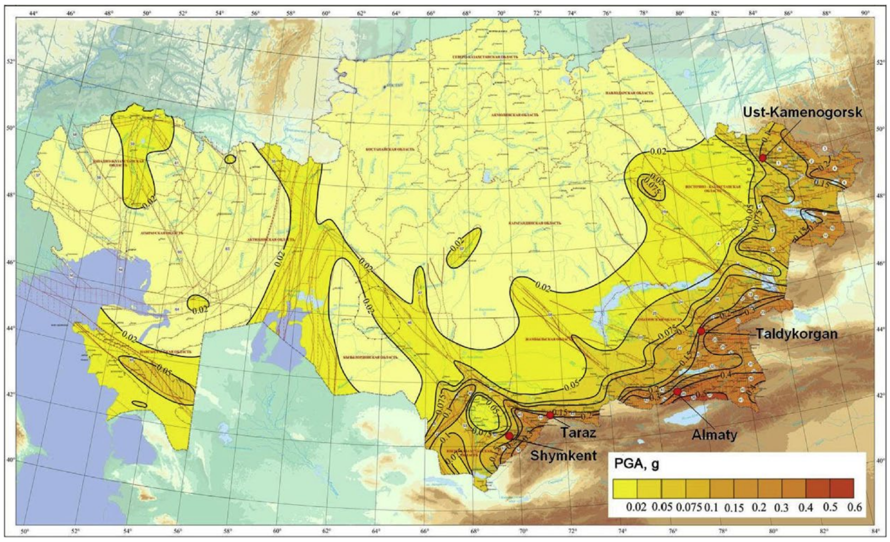
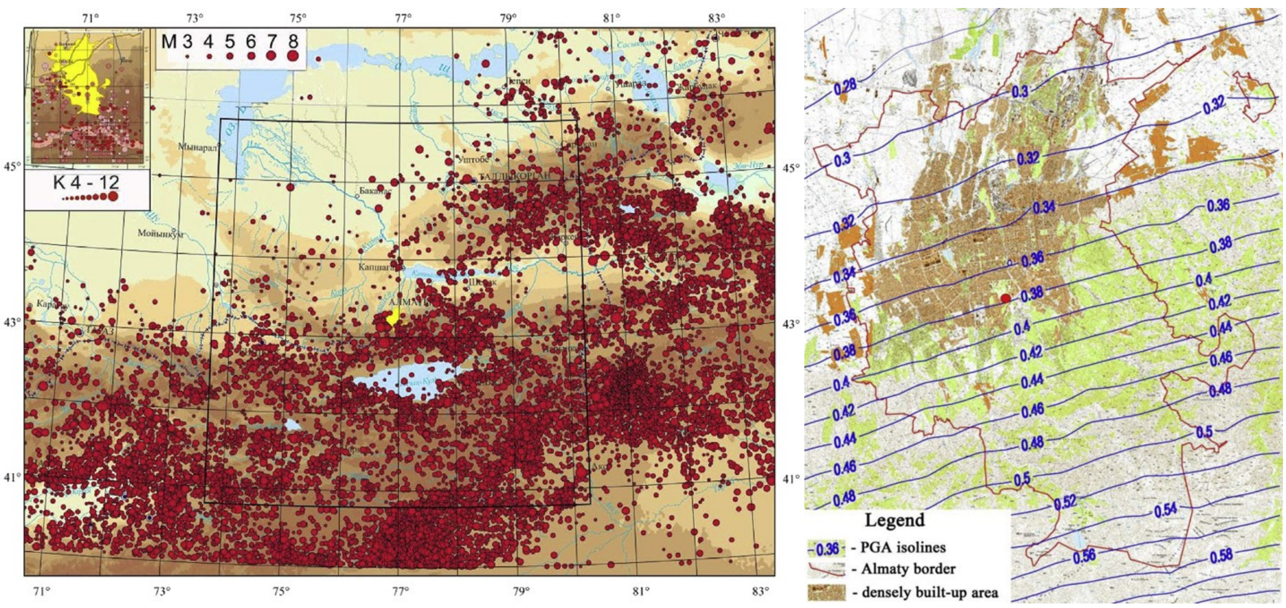


Figure 9. Seismic zoning of the territory of Kazakhstan in PGA.

Seismological Observatory) clearly marked in red, thereby highlighting the critical location used for hazard assessment [27]. Additionally, **Figure 11** incorporates test results on shear wave velocity and the corresponding response spectrum [28], both of which are essential for the response spectrum analysis for the specific RC structure in this research.



(a) Earthquakes occurred near Almaty in 2014-2016 (b) Seismic hazard maps of Almaty

Figure 10. Seismic activities in Almaty city.

Soil engineering properties are critical in seismic analysis because they directly influence how seismic waves travel through the ground and affect the behavior of overlying structures. In this research, **Table 3** provides a detailed illustration of the soil engineering properties for a specific zone in Almaty City, obtained through seismic reflection testing. Complementing this data, **Figure 11(a)** presents the shear wave velocity profile of the testing zone, offering insights into the subsurface soil stratification and its dynamic characteristics. The shear wave velocity is a main parameter in determining the response spectrum of the site, as it reflects the ability of the soil to resist shear deformation under seismic loads.

Table 3. Soil engineering properties

Soil type	Loam and sandy loam
Unit weight	16.1 kN/m^3
Cohesion	18 kPa
Internal friction angle	21˚
Undrained shear strength	59.3 kPa

The determination of shear wave velocity profiles is a critical step in seismic analysis, as these profiles help to characterize the dynamic response of the soil layers beneath a structure. To calculate these profiles as represented in **Figure 11(a)**, this research relies on the standardized methodology outlined in SP RK 2.03-30-2017. This standard provides specific equations that are used to compute the average shear wave velocity to a depth of 30 m as below:

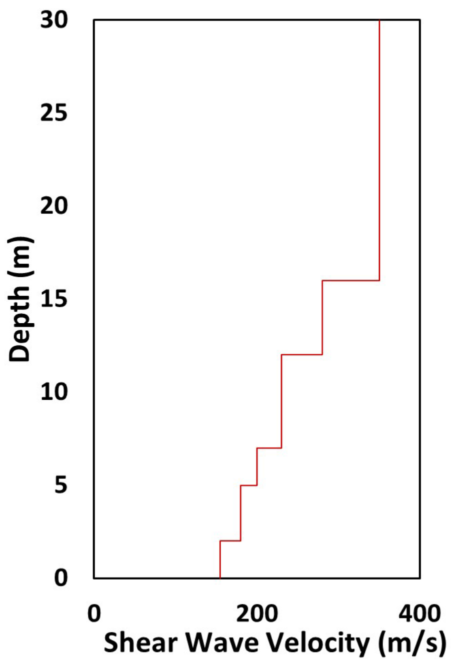
$$v_s 30 = \frac{30}{\sum_{i=1}^{N} \frac{h_i}{v_i}} \tag{1}$$

$$\rho_s 30 = \frac{30}{\sum_{i=1}^{N} \frac{h_i}{\rho_i}} \tag{2}$$

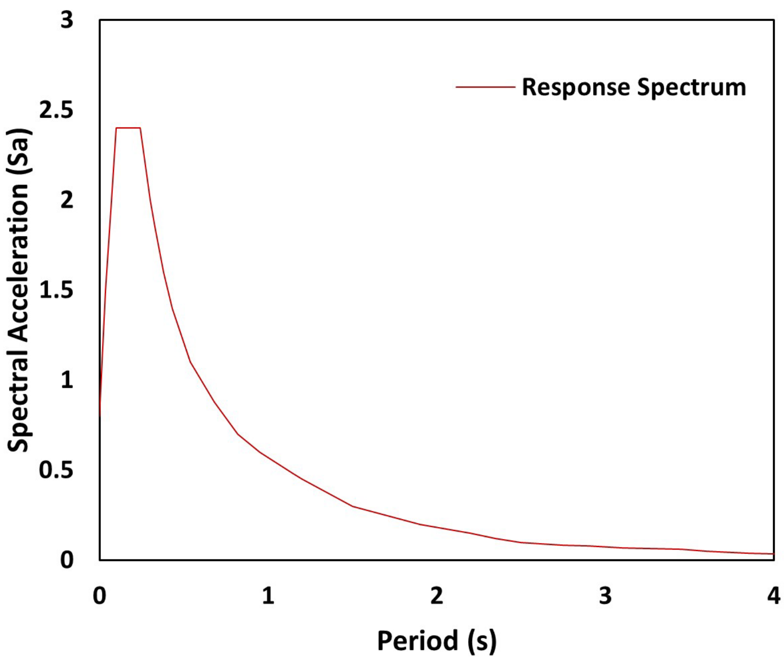
where h_i, v_i, and ρ_i indicate the depth, shear wave velocity, and density of the i-th soil layer considering the N total number of layers within 30 m depth.

Following **Equation (1)**, the analysis determined that the $v_s 30$ for the specific testing zone is 269 m/s, a value that is crucial for understanding the dynamic behavior of the soil under seismic loading. This parameter directly influences the ability of the soil to transmit seismic waves, thereby affecting the overall response of the structure during an earthquake. In conjunction with this, **Table 3** details that the c_u (Undrained shear strength) of the testing zone is 59.3 kPa, a measure of the resistance to shear deformation of the soil under rapid loading conditions without drainage.

Considering the Kazakhstan approach, the soil in the specific testing zone is classified as soil category III based on its seismic properties, particularly because its $v_s 30$ value is less than 270 m/s. This classification implies that the seismic operational conditions coefficient ($\gamma_{c,eq}$) is set at 0.6 and necessitates a reduction in the design friction angles (φ_1) by 7°, ensuring that the soil's behavior under seismic loading is accurately accounted for. Moreover, the soil engineering properties (φ_1) of 21˚ as detailed in **Table 3** further yield coefficients F_1, F_2, and F_3 of 7.50,



(a) Shear wave velocity



(b) Response spectrum in Almaty city

Figure 11. Observation and analysis of the seismic event in Almaty City.

3.62, and 10.33, respectively, which are critical for evaluating the response to dynamic forces of the soil. In contrast, the European approach categorizes the same soil as ground type C, defined by a v_s30 range between 180 m/s and 360 m/s, and assigns it a soil factor of $s = 1.5$. Additionally, following the guidelines of SP RK 2.03-30-2017, the design ground acceleration for Almaty city is determined to be $a_g = 0.633g$ for soil category III.

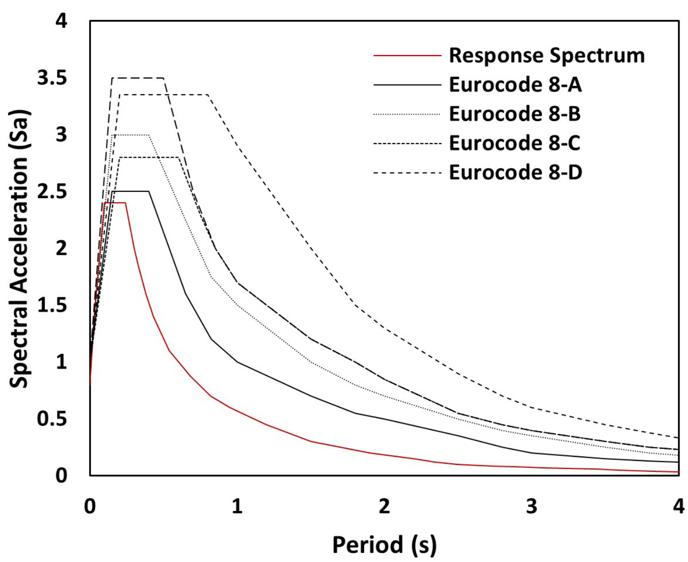


Figure 12. Comparison between the observed results and Eurocode 8.

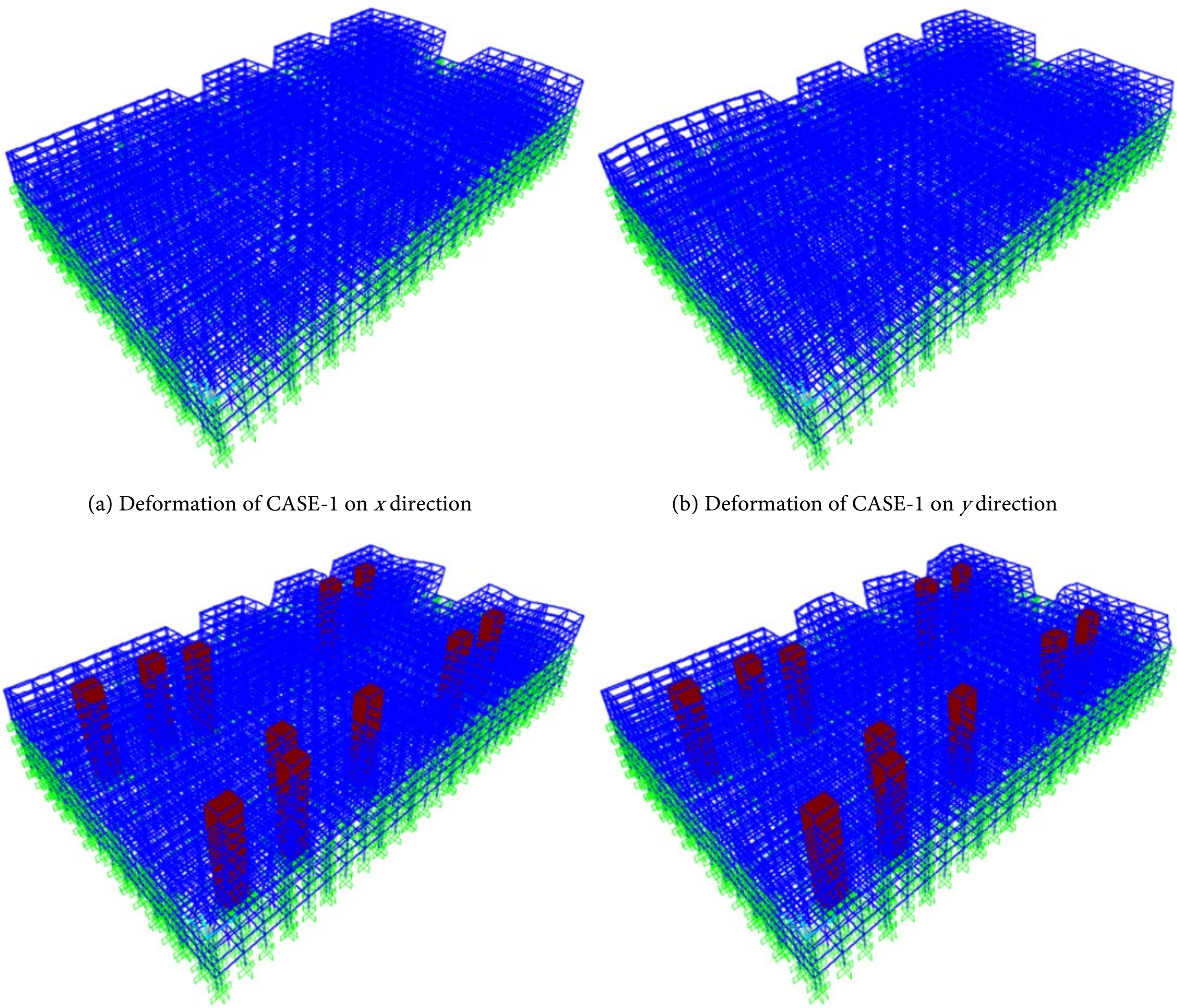
As depicted in **Figure 11(b)**, the design response spectrum curves illustrate the expected dynamic behavior of the soil in the specific testing zone in Almaty City during seismic events. Moreover, the analysis incorporates the response spectrum function for ground type C, which is particularly relevant given the soil classification for the area. This function is mathematically defined by a series of equations outlined in the European Standard EC8, and the four distinct response spectrums (Eurocode 8-A, B, C, and D) with EC8 are clearly presented in **Figure 12**. By combining the empirical data from the design response spectrum curves with the theoretical framework of EC8, this research ensures a robust understanding of the soil behavior under seismic loading, thereby assisting the response spectrum analysis for the specific RC structure in this research.

According to previous research, explicit consideration of soil-structure interaction is critical in structural seismic analysis because the dynamic response of a structure can be significantly influenced by the characteristics of the underlying soil, especially in underground stories where such effects are more pronounced [29]-[33]. In this research, the specific soil properties of a zone in Almaty City (Loam and sandy loam) are comprehensively analyzed, as detailed in **Table 3**. The specific soil parameters directly inform the formulation of the response spectrum used in the seismic analysis of the public commercial hub in Astana, Republic of Kazakhstan. By considering the soil-structure interaction into the response spectrum in this research, the fixed-boundary conditions of the structure can be modeled with greater accuracy, leading to more reliable predictions of its seismic performance.

3. Discussions

For the structural deformation analysis of the RC structure of the public commercial hub in Astana, Republic of Kazakhstan, response spectrum analysis is employed to assess the structural performance under seismic loading in this research. **Figure 13** illustrates the structural deformation for both configurations of the RC structure (CASE-1: without elevator shafts/CASE-2: with elevator shafts) across the two principal analytical directions as x and y. This comparative visualization is critical because it not only highlights the overall displacement behavior of the specific RC structure but also delineates the directional differences in deformation.

Referring to **Figure 13**, the analysis compares two distinct structural configurations (CASE-1: without elevator shafts/CASE-2: with elevator shafts) across both the x and y directions, revealing that the inclusion of elevator shafts significantly alters stress distribution and structural deformation. This difference in behavior suggests that elevator shafts play a vital role in enhancing the seismic resilience of the RC structure by effectively redistributing stresses and mitigating structural deformations for seismic activities. Moreover, combined with the following detailed discussions on base reaction, structural period, frequency, acceleration, layer displacement, layer radians, and layer drift ratio, this research comprehensively evaluates the dynamic behavior of both RC structures under seismic activities by response spectrum analysis.



(a) Deformation of CASE-1 on x direction

(b) Deformation of CASE-1 on y direction

(c) Deformation of CASE-2 on x direction

(d) Deformation of CASE-2 on y direction

Figure 13. RC structural deformation of CASE-1 and CASE-2.

3.1. Base Reaction

The base reaction results form a fundamental component of evaluating the overall structural performance under response spectrum analysis, as the base shear represents a critical measure of the seismic forces acting on the structure [34] [35]. Referring to the research of Kimleng Khy *et al.* [36], shear and moment are essential in assessing how the structural foundation will react to seismic activities and determining the safety and stability of the entire structure. **Table 4** provides a detailed illustration of the shear forces and moments for two analytical directions, which are examined for both cases as one where the RC structure is modeled without elevator shafts, and another where the elevator shafts are incorporated. This comparative analysis highlights the structural influence of elevator shafts on the distribution of seismic forces.

Table 4. Base Reactions

Types	Directions	Shear Force (x)	Shear Force (y)	Moment (x)	Moment (y)
		kN	kN	kN·mm	kN·mm
CASE-1	RS_x	188954.64	2717.75	38435.32	1117361.09
	RS_y	2717.78	142060.35	946303.75	29377.12
CASE-2	RS_x	228929.40	8879.19	37531.84	1166052.46
	RS_y	8879.11	109908.41	669819.95	58512.92
Ratio	x	17.46%	69.39%	−2.41%	4.18%
	y	69.39%	−29.25%	−41.28%	49.79%

Referring to the analytical results presented in Table 4, the response spectrum analysis reveals distinct directional behaviors in the base reactions of the RC structure. When the analysis is conducted along the x-axis, the structure exhibits a significantly higher shear force in that same x-direction, while a similar pattern is observed along the y-axis, the shear forces are notably higher in the y-direction. In contrast, the moment responses display an opposite trend as when the analysis is performed along the x-axis, the structure develops a higher moment in the y-direction, when the analysis is conducted along the y-axis, a higher moment is observed in the x-direction.

When comparing the analytical results for the RC structure of the public commercial hub in Astana that is evaluated in two configurations (CASE-1 without elevator shafts and CASE-2 with elevator shafts) as shown in Table 4, it becomes evident that the inclusion of elevator shafts significantly alters the shear force distribution. When the analysis is aligned with the x-axis, the structure without elevator shafts exhibits relatively lower shear forces in both the x and y directions. In contrast, the structure with elevator shafts shows an increase in shear force, with a 17.46% higher shear force in the x-direction and a 69.39% higher shear force in the y-direction. Conversely, when the analytical direction is aligned with the y-axis, the presence of elevator shafts results in a 69.39% increase in shear force in the x-direction, but a 29.25% decrease in the y-direction compared to the structure without elevator shafts. This comparative analysis highlights the significant structural influence that the integration of elevator shafts can have on the directional behavior of shear forces, emphasizing the need to consider these variations carefully in the seismic design and evaluation of RC structures.

Regarding the moment distribution as presented in Table 4, the analytical results reveal directional variations in the RC structural performance under the response spectrum analysis. When the analysis is aligned with the x-axis, the RC structure without elevator shafts exhibits higher moment values in both the x and y directions. In contrast, when elevator shafts are included, the structure experiences a reduction in moment as a 2.41% lower moment in the x direction and an even more pronounced 41.28% lower moment in the y direction. However, the moment results shift notably when the analytical direction is switched to the y-

axis. In this case, the inclusion of elevator shafts results in a 4.18% increase in the moment in the *x* direction and a 49.79% increase in the moment in the y direction compared to the RC structure without elevator shafts. These contrasting results underscore the complex interaction between the structural moment and the directions of seismic forces, highlighting the structural influence of elevator shafts on the aspect of the structural moment.

3.2. Modal Analysis

For the response spectrum analysis of the RC structure of the public commercial hub in Astana, Republic of Kazakhstan, a comprehensive structural modal analysis was conducted, identifying 12 distinct modes as illustrated in Figure 14. Each mode represents a unique pattern of structural deformation under seismic loading, and the results clearly delineate both the spatial distribution of these modes and the corresponding dynamic properties [37]-[40]. Specifically, Figure 14 details the structural period that indicates the time required for one complete cycle of vibration, and the associated frequency for each mode.

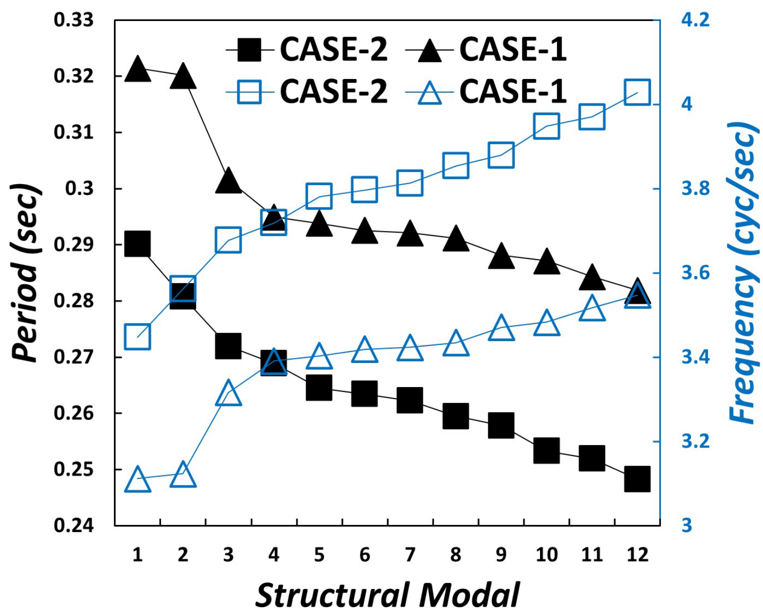


Figure 14. Structural period and frequency.

Regarding the structural period of the RC structure under response spectrum analysis as illustrated in Figure 14, the results reveal a clear decreasing trend in period with increasing modal order, regardless of whether the structure includes elevator shafts or not. This behavior is characteristic of multi-degree-of-freedom systems, where low-order modes, such as the first and second modes, capture the overall dynamic response of the structure through global phenomena like bending or shear deformations. The modes with longer periods reflect the combined stiffness and mass distribution of the entire structure. In contrast, higher-order modes (third mode and above) predominantly exhibit local vibrations associated with individual components, such as floors, beams, or columns, where the local stiffness is significantly greater, resulting in shorter vibrational periods. Through the analytical results in **Figure 14**, the periodic order relationship can be summarized as the period of the structure generally satisfies $T_1 > T_2 > T_3 > \cdots > T_n$, which is the inherent law of the dynamic characteristics of multi-degree-of-freedom systems.

For the comparison between the two cases within CASE-1 (the RC structure without elevator shafts) and CASE-2 (the RC structure with elevator shafts), as illustrated in **Figure 14**, the analysis reveals that the structure without elevator shafts consistently exhibits a longer structural period across all-order modes. This indicates that the inclusion of elevator shafts effectively decreases the structural period, which is beneficial because a lower structural period generally corresponds to higher structural stiffness. A stiffer structure experiences reduced inter-story displacements and overall deformation during seismic events, which in turn lowers the risk of damage to non-structural components such as partition walls, curtain walls, and equipment pipelines. Additionally, smaller structural displacements mitigate the additional bending moments caused by the P-Delta effect as an important consideration for maintaining structural stability, especially in structures with large height-to-width ratios. Therefore, the results clearly emphasize the structural advantages of incorporating elevator shafts, as they contribute to enhanced seismic resistance performance by reducing the structural period and the associated displacement demands.

Regarding the structural frequency observed in the modal analysis under the response spectrum approach, **Figure 14** clearly illustrates an increasing trend in structure frequency across from lower-order mode to the higher-order mode orders for both cases whether the RC structure is modeled without elevator shafts (CASE-1) or with elevator shafts (CASE-2). This increasing trend in structural frequency is the inverse of the trend observed in the structural period, as the period decreases while the mode order increases, which the analytical results in this research are consistent with the well-established inverse relationship between frequency and period. In other words, lower structural frequencies are associated with longer structural periods, reflecting the overall, global vibration modes of the structure, while higher structural frequencies correspond to shorter periods, indicative of more localized, higher-order dynamic responses.

When comparing the analytical results of the structural frequency for CASE-1 and CASE-2 under response spectrum analysis, it is evident that the RC structure without elevator shafts (CASE-1) consistently exhibits lower frequencies across all modal orders. This finding in light of the discussion on the structural period also underscores the seismic benefits provided by incorporating elevator shafts as a higher structural frequency that is seen in the structure with elevator shafts is indicative of increased stiffness. This enhanced stiffness translates into reduced overall deformation and smaller inter-story displacements during seismic events, which is crucial for protecting non-structural components such as infill walls, curtain walls, and piping systems. Moreover, the higher structural frequency associated with the inclusion of elevator shafts helps mitigate the P-Delta effect by limiting additional bending moments induced by gravity loads. This reduction in displacement and additional moment is particularly important for structures with large height-to-width ratios, such as high-rise core tubes, where even minor displacements can compromise structural stability. As a conclusion for the discussion of the structural frequency, these analytical results clearly demonstrate that integrating elevator shafts contributes significantly to improved seismic resistance by enhancing the stiffness and dynamic performance of the RC structure.

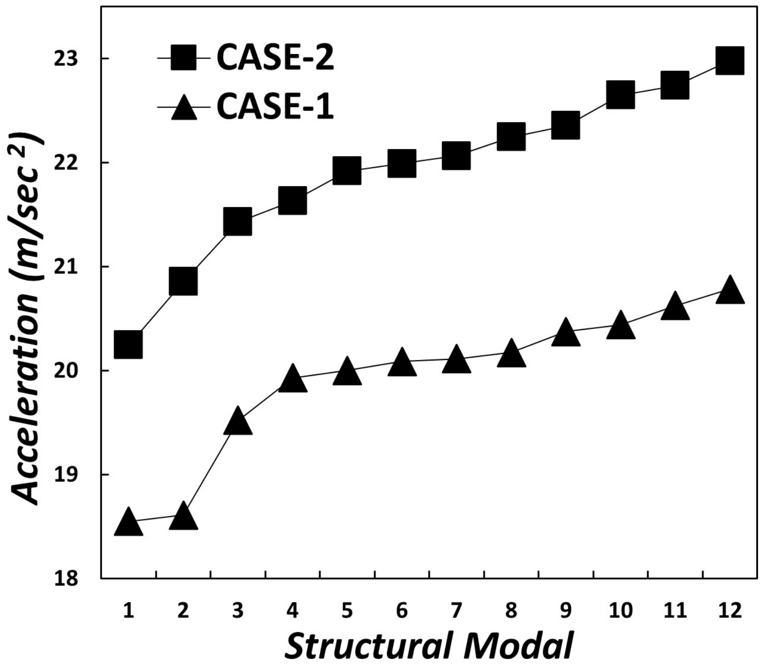
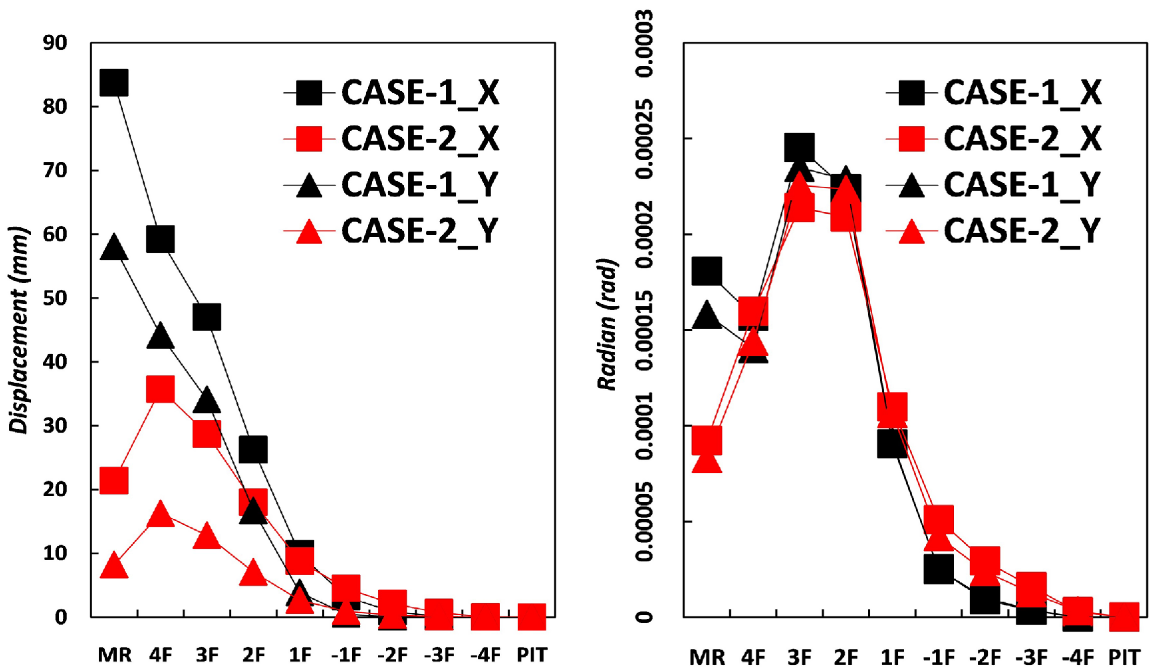


Figure 15. Structural acceleration.

Referring to the discussion on structural frequency as **Figure 14** illustrates, **Figure 15** illustrates that structural acceleration increases from lower-order modes to higher-order modes for both RC structures without and with elevator shafts, a trend attributed to the shorter vibration periods characteristic of individual components in higher modes. When comparing the analytical results, the RC structure incorporating elevator shafts (CASE-2) consistently exhibits faster structural acceleration than the RC structure without elevator shafts (CASE-1). This observation suggests that the integration of elevator shafts enhances the overall dynamic response of the structure by promoting a higher acceleration, which in turn helps to rapidly attenuate the dynamic response following seismic excitation. A faster decay in vibration is beneficial because high-frequency structures, due to their short vibration periods, dissipate energy more quickly, especially when the damping ratio remains constant, thus reducing the cumulative damage sustained during strong earthquakes. Moreover, this rapid acceleration helps avoid the concentration of seismic energy at long periods, which is a common issue in soft soil or alluvial sites with a relatively T_g (Long characteristic period). By operating predominantly in the short-period range, high-frequency structures lower the likelihood of resonance phenomena and in the case of far-field earthquakes or long-period seismic waves (such as velocity pulse earthquakes), they minimize cumulative displacement effects by responding quickly. Therefore, the findings of the structural acceleration highlight the seismic performance also advantages conferred by the inclusion of elevator shafts in RC structures.

3.3. Layer Displacement, Radian, and Drift

Layer displacement and layer radian are critical parameters for evaluating the structural performance under response spectrum analysis because they directly reflect how the structure deforms during seismic activities [41]-[43]. Specifically, layer displacement measures the structural lateral movement for every single story of the structure, indicating how much the specific story shifts on the lateral orientation relative to the structural state before the deformation, while layer radian quantifies the angular rotation that occurs at each joint between column and beam within the specific structural story. These analytical results provide a detailed structural behavior of both the translational and rotational deformations that the structure experiences under dynamic earthquake loads, which are the main aspects of understanding potential damage mechanisms. Including the RC structure without and with the elevator shafts, the analytical results show the distribution and magnitude of layer displacements and radians throughout the RC structure as illustrated in Figure 16(a) and Figure 16(b).



(a) Layer Displacement (b) Layer Radian

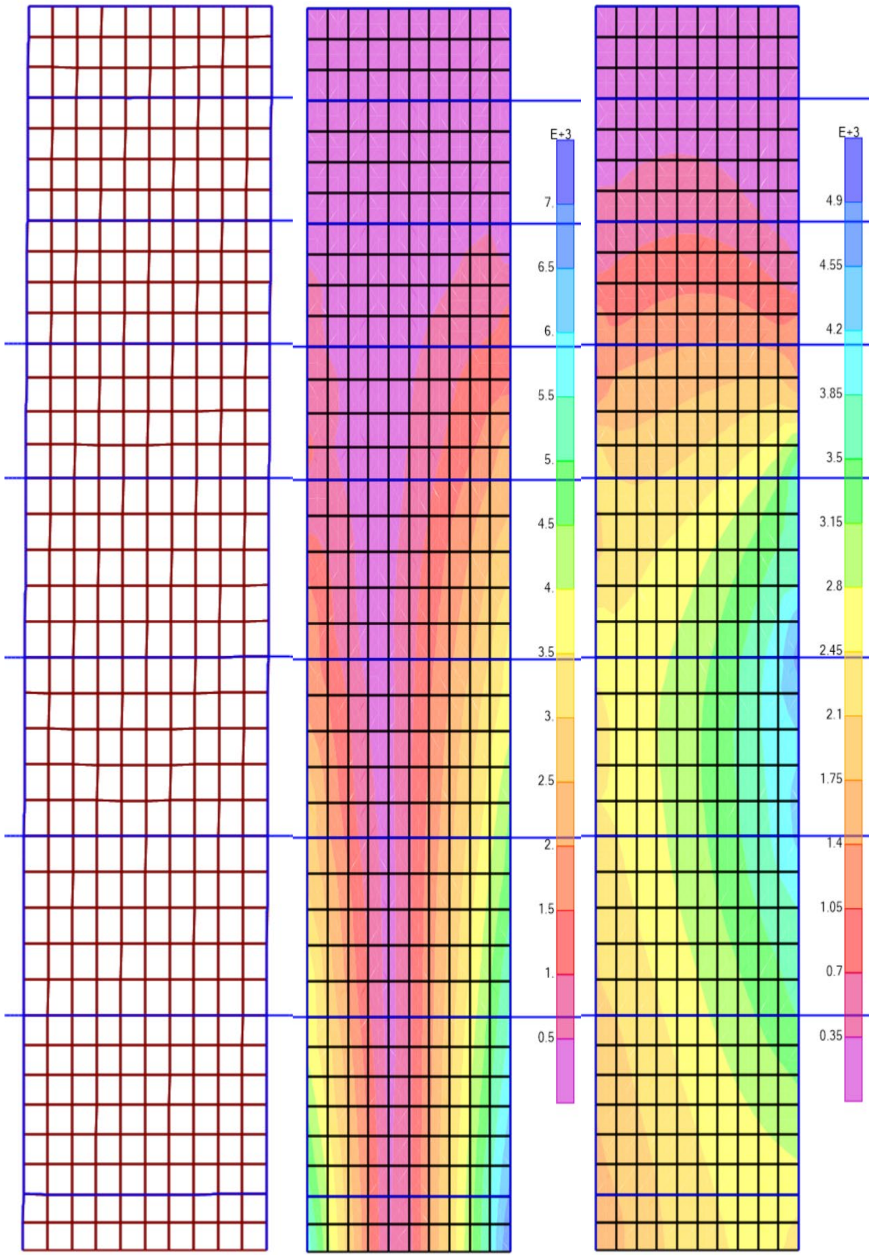
MR: Machine Room.

Figure 16. Layer displacement and radian.

The analytical results for layer displacement reveal that the RC structure incorporating elevator shafts consistently exhibits lower displacement values compared to the structure without elevator shafts as Figure 16(a) illustrates. This suggests that the shear wall effect provided by the elevator shafts plays a critical role in absorbing and dissipating the cumulative energy generated by seismic activity, thereby reducing the extent of structural deformation. In practical terms, a shorter layer displacement implies that the structure undergoes less lateral story movement during an earthquake, which in turn minimizes the potential for structural damage. The observed trend holds true across both analytical directions (x and y), reinforcing the conclusion that the incorporation of elevator shafts significantly enhances the seismic performance of the structure. By limiting the overall deformation, the elevator shafts are expected to assist protect both the primary structural components and the non-structural elements, such as infill walls, curtain walls, and piping systems from damage. Moreover, this reduction in lateral story displacement contributes to mitigating secondary effects, such as the P-Delta phenomenon, thereby lowering the risk of further instability under seismic loads.

Considering both the x and y analytical directions, the analysis of layer radian results in this research reveals that the RC structure with elevator shafts exhibits notably smaller layer radians on the floors where higher rotational deformations are typically observed, the third and fourth floors specifically as illustrated in Figure 16(b). This reduction in layer radian is significant because it is directly related to layer displacement as longer displacements lead to larger rotational angles between beams and columns, so a smaller radian suggests that the structure experiences less overall deformation during seismic activities generally. Consequently, the presence of elevator shafts appears to enhance the seismic resistance performance of the RC structure by mitigating excessive rotations and controlling deformation. In contrast, including the underground stories, when examining the lower stories, the analytical results indicate larger radian values in the lower levels of the RC structure with the elevator shafts. This phenomenon can be attributed to the behavior of the shear walls associated with the elevator shafts because each individual mesh of the shear wall exhibits considerable angular deformation as shown in Figure 17.

For the structural analysis of the shear wall associated with the elevator shafts in the RC structure, Figure 17 provides a detailed illustration of the behavior of one such elevator shaft in the public commercial hub in Astana, Republic of Kazakhstan, under response spectrum analysis. Specifically, Figure 17(a) depicts the overall deformation of that one elevator shaft, capturing the dynamic response under seismic loading. In addition, Figure 17(b) and Figure 17(c) present the shear stress distribution within the shear wall of that one elevator shaft along the x and y analytical directions respectively. Figure 17(b) and Figure 17(c) highlight notable differences in shear wall stress between the two directions, with the analysis revealing a significantly larger stress in the y direction. This elevated stress in the y direction is interpreted as an indication of higher structural stiffness in that axis, which corresponds to shorter lateral layer displacements and smaller structural layer radians as discussed earlier in Figure 16. Such behavior confirms that the inclusion of elevator



(a) Elevator shaft deformation (b) Shell stresses—x (c) Shell stresses—y

Figure 17. Structural behavior of elevator shaft.

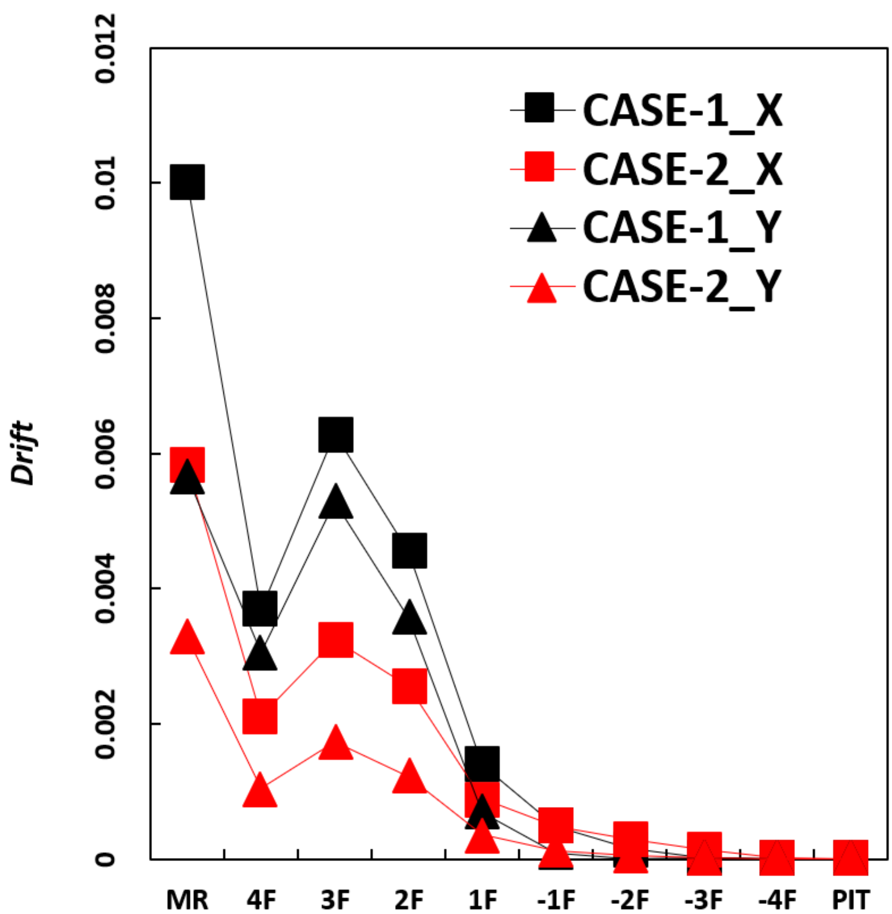
shafts not only enhances the overall seismic resistance of the structure but also contributes to more efficient energy dissipation and deformation control.

The drift ratio is a critical parameter in seismic design because it quantifies the relative lateral displacement between consecutive floors as a fraction of the story height, thereby providing a direct measure of the deformation a structure undergoes during an earthquake. Many previous research have highlighted its importance, emphasizing that maintaining a low drift ratio is essential to ensuring that structures can withstand seismic forces without compromising safety, functionality, or usability [44]-[47]. This metric effectively bridges the gap between dynamic analysis (such as response spectrum analysis) and practical design criteria by addressing not only code compliance and secondary damage effects on non-structural components but also the overall performance goals of a structure under seismic loads. In this research, the layer drift ratio is calculated by incorporating the lateral displacement of each story and the corresponding story height, following the methodology and equations according to the research of Mo. Shi *et al.* [48] as the equations shown below:

$$\Delta = \delta_x - \delta_{x-1} \tag{3}$$

$$\Delta_{ratio} = \frac{\Delta}{h} \tag{4}$$

where, δ_x represents the displacement observed at the x th floor, while δ_{x-1} denotes the displacement at the floor immediately below as the $x-1$ th floor. The difference between these two displacements of Δ in **Equation (3)** defines the drift between the two consecutive floors, as a key indicator of the lateral movement experienced during seismic activities. The height of the story which is indicated by h, is used to normalize this drift, allowing for the computation of the drift ratio as illustrated in **Equation (4)** as Δ_{ratio}.



MR: Machine Room.

Figure 18. Layer drift ratio.

Based on the analytical results of the structural lateral displacements measured in both the x and y directions, and taking into account the RC structural design of the public commercial hub in Astana, Republic of Kazakhstan, the layer drift ratios for both configurations (with and without elevator shafts) can be calculated using **Equations (3)** and **(4)**. The layer drift ratio relates the inter-story displacements to the corresponding story heights, thereby providing a normalized measure of the lateral deformations experienced by the structure during seismic activities. The calculated layer drift ratios are critical as they help assess the seismic performance of the structure by ensuring that the inter-story movements remain within acceptable limits which in turn protects both structural and non-structural components. The results for each case under both the x and y directions are comprehensively presented in **Figure 18**, allowing for a clear comparison of how the presence of elevator shafts influences the structural overall drift behavior and seismic resilience.

Referring to the calculated results of the layer drift ratio as illustrated in **Figure 18**, the RC structure without elevator shafts consistently shows larger layer drift ratios in both the x and y analytical directions, while this is evident from the response spectrum analysis based on the specific design of the public commercial hub in Astana, with testing data derived from Almaty City. For the analytical direction of x, the noticeably higher layer drift ratio in the structure lacking elevator shafts indicates that the inclusion of these shafts effectively enhances the structural ability to resist lateral seismic forces. Similarly, when examining the results of the analytical direction of y, the larger layer drift ratios in the structure without elevator shafts further confirm that the elevator shafts play a critical role in mitigating seismic-induced displacements in that direction as well. These benefits are primarily considered as the elevator shafts serve as integral shear wall components, acting as structural cores that absorb and dissipate seismic energy. Unlike typical single-core office building designs as shown in **Figure 1**, the RC structure of the public commercial hub in Astana utilizes multiple structural cores with eleven elevator shafts, which significantly enhance the seismic resistance performance.

Table 5. Layer drift ratio.

	Story	CASE-1	CASE-2	CASE-1	CASE-2
		Drift (x)	Drift (x)	Drift (y)	Drift (y)
Aboveground	MR	0.010011692	0.005849271	0.005668646	0.003282953
	4F	0.003687407	0.002112066	0.003049359	0.001047220
	3F	0.006300559	0.003252394	0.005285275	0.001742166
	2F	0.004544652	0.002559462	0.003569958	0.001228467
	1F	0.001392340	0.000894698	0.000697643	0.000358051
Underground	-1F	0.000487345	0.000490633	0.000097216	0.000129742
	-2F	0.000155103	0.000293204	-0.000004472	0.000050276

Continued

Underground	-3F	0.000028565	0.000145384	0.000012857	0.000014601
	-4F	0.000000000	0.000025047	0.000000000	0.000002885
	PIT	0.000000000	0.000000000	0.000000000	0.000000000

MR: Machine Room.

On the other hand, when focusing on the underground structural components, Table 5 shows that the RC structure with elevator shafts exhibits a slightly larger layer drift ratio compared to the structure without elevator shafts. This increased drift in the underground section can be attributed to the higher inertia associated with the elevator shafts, which function as integral parts of the shear wall system in the underground stories. Essentially, while the inclusion of elevator shafts enhances seismic resistance for the aboveground portion by reducing lateral displacements and overall deformation, the added mass and stiffness in the underground areas lead to a somewhat higher drift ratio, indicating increased structural deformation of the underground stories. Therefore, the combined findings from Figure 18 and Table 5 highlight a dual effect as the elevator shafts improve the seismic performance of the RC structure aboveground by mitigating drift, yet in the underground part, they contribute to slightly larger deformation.

4. Conclusions

Seismic activities have long been responsible for immense human suffering and economic loss, making it imperative to design structures with superior seismic resistance to mitigate these risks. Due to this, this research focuses on an actual construction project as the public commercial hub in Astana, Republic of Kazakhstan, which is subjected to response spectrum analysis to simulate its behavior under seismic activity. This research specifically examines the structural influence due to the elevator shafts, because the elevator system serves as the primary vertical transportation tool in urban environments currently. By analyzing the actual RC structure without and with the elevator shafts as CASE-1 and CASE-2 show, this research not only addresses the safety concern but also aims to provide insights that could inform more effective design of the elevators in the RC structure, improving the seismic performance of such structures is essential for safeguarding both lives and economic assets in the face of future earthquake events.

Based on the discussion of base reaction results, the RC structure incorporating elevator shafts generally exhibits larger shear forces and base moments. This observation suggests that the elevator shafts contribute positively to the structural performance under seismic activities by providing enhanced lateral support and a more robust energy dissipation mechanism. Additionally, the response spectrum analysis shows that the structure with elevator shafts features a lower structural period, higher structural frequency, and faster structural acceleration. These dynamic characteristics are beneficial because they indicate a stiffer, more responsive structure that experiences reduced inter-story displacements and overall deformations during an earthquake. In essence, the elevator shafts that function as integral shear walls not only help to redistribute seismic forces but also mitigate the effects of dynamic loads, thereby reducing potential structural damage.

Moreover, the analysis of layer displacement, layer radian, and layer drift ratio further confirms the beneficial influence of incorporating elevator shafts on the seismic performance of the RC structure. Specifically, the structure with elevator shafts exhibits shorter inter-story displacements, smaller rotational deformations (layer radian), and a lower drift ratio compared to the configuration without them. These improvements indicate that the elevator shafts, acting as integral shear walls, contribute to a stiffer overall system that can better resist seismic forces, as also supported by the shell stress analysis. However, the analytical results also reveal that the underground stories experience slightly longer displacements, larger layer radians, and a higher drift ratio when elevator shafts are included, suggesting that while the elevator shafts enhance the structural performance of the aboveground stories, the underground stories may require additional reinforcement to mitigate the observed structural deformations under the response spectrum analysis in this research. In this context, previous research supports the use of CFRP jackets [49]-[52] on the elevator shaft columns as a means to improve seismic performance by enhancing structural stiffness and thereby reducing displacements, rotational deformations, and drift ratios in the underground stories. Furthermore, substituting the traditional shear wall with a steel structure [53] [54] in the underground stories is proposed as an alternative solution, as the lower mass and inertia associated with steel could lead to diminished seismic displacements and improved overall dynamic performance of the structure.

Elevators are essential for vertical transportation in urban environments, and their integration has been a focus of extensive research aimed at understanding the influences on structural behavior, whether in new construction or as external systems in existing buildings [55]-[58]. In this research, response spectrum analysis is employed on the public commercial hub in Astana, Republic of Kazakhstan, to examine how multi-elevator shafts influence the seismic performance of RC structures. Unlike typical office buildings that often feature a single elevator shaft, the multi-elevator configuration analyzed in this research offers valuable references on the dynamic interplay between multiple elevator shafts and the overall RC structure. The findings in this research not only provide valuable insights into how these systems enhance seismic resistance but also highlight the distinct structural behaviors between the aboveground and underground stories. These analytical results are expected to serve as a valuable reference for future research into elevator system-structure interactions and to inform the design of multi-elevator systems in similar construction projects.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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