Response Spectrum Analysis of Adding External Elevators to Existing RC Buildings

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Abstract

In contemporary society, elevators stand as indispensable facilitators, particularly for users in tall buildings, contributing significantly to convenience. Their role becomes even more crucial for individuals with disabilities, serving as a vital means of transport to enable them to partake in modern life. However, a challenge emerges in the form of buildings erected during the 1970s or 1980s, lacking initial designs of elevators. This absence of elevator well designs presents substantial issues for building users, especially residents. However, many of these buildings have not reached the end of their service life. Undertaking removal and reconstruction efforts, while a potential solution, raises serious environmental concerns. The associated carbon dioxide emissions and the environmental impact of such activities underscore the need for alternative, environmentally conscious approaches. In this context, the introduction of external elevator structures to existing buildings emerges as a meaningful and sustainable avenue for researchers to explore. The proposed solution not only addresses the practical challenges faced by residents but also aligns with broader environmental goals, contributing to the reduction of carbon emissions and the preservation of existing building structures. Many researchers emphasize the critical importance of assessing structural performance under seismic loads to ensure safety. This research, centered on a typical educational RC frame structure at Kyungpook National University, employs the RSA (Response Spectrum Analysis) method to comprehensively evaluate seismic performance. This research specifically compares analytical results using RSA for the RC frame with and without the external elevator structure (RCE and RC, respectively).

Keywords

External Elevator Structure; RC Frame Structure; Response Spectrum Analysis.

1. Introduction

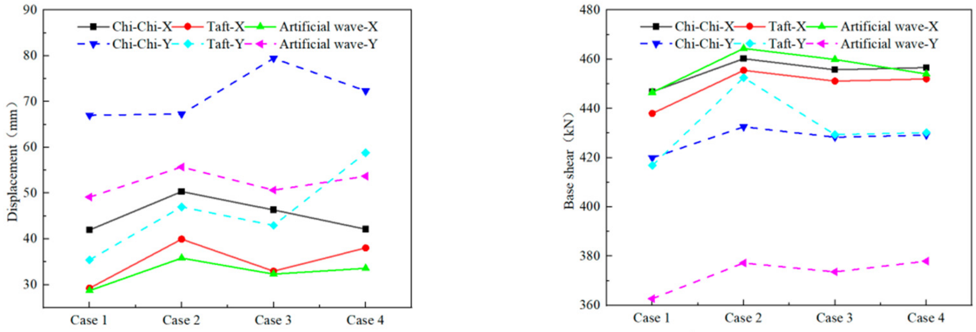
As society has progressed over the decades, the necessity of elevators in contemporary buildings has become undeniable. However, the RC (Reinforced Concrete) frames constructed in the 1970s and 1980s were not originally designed with the usage of elevators in mind. This oversight has resulted in significant challenges in integrating elevators into these structures, particularly in the absence of a designated elevator well. A critical concern arises from the fact that a substantial number of these RC frame structures have not yet surpassed their expected lifespan. The prospect of demolishing and rebuilding these buildings poses a considerable economic expense, not to mention the accompanying environmental damage associated with such large-scale construction activities. In light of the imperative to balance environmental protection and economic efficiency, the notion of adding external elevators to existing buildings emerges as a highly practical and relevant research endeavor. Researchers are increasingly recognizing the importance of exploring innovative solutions that can enhance the functionality of older buildings without resorting to drastic measures of demolition and reconstruction. This approach aligns with the broader goal of sustainable development, where retrofitting existing structures proves to be a strategic and resource-efficient way to address the evolving needs of modern society.

Nevertheless, the impact of external elevators on the structural performance of existing buildings is crucial, necessitating consideration. Additionally, researchers must analyze and evaluate the safety implications, especially in the context of earthquakes. Existing studies on the effects of external elevators on RC frame structures suggest potential advantages for incorporating these elevators into existing buildings.

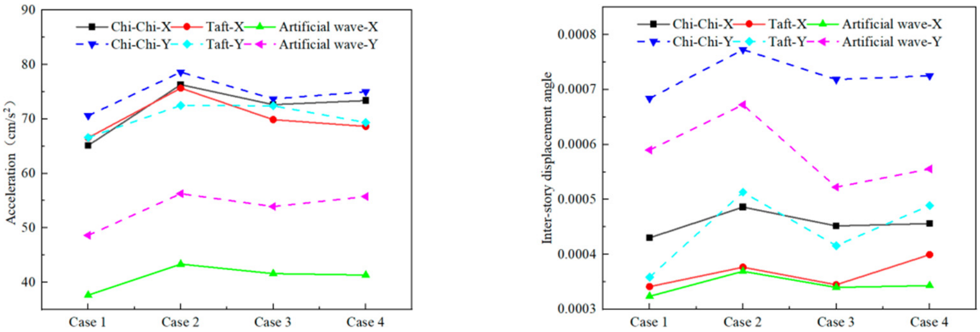
(a) Existing building (b) Post-installed elevator structure

Figure 1. Specific structure models

In a comprehensive examination conducted by Yuguo Chen, Linmin Shen, Ming Wen, Baokui Chen, and Jian Jiang (2023), as visually depicted in Figure 1, the seismic response characteristics of a 26-story-frame shear wall structure were scrutinized both before and after the installation of elevators. The ensuing analysis, presented in Figure 2, reveals that the integration of post-installed elevators exerts a relatively modest influence on the seismic performance of the pre-existing building. Notably, there is a discernible but slight reduction in the overall seismic response of the structure.



(a) Peak displacement (b) Peak base shear



(c) Peak acceleration (d) Peak interstory displacement angle

Figure 2. Results of frequent-earthquake time-history analysis

One noteworthy aspect highlighted by the authors pertains to the impact of elevator shaft characteristics on seismic behavior. It is emphasized that an increase in the standard shaft height leads to a reduction in stiffness and a corresponding increment in seismic response. Importantly, the authors argue that this trade-off is justifiable due to the concurrent reduction in construction costs associated with taller shafts. Moreover, the research findings shed light on a critical variable in the seismic response equation—installation location. The study underscores that the seismic response of post-installed elevators is significantly influenced by where they are installed within the structure. This revelation implies that careful consideration of placement is paramount in optimizing the seismic performance benefits of post-installed elevators.

A study conducted by Feng Dean, Wen Kai, Zhao Xiaobin, and Ding Jintang (2019) delves into the intricate dynamics of adding external elevators to existing buildings. The researchers meticulously monitored the displacement results in the x, y, and z directions of a 7-story building undergoing external elevator construction. The research places a particular emphasis on the connection between the foundation and the newly added external elevator. The findings suggest that this connection exerts a substantial influence on the overall structural performance of the building. Importantly, the study advocates for the implementation of advanced connection methods, noting that such measures can effectively improve structural performance, especially when subjected to seismic loads. Furthermore, the investigation extends its focus to the connection between the elevator well and the existing building structure. The research underscores the pivotal role played by this connection, emphasizing its significance in influencing the overall stability and safety of the existing building. The authors explicitly state that ensuring the safety of these connection points, both between the elevator well and the foundation and the existing building is of utmost seriousness.

The scope of this research centers around a detailed analysis of a typical 4-story educational usage RC (Reinforced Concrete) frame structure situated within Kyungpook National University, located in Daegu Metropolitan City, the Republic of Korea. Employing RSA (Response Spectrum Analysis), the study aims to explore the repercussions of integrating an external elevator into an existing RC frame structure dating back to the 1980s.

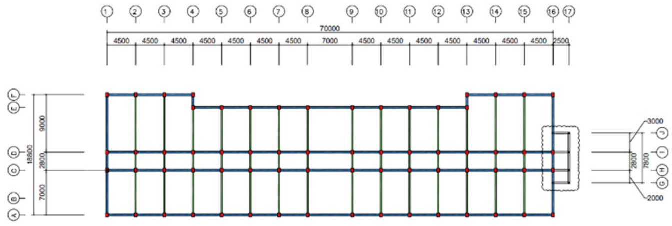
The selected structure serves as a representative case study to investigate the intricate dynamics associated with the addition of external elevators. By utilizing RSA, the research endeavors to comprehensively understand the structural response and behavior of the RC frame structure under the influence of external elevator modification. The crux of the investigation lies in the comparative analysis between the specific RC frame structure with the addition of an external elevator and the same structure without this modification.

This comparative study is poised to yield valuable insights into the structural implications, seismic response, and overall performance of the building when subjected to the addition of external elevators. The findings are anticipated to provide a significant reference point for researchers and practitioners engaged in the broader exploration of incorporating external elevators into existing buildings. As such, the research contributes not only to the understanding of a specific case but also to the broader body of knowledge surrounding the integration of elevators into existing structures, particularly those constructed in the past.

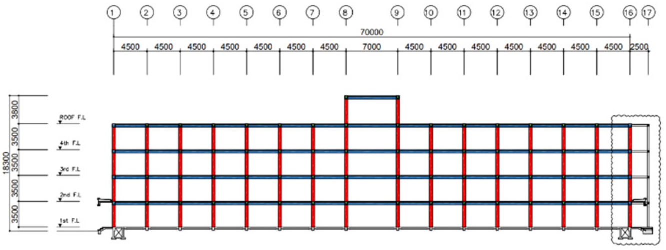
2. Structure Description and Analysis Design

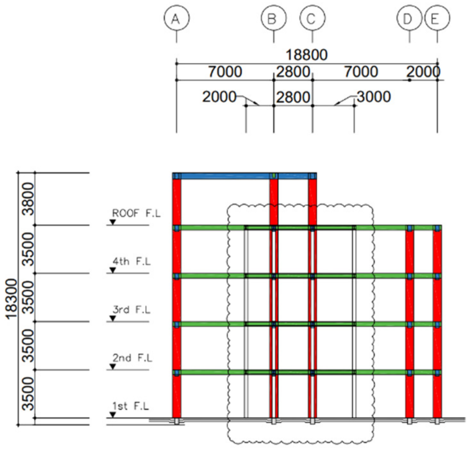
2.1. Structure Description

The research centers on analyzing an educational building from the 1970s, particularly focusing on an RC frame structure within the Department of Architectural Engineering at Kyungpook National University in Daegu, South Korea. The selected building's geographical coordinates are specified as a longitude of 128°60’85’’E and a latitude of 35°88’76’’N.



(a) Floor plan

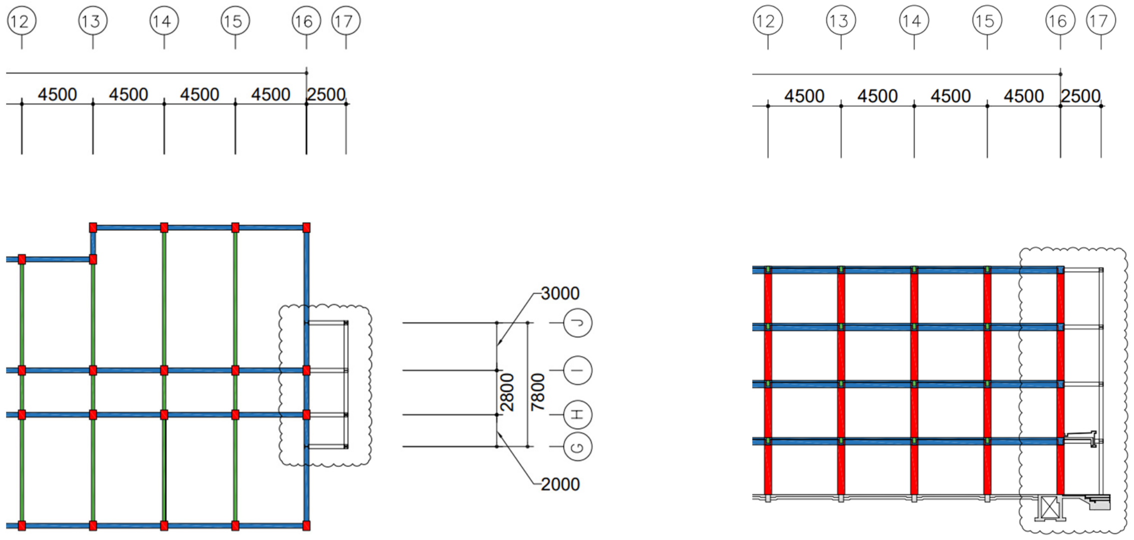




(b) Front elevation (c) Side elevation

Figure 3. The design of the target RC frame structure (Unit: mm)

The subject of scrutiny in this investigation is the RC frame structure, meticulously detailed in Figure 3. This architectural entity spans a considerable area, measuring 1316m^2. The structure boasts specific dimensions, with a length extending to 70m, a width of 18.8m, and an overall height of 18.3m. Within this RC frame structure, the classrooms are designed to accommodate different spatial needs. Those situated on the sides are constructed with dimensions of 7m in length and 4.5m in width, providing a more compact educational space. In contrast, the larger classrooms, as well as the central stair room, adhere to a slightly larger footprint, measuring 9m in length 4.5m in width, and 7m by 7m, respectively. A central corridor, integral to the structure and observable in both floor plan and side elevation, possesses a width of 2.8m. This corridor serves as a pivotal element in facilitating movement and connectivity within the building. Upon closer examination of the architectural configuration, it is evident that the RC frame structure is organized into four stories, each maintaining a consistent height of 3.5m. Additionally, a noteworthy feature is the presence of a final stair room situated on the roof, ascending to a height of 3.8m, as visually depicted in Figure 3.



(a) Elevator well (Floor plan) (b) Elevator well (Front elevation)

Figure 4. Design of structure of elevator well

The design of the external elevator structure for the target RC frame structure, depicted in Figure 3, is positioned alongside the entire structure, as illustrated by the cloud mark in the figures. Figure 4 provides a detailed view of the external elevator structure, emphasizing its specific design with an enlarged floor plan and front elevation. According to Figure 4, the external elevator structure is 7.8m in length and 2.5m in width, featuring an elevator lobby measuring 2.5m × 4.8m and an elevator well designed at 2.5m × 3m.

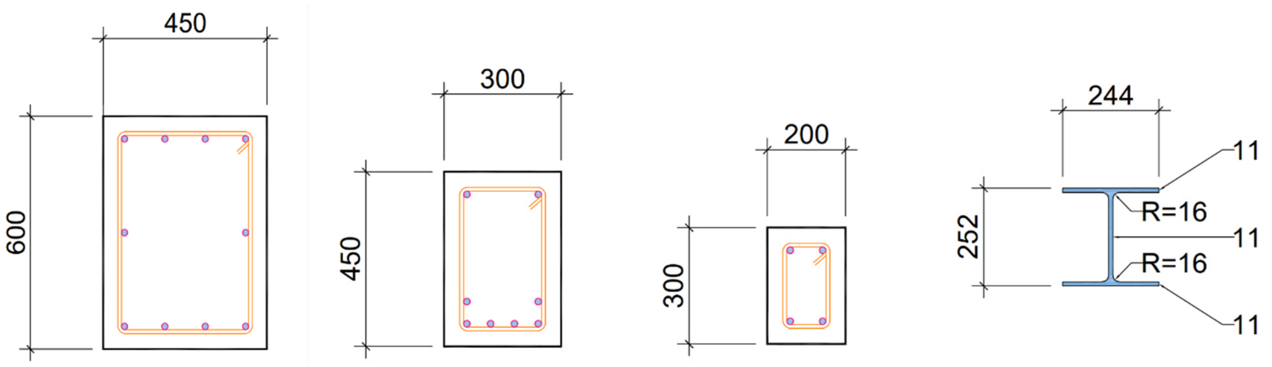
The design specifics of the structure utilize color codes, where red denotes columns, blue represents girders, green signifies beams and white in the cloud mark indicates the external elevator structure. Girders encompass the structure horizontally, including sections alongside the corridor, while beams seamlessly integrate vertically into the entire RC frame structure. The external elevator structure is positioned alongside the entirety of the specific RC frame structure, emphasizing both spatial considerations and the use of color codes for clarity in comprehending the structural elements.

2.2. Section Designs and Materials Description

Figure 5 visually illustrates the design of the column section with an area of 270,000mm^2. The column section measures 450mm × 600mm and features ten longitudinal rebars of D19 (or Φ19), along with hoop rebars of D10 (or Φ10) spaced at 300mm intervals. The design adheres to the specifications outlined in KDS 14 20 50: 2022, maintaining a concrete covering depth of 40mm.

The girder in the specific RC frame structure has a cross-sectional area of 135,000mm^2, featuring a width of 300mm and a height of 450mm. Its structural reinforcement consists of eight longitudinal rebars, with two D16 (or Φ16) rebars at the top and six D16 (or Φ16) rebars at the bottom. Hoop rebars of D10 (or Φ10) are strategically placed at 300mm intervals to enhance structural stability. The design adheres to the guidelines in KDS 14 20 50: 2022, maintaining a concrete cover depth of 40mm.

The beam in the RC frame structure has a cross-sectional area of 60,000mm^2, achieved through dimensions of 200mm width and 300mm height. It is reinforced with four longitudinal rebars—two D16 (or Φ16) rebars at the top and two at the bottom. Similar to the girder design, hoop rebars (D10 or Φ10) are incorporated at 300mm intervals. The concrete cover depth adheres to the guidelines outlined in KDS 14 20 50: 2022, maintaining a depth of 40mm. The beam's design, akin to the girder, is essential for ensuring optimal load-bearing capabilities in the framework. Specific placement and sizing of longitudinal and hoop rebars, aligned with established standards, enhance the beam's strength and durability. The consistency in design elements between the girder and beam reflects a unified and systematic approach to overall structural integrity, ensuring seamless collaboration within specified guidelines. This design enhances the reliability and performance of structural elements under diverse load conditions.



(a) Column (b) Girder (c) Beam (d) H-Beam

Figure 5. Design of the cross-section

In adherence to the specifications outlined in KS D 3502, which delineates the dimensions, mass, and permissible variations of hot rolled steel sections, the design of the H beam for the external elevator structure is detailed, as depicted in Figure 5. The H beam, serving as a crucial load-bearing element, is crafted with dimensions of 244mm in width and 252mm in height, conforming to the prescribed standards. The specific H beam configuration involves a flange with a dimension of 11mm and a web, the vertical section, also measuring 11mm. This design choice is consistent with the standards, ensuring structural stability and resilience in alignment with industry requirements. Furthermore, the radius of the specific H beam is specified at 16mm, contributing to the overall geometric characteristics and reinforcing the H beam's capacity to distribute loads effectively. Also, a crucial metric in evaluating the structural capability of the H beam is its cross-sectional area. Based on calculations, the cross-sectional area of the specific H beam designed for the external elevator structure is determined to be 8206mm^2.

The construction employs concrete conforming to the standards outlined in KS F 4009:2021 for ready-mixed concrete. In alignment with design guidelines from the Republic of Korea's Ministry of Education for 1980s educational buildings, the specified compressive strength is denoted as F_{ck}=15.12MPa, with an anticipated compressive strength of F_{ek}=18.14MPa, as outlined in Table 1. In accordance with KS D 3504:2021 guidelines for steel bars in concrete reinforcement and drawing from the 1980s educational building design specifications of the Republic of Korea's Ministry of Education, the rebar's strength is specified as F_y=240MPa in Table 1. The anticipated stress is designed to be F_{ey}=300MPa. This research underscores the significance of following the guidelines set forth in KS D 3504:2021, which specifically governs the use of steel bars in concrete reinforcement. Adherence to these standards is crucial as it guarantees that the steel bars possess the necessary strength and performance characteristics required for the structural integrity of the building. Furthermore, the decision to align the strength of the reinforcement bars with historical practices signifies an approach to design. This design aims to accommodate the unique structural requirements of the project.

Table 1. Design of column and beam

<table>
<tr><td rowspan="8">Concrete</td><td colspan="2">Weight per unit volume</td><td colspan="2">23.54 kN/m^3</td></tr>
<tr><td colspan="2">Mass per unit volume</td><td colspan="2">2.4004 kN/m^3</td></tr>
<tr><td colspan="2">Modulus of Elasticity (E)</td><td colspan="2">22334 MPa</td></tr>
<tr><td colspan="2">Poisson (U)</td><td colspan="2">0.1667</td></tr>
<tr><td colspan="2">Coefficient of Thermal Expansion (A)</td><td colspan="2">1.100E-05</td></tr>
<tr><td colspan="2">Shear Modulus (G)</td><td colspan="2">9571.4408</td></tr>
<tr><td colspan="2">Specified Compressive Strength (F_{ck})</td><td colspan="2">15.12 MPa</td></tr>
<tr><td colspan="2">Expected Compressive Strength (F_{ek})</td><td colspan="2">18.14 MPa</td></tr>
<tr><td rowspan="7">Rebar</td><td colspan="2">Weight per unit volume</td><td colspan="2">77 kN/m^3</td></tr>
<tr><td colspan="2">Mass per unit volume</td><td colspan="2">7.85 kN/m^3</td></tr>
<tr><td colspan="2">Modulus of Elasticity (E)</td><td colspan="2">200000 MPa</td></tr>
<tr><td colspan="2">Poisson (U)</td><td colspan="2">0.3</td></tr>
<tr><td colspan="2">Coefficient of Thermal Expansion (A)</td><td colspan="2">1.170E-05</td></tr>
<tr><td colspan="2">Minimum Yield Stress (F_y)</td><td colspan="2">240 MPa</td></tr>
<tr><td colspan="2">Expected Yield Stress (F_{ey})</td><td colspan="2">300 MPa</td></tr>
<tr><td rowspan="2">Column</td><td>Longitudinal Rebar</td><td>10-D19</td><td>Stiffness of Shear</td><td>0.45</td></tr>
<tr><td>Hoop Rebar</td><td>D10@300</td><td>Stiffness of Moment</td><td>0.70</td></tr>
<tr><td rowspan="2">Girder</td><td>Longitudinal Rebar</td><td>8-D16</td><td>Stiffness of Shear</td><td>0.45</td></tr>
<tr><td>Hoop Rebar</td><td>D10@300</td><td>Stiffness of Moment</td><td>0.35</td></tr>
<tr><td rowspan="2">Beam</td><td>Longitudinal Rebar</td><td>4-D16</td><td>Stiffness of Shear</td><td>0.45</td></tr>
<tr><td>Hoop Rebar</td><td>D10@300</td><td>Stiffness of Moment</td><td>0.35</td></tr>
</table>

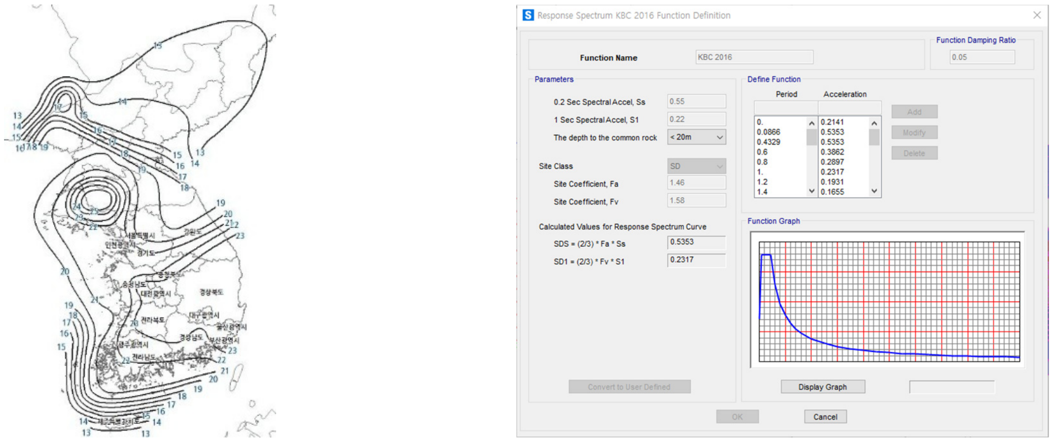
Following design principles of typical school buildings from the 1980s and referencing KISTEC 2021's Table 5.3.1, shear and moment stiffness values for column and beam sections are specified. The column section has a shear stiffness of 0.45 and a moment stiffness of 0.7, emphasizing resistance to bending. Conversely, the beam section has a shear stiffness of 0.45 and a moment stiffness of 0.35, indicating responsiveness to shearing forces. These stiffness values are crucial for determining structural behavior, aligning with historical design practices for 1980s school buildings.

Table 2. Design of H-Beam

H-Beam	Weight per unit volume	77 kN/m^3
	Mass per unit volume	7.85 kN/m^3
	Modulus of elasticity (E)	206000 MPa
	Poisson (U)	0.3
	Coefficient of Thermal expansion (A)	1.200E-05
	Shear Modulus (G)	79230.77
	Minimum Yield Stress (F_y)	235 MPa
	Minimum Tensile Stress (F_u)	370 MPa
	Expected Yield Stress (F_{ey})	260 MPa
	Expected Tensile Stress (F_{eu})	410 MPa

Drawing inspiration from various external elevator construction projects in mainland China and adhering to the Chinese standard GB/T 700-2006 for carbon structure steels, this research employs H-beams in the external elevator structure. The H-beams conform to the standards outlined in KS D 3503:2018 for rolled steels for general structure. Aligning with design guidelines from SS235, the specified minimum yield strength (F_y) is denoted as 235MPa, the specified minimum tensile strength (F_u) is denoted as 370MPa, with an expected yield strength (F_{ey}) of 260MPa and an expected tensile strength (F_{eu}) of 410MPa, as detailed in Table 2.

2.3. Approaches of RSA (Response Spectrum Analysis)



Response Spectrum KBC 2016 Function Definition

Function Name: KBC 2016
Function Damping Ratio: 0.05

Parameters
0.2 Sec Spectral Accel, Ss: 0.55
1 Sec Spectral Accel, S1: 0.22
The depth to the common rock: < 20m
Site Class: SD
Site Coefficient, Fa: 1.46
Site Coefficient, Fv: 1.58

Calculated Values for Response Spectrum Curve
SDS = (2/3) * Fa * Ss: 0.5353
SD1 = (2/3) * Fv * S1: 0.2317

Define Function

Period	Acceleration
0.	0.2141
0.0866	0.5353
0.4329	0.5353
0.6	0.3862
0.8	0.2897
1.	0.2317
1.2	0.1931
1.4	0.1655

(a) Earthquake hazard map (b) Response spectrum

Figure 6. Earthquake hazard map and Response spectrum (KBC 2016)

The research utilizes the response spectrum methodology based on KISTEC 2021 to analyze the target structure. This involves employing the response spectrum derived from KBC 2016, as illustrated in Figure 6. The earthquake hazard map of the Republic of Korea, also from KBC 2016, is depicted in Figure 6 to guide the definition of the response spectrum for site class SD.

This classification is determined by the specific location of the target building (No.401) at Kyungpook National University's Department of Architectural Engineering in Daegu Metropolitan City. The corresponding response spectrum for the SD classification is illustrated on the right side of Figure 6.

The analysis methodology involves a multi-step process utilizing Figure 6 from KBC 2016, which provides the response spectrum crucial for evaluating the structural response of the target building. Figure 6 also includes the earthquake hazard map of the Republic of Korea, offering an overview of seismic risks. This map guides the determination of the response spectrum for site class SD, considering the geographical location (128°60’85”E, 35°88’76”N) of the target building at Kyungpook National University. The dual representation in Figure 6 enhances clarity, with the left side showing the earthquake hazard map and the right side displaying the corresponding response spectrum, ensuring accurate consideration of site-specific seismic characteristics.

The calculation of spectral accelerations is a crucial step in seismic analysis. KBC 2016 provides an equation that serves as a methodological framework for computing these accelerations, considering specific seismic characteristics relevant to structural assessment. The 1-sec and 0.2-sec spectral accelerations are essential parameters, offering insights into how a structure responds to seismic forces over different time intervals. This computational process quantifies ground motion magnitude, contributing to a comprehensive seismic analysis in line with established standards. Utilizing the equations from KBC 2016, the computation of both spectral accelerations becomes feasible as below:

$$S_{D1} = S \times F_v \times {}^{2}\!/_{3} \tag{1}$$

$$S_{DS} = S \times 2.5 \times F_a \times {}^{2}\!/_{3} \tag{2}$$

Where S represents the effective ground acceleration value for a 2400-year return period earthquake, sourced from Table 0306.3.1 of KBC 2016. Additionally, the factors F_a and F_v, are found in Table 0306.3.3 and Table 0306.3.4 respectively as per KBC 2016. These parameters contribute to the calculation of S_{D1} for the 1-sec spectral acceleration and S_{DS} for the 0.2-sec spectral acceleration. Utilizing the provided equations, the computed 1-sec spectral acceleration is 0.22g, and the 0.2-sec spectral acceleration is 0.55g. These results are visually depicted on the right side of Figure 6.

3. Discussions

3.1. Modal Analysis

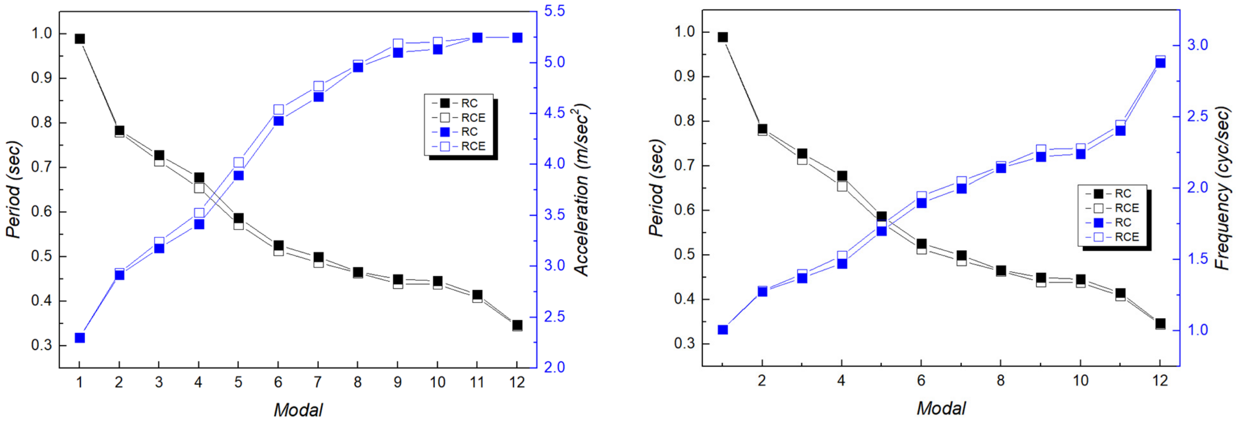
Modal analysis is a technique that allows researchers to study the dynamic behavior of a structure under vibration or external forces. It can be used to determine the natural frequencies, mode shapes, modal masses, and damping ratios of a structure. These parameters are important for understanding the structural response to dynamic loads, such as earthquakes, wind, or traffic.

To perform a modal analysis for the RC frame structure in this research, solving the eigenvalue problem of the equation of motion as below:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{f(t)\} \tag{3}$$

where $[M]$ is the mass matrix, $[C]$ is the damping matrix, $[K]$ is the stiffness matrix, $\{u\}$ is the displacement vector, $\{\dot{u}\}$ is the velocity vector, and $\{\ddot{u}\}$ is the acceleration vector. The eigenvalues of this equation are the natural frequencies squared, and the eigenvectors are the mode shapes.

The modal analysis results for a specific RC frame structure, both with and without the external elevator structure, are presented in Figure 7. The left side of Figure 7, labeled (a), illustrates the correlation between different modals, periods, and accelerations. Meanwhile, the right side, labeled (b), depicts the relationship between different modals, periods, and frequencies.



(a) Period & Acceleration (b) Period & Frequency

Figure 7. Result of Modal analysis

In Figure 7, graphs (a) and (b) present the results of the period analysis for a specific RC frame structure with and without an external elevator structure. The analytical findings indicate that the RC frame structure without the external elevator exhibits larger periods compared to the structure with the external elevator. This suggests that the external elevator structure significantly reduces the structural period. A longer period implies reduced sensitivity to higher frequency ground motion components, potentially lowering seismic demand and increasing ductility capacity. However, a longer period may also make the structure more susceptible to resonance, amplifying seismic response and causing damage. Despite the period-reducing benefits of the external elevator structure, determining the optimal period involves considering factors such as seismic hazard, structural system, design criteria, and code provisions.

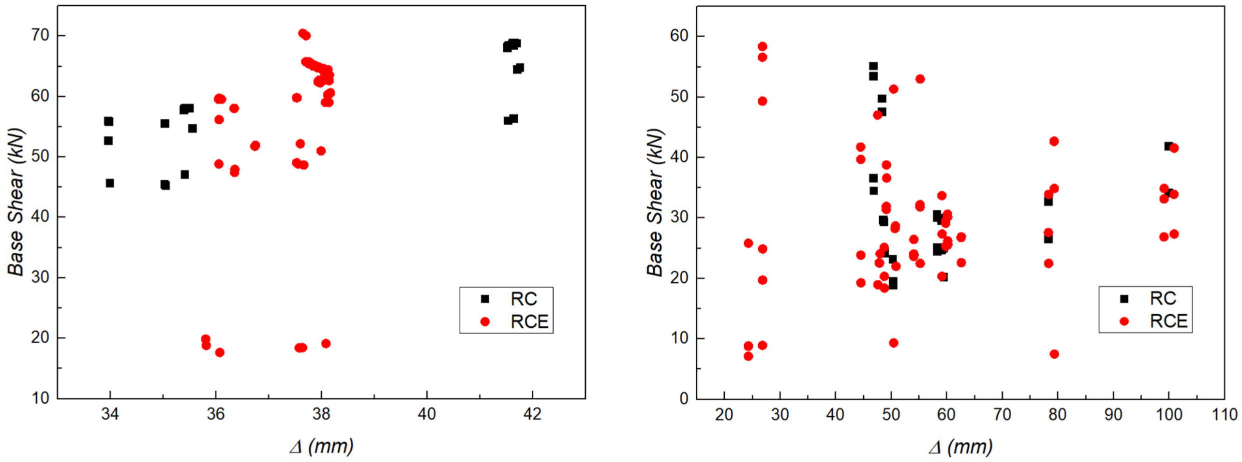
According to Figure 7, graph (a) presents the results of acceleration analysis for a specific RC frame structure with and without an external elevator structure. The findings reveal that the RC frame structure without the external elevator experiences lower acceleration compared to the structure with the external elevator. This suggests that the addition of an external elevator structure increases the structural acceleration significantly. The relationship between structural period and acceleration is noted to be inversely proportional, dependent on the mass of the structure.

Graph (b) on the right side of Figure 7 indicates that the specific RC frame structure without the external elevator has a lower frequency compared to the structure with the external elevator. This suggests that the addition of an external elevator significantly improves the structural frequency. A lower frequency may imply increased susceptibility to resonance, amplifying seismic response and causing damage. The frequency results, aligned with the discussion on acceleration, affirm the inverse relationship between period and frequency, both dependent on the structure's mass. Similar to the discussion of the period, despite the potential benefits of increased frequency due to the external elevator, determining the optimal period involves considering various factors such as seismic hazard, structural system, design criteria, and code provisions.

3.2. Base Shear and Base Moment

3.2.1. Discussion of Base Shear

The outcomes of roof displacement and base shear force analyses, conducted within the response spectrum framework, serve as indicators of the structure's performance. In this research, the specific RC frame is scrutinized at 132 monitored points on the foundation (66 monitored points) and roof (66 monitored points). With the addition of the external elevator structure, the total monitored points increase to 144 (72 × 2 monitored points). Figure 8 visually presents the correlation between roof displacement and foundation base shear in both the x and y directions.



(a) Direction-x (b) Direction-y

Figure 8. Results of displacement and base shear

In Figure 8, the left side illustrates that the external elevator structure has varied effects on monitored points' displacements in the x-direction. While some points experience a reduction in displacement, others show an increase. Overall, the external elevator structure influences displacement results at each monitored point, mitigating maximum displacements seen in the specific RC frame without the external elevator. Comparing base shear in the x-direction, results indicate that the external elevator structure itself yields distinguished smaller base shear values compared to the monitored points on the specific RC frame. Excluding monitored points for the external elevator structure, a comparison of base shear between the RC frame with and without the external elevator reveals mixed results—some larger and some smaller values. This suggests that the external elevator structure can bring different points' base shear forces closer together.

In the right side of Figure 8, the monitored points reveal that, while the maximum displacements remain largely unchanged, many minimum displacement points in the specific RC frame with the external elevator structure appear. This suggests that the external elevator structure has the potential to decrease overall structural displacement. However, when assessing base shear force results in the y-direction, it becomes apparent that the RC frame with the external elevator structure exhibits both larger and smaller base shear forces at different monitored foundation points. Despite this variation, the overall trend across various cases indicates that the external elevator structure can contribute to a reduction in foundation base shear force.

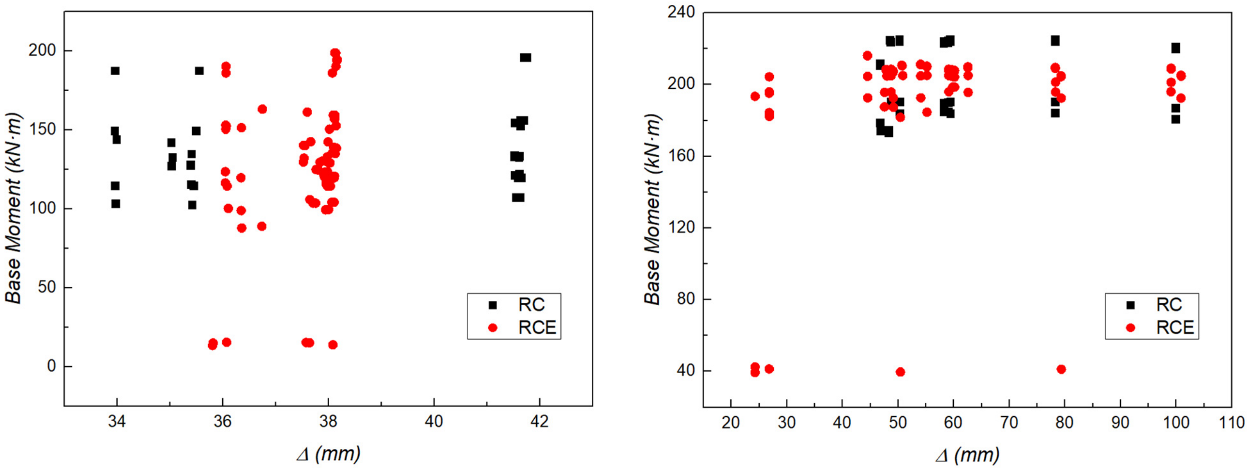
Table 3. Average displacement and average base shear

Types	Displacement mm	Base Shear kN
RC-X	60.08647	38.153016
RCE-X	57.096569	37.497213
RC-Y	31.112212	62.068816
RCE-Y	28.954806	57.670215

Especially, Table 3 particularly focusing on average displacement and average base shear results, highlights that the external elevator structure has a consistent and notable impact. In both x and y directions, the findings demonstrate that the external elevator structure is effective in reducing both structural displacement and foundation base shear.

3.2.2. Discussion of Base Moment

The assessment of base moment and displacement involves a total of 132 monitored points on the foundation (66 monitored points) and roof (66 monitored points) for the specific RC frame structure. With the inclusion of the external elevator structure, the total monitored points increase to 144 (72 × 2 monitored points) for comprehensive checking and analysis. Figure 9 visually depicts the correlation between roof displacement and foundation base moment in both the x and y directions.



(a) Direction-x (b) Direction-y

Figure 9. Results of displacement and base mement

The left graph in Figure 9 illustrates a consistent pattern in the base moment in the x-direction, mirroring the behavior observed in base shear. The external elevator structure consistently exhibits smaller base moments compared to the specific RC frame structure. In the comparison of base moments between the RC frame with and without the external elevator, the left graph in Figure 9 reveals nearly identical results in base moment values. This indicates that the external elevator structure has minimal impact on the performance of structural base moments along the x-direction under response spectrum analysis.

The right graph in Figure 9 depicts the base moment in the y-direction, revealing a consistent trend similar to the result along with the direction x, where the external elevator structure consistently exhibits smaller base moments than the specific RC frame structure. This reduction in base moments holds true along the y-direction. When excluding monitored points for the external elevator structure, a detailed comparison of base moments between the RC frame with and without the external elevator shows varied results—some points show larger values, while others show smaller ones. Overall, the base moment results suggest that the external elevator structure has the potential to equalize base moments across different points.

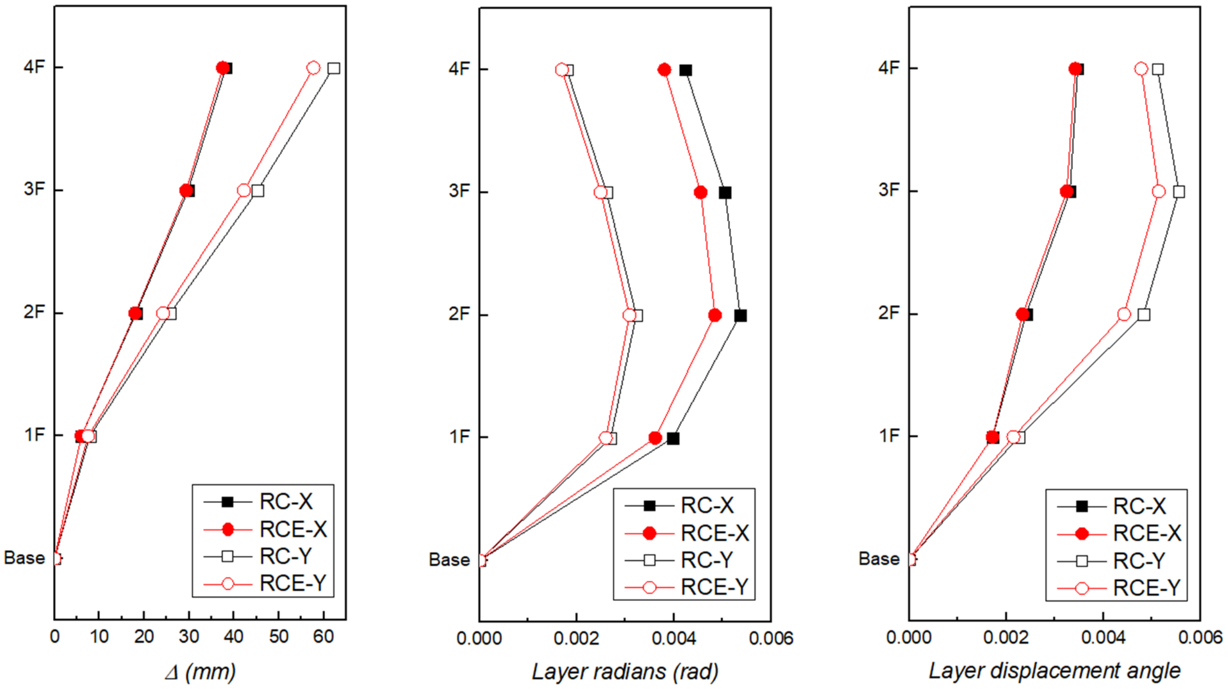
Table 4. Average displacement and average base moment

Types	Displacement mm	Base Moment kN·m
RC-X	60.08647	137.31937
RCE-X	57.096569	125.09469
RC-Y	31.112212	202.65798
RCE-Y	28.954806	188.82428

The numerical results presented in Table 4 indicate that, including the phenomenon of displacement-reducing effects from the external elevator structure on the specific RC frame structure, the external elevator structure also has the capacity to reduce the foundation base moment of the specific RC frame structure.

3.3. Layer Displacement, Layer Radians and Layer Displacement Angle

This research underscores the significance of assessing the seismic performance of the RC frame structure by considering analytical average displacement and radians on each floor. In the specific RC frame structure under study, equipped with both 66 and 72 monitored points for each floor (without and with the external elevator structure, respectively), the findings, including average layer displacement and average layer joint radians, are illustrated in Figure 10 through graphs (a) and (b).



(a) Layer displacement (b) Layer radians (c) Layer displacement angle

Figure 10. Layer displacement, radians, and displacement angle

The findings, illustrated in graph (a) of Figure 15, reveal an ascending pattern of average displacement correlated with the increasing number of stories in the specific RC frame structure. Notably, a comparative analysis between the RC frame structures with and without the external elevator structure indicates that, in the x-direction, the structure lacking the external elevator exhibits a slightly greater displacement. In the y-direction, a notable distinction emerges, with the RC frame structure without the external elevator displaying a significantly longer displacement than its counterpart with the external elevator structure. The comparative analysis between the RC frame structures provides valuable insights into the impact of the external elevator structure on displacement patterns. While the overall trend indicates an increase in displacement with additional stories, the differences in the x and y directions underscore the significance of the external elevator structure in influencing and potentially mitigating displacement along specific axes.

Furthermore, the analysis extends to the examination of joint radians on various stories, with a specific focus on Figure 15, depicted in graph (b). The findings reveal that, in the x-direction, the specific RC frame structure without the external elevator structure exhibits slightly larger radians compared to its counterpart with the external elevator. Moreover, in the y-direction, a consistent trend emerges, showcasing distinctly larger radians in the RC frame structure without the external elevator compared to the RC frame structure with the external elevator.

Table 5. Result of Layer displacement, and layer radians

Stories	RC				RCE			
	Displacement		Radians		Displacement		Radians	
	Dir.-x	Dir.-y	Dir.-x	Dir.-y	Dir.-x	Dir.-y	Dir.-x	Dir.-y
	mm	mm	rad	rad	mm	mm	rad	rad
BASE	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
1F	6.0076	7.8880	0.0040	0.0027	6.0092	7.5102	0.0036	0.0026
2F	18.1448	25.7688	0.0054	0.0032	17.9759	24.2256	0.0048	0.0031
3F	29.7288	45.1864	0.0051	0.0026	29.3215	42.1992	0.0046	0.0025
4F	38.1530	62.0688	0.0042	0.0018	37.4972	57.6702	0.0038	0.0017

The data in Table 5 demonstrates that the external elevator structure effectively mitigates structural layer displacement in both the x and y directions for the specific RC frame structure. Additionally, there is a reduction in structural layer radians in both directions. These results collectively lead to the conclusion that the external elevator structure serves as a reinforcing element for the specific RC frame structure. By effectively curbing both translational and rotational movements, the external elevator structure contributes to an overall improvement in the structural performance of the RC frame.

The layer displacement angle, considered pivotal in structural performance analysis during seismic events, is a focal point in numerous prior studies. This research gathers data from 66 monitored points per story in the specific RC frame without the external elevator structure and 72 monitored points per story in the specific RC frame with the external elevator structure. Graph (c) in Figure 10 is employed to visually depict the average layer displacement angle, offering insights into the structural response in both the x and y directions.

The analysis of the average layer displacement angle explores variations in different situations, comparing the specific RC frame structure with and without the external elevator structure. In the x direction, the RC frame without the external elevator exhibits a larger layer displacement angle, and a similar trend is observed in the y direction. Graph (c) in Figure 10 visually depicts these findings, emphasizing the significant influence of the external elevator structure. This influence manifests as a reduction in the layer displacement angle for the specific RC frame structure in both the x and y directions. The external elevator structure emerges as a mitigating factor, contributing to a reduction in the layer displacement angle for the specific RC frame structure. This reduction implies enhanced stability and minimized rotational movement, particularly under seismic loads.

Table 6. Result of Layer displacement angle

Stories	RC		RCE	
	Direction-x rad	Direction-y rad	Direction-x rad	Direction-y rad
BASE	0.00000	0.00000	0.00000	0.00000
1F	0.00172	0.00225	0.00172	0.00215
2F	0.00241	0.00482	0.00234	0.00442
3F	0.00331	0.00555	0.00324	0.00514
4F	0.00347	0.00511	0.00342	0.00478

Table 6 reveals numerical results indicating that the external elevator structure effectively diminishes the structural layer displacement angle in both the x and y directions for the specific RC frame structure. This observation aligns with the earlier discussions on layer displacement and layer radians. Considering these findings collectively, it can be deduced that the external elevator structure reinforces the specific RC frame structure by minimizing layer displacement, reducing radians, and mitigating layer displacement angles.

4. Conclusion

In our contemporary society, elevators have evolved into indispensable components, particularly facilitating the convenience of users in towering structures. Their significance extends further for individuals with disabilities, providing them with essential means of transportation and access to modern life. However, a noteworthy challenge arises from the fact that many buildings constructed in the 1970s or 1980s were not originally designed to accommodate elevators. This absence of elevator infrastructure poses substantial issues for building users, especially residents, impeding their ability to fully utilize these structures. Given that numerous buildings from the 1970s and 1980s have not reached the end of their service life, the incorporation of external elevator structures has emerged as a meaningful and pertinent research area. This endeavor seeks to address the pressing need for retrofitting existing buildings with elevator systems, ensuring they remain accessible and functional for all users. Moreover, based on the devastating impact of earthquakes on both human lives and structural integrity. This research underscores the critical imperative for seismic design measures to mitigate potential human and economic losses. In this context, this research under consideration delves into the seismic analysis of a typical educational RC frame structure located at Kyungpook National University. The chosen method for this analysis is the RSA (Response Spectrum Analysis), a widely employed approach in earthquake engineering. Notably, the study aims to assess the seismic effects and implications of integrating an external elevator structure with the existing RC frame structure, providing valuable insights into the structural dynamics and seismic resilience of such retrofitting endeavors.

The analysis of modal characteristics reveals meaningful insights into the positive impact of integrating an external elevator structure with the existing RC frame. Notably, the outcomes highlight a series of advantages that collectively contribute to the enhancement of structural seismic performance. The effects of the external elevator structure result in a shorter period, higher acceleration, and increased frequency of the specific existing RC frame structure, collectively contributing to an overall improvement in the seismic performance of the specific RC frame structure.

Upon delving into the analysis of base shear and base moment, the findings from this research offer conclusions regarding the seismic performance improvement of the specific RC frame structure with an external elevator. Primarily, the external elevator structure demonstrates its effects by significantly reducing structural displacement along both the x and y directions. This reduction in displacement is a crucial indicator of improved seismic performance, suggesting that the external elevator contributes to minimizing the structure's response to ground motion in various orientations. Moreover, the examination of shear forces and moments on the foundation provides insights that the external elevator structure leads to comparatively smaller shear forces and moments on the foundation of the specific RC frame structure. This outcome is noteworthy as it implies a more favorable distribution of forces, potentially reducing the load and stress on the foundation elements. Through the application of RSA (Response Spectrum Analysis), the collective effects of the external elevator structure are interpreted as reinforcing the specific RC frame structure, thereby enhancing its seismic performance.

An in-depth examination of layer displacement, layer radians, and layer displacement angle yields crucial insights into the influence of the external elevator structure on the seismic performance of the existing building. The results, as derived from the meticulous analysis using RSA (Response Spectrum Analysis), underscore the significant role played by the external elevator structure in mitigating potential damage. In essence, the external elevator structure emerges as a pivotal factor in reducing layer displacement. The findings indicate a tangible decrease in the extent of layer movement, particularly noteworthy in both the x and y directions. This reduction in layer displacement is of paramount importance, as excessive movement can contribute to a higher percentage of structural damage during seismic events. Similarly, the external elevator structure is shown to have a positive impact on layer radians. By diminishing the angular deflection of layers within the structure, the external elevator contributes to the overall stability of the building under seismic forces. This reduction in layer radians signifies an enhanced ability of the structure to withstand and adapt to ground motion. Moreover, the findings reveal a notable reduction in layer displacement angle facilitated by the external elevator structure. A smaller layer displacement angle is indicative of a more controlled and less disruptive response to seismic forces. Given that larger displacement angles are often associated with increased structural vulnerability, the mitigating effect of the external elevator structure is instrumental in bolstering the seismic safety of the existing building.

Although this research underscores the positive impact of the external elevator structure, it is crucial to acknowledge a reality that does not perfectly align with the outcomes of the simulation. The complexities inherent in the structural performance of buildings dating back to the 1970s or 1980s, coupled with the situations of external elevator construction, notably the vibrations associated with the elevator, were not comprehensively accounted for in the simulation conducted in this research. As a consequence, the identified benefits of the external elevator structure, while significant within the confines of the study, should be viewed with a degree of caution in their direct application to real-world situations. The simulation, by nature, simplifies certain aspects and may not capture the full spectrum of influences that occur in practical, on-the-ground scenarios. The positive effects of the external elevator structure elucidated in this research serve as a valuable reference for subsequent studies. These findings provide a foundation for further exploration and research into the practical implications and performance of external elevator structures, especially when integrated into existing buildings. The research, therefore, is expected to be a valuable reference for the research to add the external elevator to the existing buildings.

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