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Influences of the Different Analytical Modes in the Nonlinear Pushover Analysis based on the External Elevator Well

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Abstract: Elevators are essential vertical transportation tools in contemporary society, providing convenience and crucial utilities, especially for the disabled. However, many existing RC (Reinforced Concrete) buildings were not designed with elevators. Demolishing these existing RC buildings for new construction could cause significant environmental issues, as rebuilding increases carbon dioxide emissions and conflicts with sustainable development goals. Consequently, adding external elevators to existing RC buildings is a practical solution to satisfy modern requirements. Despite their benefits, external elevators may cause structural issues during seismic events, while this is a topic that has received limited research attention. Addressing this gap, this research evaluates the structural performance of an external elevator well in an actual project on Jinzhong Rd, Shanghai City, using nonlinear pushover analysis. The study employs five different analytical modes (Point, Multipoint Uniform, Multipoint Triangle, Line Uniform, and Line Triangle) to analyze the specific external elevator well. By examining these analytical modes, this research aims to provide valuable insights and serve as a significant reference for future engineering projects involving nonlinear pushover analysis of external elevators in existing RC buildings. The findings are expected to enrich the analytical approach to nonlinear pushover analysis, contributing to a beneficial understanding and improved seismic performance of external elevator structures.

Keywords: Nonlinear Pushover Analysis; External Elevator; Existing RC Buildings; Analytical Modes; Seismic Analysis.

1. Introduction

Elevator systems are indispensable tools for vertical transportation in contemporary society, providing crucial convenience for building accessibility. This is especially significant for disabled individuals, as elevators are often the primary means for them to navigate multi-story buildings. However, many buildings constructed in the 1970s and 1980s were designed without elevator designs and did not satisfy modern accessibility requirements, particularly for the disabled. As a result, numerous reconstruction projects are necessary to upgrade these existing buildings to comply with current elevator design requirements. On the other hand, this widespread need for rebuilding poses significant environmental challenges, including increased greenhouse gas emissions and resource wastage. Consequently, finding sustainable solutions for retrofitting existing structures with modern elevator systems is imperative to balance accessibility improvements with environmental conservation.

Referring to the research of *Ben Chak Man Leung* [1], global warming has become a major concern due to its significant impact on climate change. One of the effective measures to address global warming is to limit and conserve energy usage worldwide. It is widely acknowledged within the scientific community that approximately 30% of the total energy consumption in modern countries is attributed to the energy used by existing buildings. In his research, *Ben Chak Man Leung* [1] introduces the concept of GEB (Greening the Existing Buildings) as a strategic approach to mitigate the global warming issue.

To satisfy modern requirements, incorporating external elevators is a crucial method for remodeling existing buildings to ensure they meet contemporary standards. Moreover, this approach is particularly important for providing vertical transportation for disabled individuals within these buildings. The research of *Yongtao Tan et al.* [2] and *Jun Li et al.* [3] underscores the significance of elevator design in existing buildings as part of green retrofit projects in Hong Kong. They highlight that adding external elevators is a vital aspect of updating buildings to modern standards while also addressing environmental concerns. Similarly, *Sui Pheng Low et al.* [4] emphasizes the importance of the LUP (Lift Upgrading Programme) in Singapore, which integrates external elevators into existing buildings to achieve green retrofit objectives. This program demonstrates that upgrading existing buildings with elevators not only improves accessibility but also contributes to sustainability efforts. Furthermore, the research of *Sergi Rotger Girgul et al.* [5] on the demand response potential of elevators in Danish buildings showcases the role of elevators in reducing greenhouse gas emissions and conserving resources. By enhancing the energy efficiency of elevators, these projects illustrate how green retrofitting existing buildings can lead to significant environmental benefits, making the addition of external elevators a meaningful and impactful strategy.

Although adding external elevators to existing buildings provides numerous advantages, there are still many technical restrictive conditions on site that can make implementation costly or impractical [6]. *Jiaqi Liu et al.* [6] points out that these technical constraints can significantly impact the feasibility of elevator installations in real projects. Furthermore, the research conducted by *Hongxia Luo et al.* [7] delves into the factors contributing to the success or failure of adding external elevators to existing buildings in China.

Hongxia Luo et al. [7] emphasizes that the process involves multiple coordination efforts, highlighting the complex challenges faced in China.

In the structural field, the influence of external elevator wells on existing buildings is a significant topic explored in many previous studies. The research of *Xin Zou* [8] delves into the design and application of prefabricated basic components for external elevators in existing buildings, leveraging BIM (Building Information Modeling). *Xin Zou* [8] indicates that improving the design and construction technology of these prefabricated components can reduce the impact of the additional elevator structure on the mechanical properties of the original building. The research emphasizes that such improvements not only shorten the production cycle and reduce manufacturing costs but also meet safety requirements without affecting the lives of the original residents during construction due to the flexibility of installation.

Moreover, referring to the research of *Haowen You et al.* [9], the overall and local wind loads on the external elevator well of existing buildings are analyzed, highlighting a significant aspect of evaluating the structural performance of these additions. The research of *Haowen You et al.* [9] underscores the importance of considering wind loads in the design and assessment of external elevator wells.

On the other hand, despite the critical nature of seismic damage, there is a notable gap in research addressing the structural performance of external elevator wells under seismic events. Drawing from extensive previous research on seismic evaluation, the nonlinear pushover analysis emerges as an indispensable approach for assessing structures during seismic events [10-24]. This method allows for a detailed examination of dynamic behavior under seismic loads and illustrates the damage process using specific structural performance metrics under plastic hinges [13-17]. By capturing this dynamic process of structural damage, nonlinear pushover analysis provides essential insights into the seismic resilience of structures.

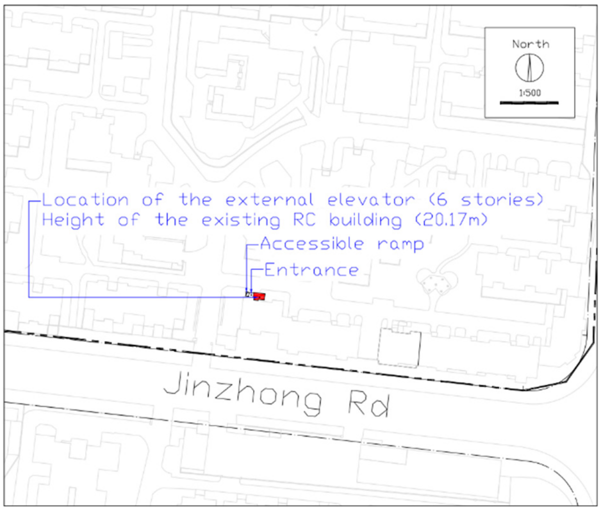


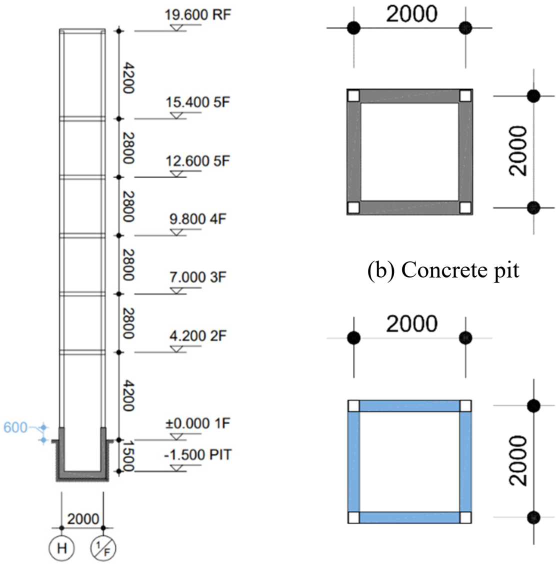
Figure 1. Location of the external elevator project

In this research, an external elevator project for an existing RC (Reinforced Concrete) building in Jinzhong Rd, Shanghai City (121°36'69"E, 31°21'99"N) serves as the focal point, as illustrated in Figure 1. This research involves simulating the specific external elevator well and conducting structural analysis using the nonlinear pushover analysis approach. To thoroughly examine the structural integrity of the external elevator well, five different analytical modes (Point, Multipoint Uniform, Multipoint Triangle, Line Uniform, and Line Triangle) of the pushover analysis are designed and applied. This research aims to investigate how these various analytical modes influence the structural behavior and performance of the external elevator well under nonlinear pushover analysis. The findings from this research are expected to offer valuable insights and serve as a significant reference for future engineering projects involving nonlinear pushover analysis of external elevators in existing RC buildings, thereby enriching the analytical approach to nonlinear pushover analysis.

2. Description of the Research

2.1. Description of the Structure

Regarding the specific external elevator project being analyzed in an existing RC building in Shanghai City, the design of the external elevator well is a central focus of this research. The elevator well is designed to be 19.6m in height and 2m in width, as illustrated in Figure 2 (a). As depicted in Figures 2 (b) and (c), the cross-section of the elevator well is square, with dimensions of 2m × 2m. Both the RC pit and footing are designed with a substantial thickness of 250mm to provide the necessary support and stability. Additionally, the steel structure of the external elevator well is designed with a thickness of 200mm, adding to the overall structural integrity and ensuring durability and safety for the elevator system.



(b) Concrete pit

(a) External elevator well

(c) Steel structure

Figure 2. Description of the structure

As illustrated in Figure 2 (a), the external elevator pit is designed to have a depth of 1.5m, and this design is consistent across all analyses conducted in this research. To thoroughly evaluate the structural performance of the external elevator, five different analytical modes of nonlinear pushover analysis are employed. Especially, these modes are Point, Multipoint Uniform, Multipoint Triangle, Line Uniform, and Line Triangle. Each mode represents a unique approach to the nonlinear pushover analysis, providing a comprehensive understanding of how the external elevator structure responds under various analytical modes. By applying these different analytical modes, the research aims to gain insights into the structural behavior and resilience of the external elevator, ensuring that the structure can withstand seismic and other dynamic forces effectively.

For the external elevator project in an existing RC building in Shanghai City, the design specifies that the concrete pit and RC footing are to be 250mm thick. This thickness is slightly larger than the 200mm thick of the square steel sections that form the main structural framework of the external elevator well, as illustrated in Figure 2 (b) and (c). The increased thickness of the concrete components ensures the structure can adequately accommodate and support the square steel installations. This design enhances the overall stability and structural integrity of the external elevator well, providing a robust foundation that can effectively support the elevator structure and ensure its reliability.

2.2. Description of Section and Material

In this research, C30 concrete is selected following the Chinese standards GB 50010-2010 (Code for Design of Concrete Structures) and GB 50011-2010 (Code for Seismic Design of Buildings), as detailed in Table 1. These standards specify the concrete compressive strength, with the expected value being 20.1 MPa. In this research, the C30 concrete is specifically utilized for constructing the external elevator pit and the RC footing components of the project.

Table 1. Concrete property

Weight per unit volume	25000 N/m^3
Mass per unit volume	2550 kg/m^3
Modulus of Elasticity (E)	30000 MPa
Poisson (U)	0.2
Coefficient of Thermal Expansion (A)	1.000E-05
Shear Modulus (G)	12500 MPa
Specified Compressive Strength (Fck)	20.1 MPa
Expected Compressive Strength (Fek)	20.1 MPa

According to the Chinese standards GB 50010-2010 (Code for Design of Concrete Structures) and GB 50011-2010 (Code for Seismic Design of Buildings), the rebar selected for this research is HRB400, as illustrated in Table 2. These standards specify that HRB400 rebar must have a minimum yield stress of 400 MPa and a minimum tensile stress of 540 MPa. This high-strength rebar is chosen to be used in conjunction with C30 concrete for the construction of the external elevator pit and RC footing parts of the project in this research.

Table 2. Rebar property

Weight per unit volume	77000 N/m^3
Mass per unit volume	7850 kg/m^3
Modulus of Elasticity (E)	200000 MPa
Poisson (U)	0.3
Coefficient of Thermal Expansion (A)	1.170E-05
Minimum Yield Stress (Fy)	400 MPa
Minimum Tensile Stress (Fu)	540 MPa
Expected Yield Stress (Fye)	440 MPa
Expected Tensile Stress (Fue)	590 MPa

The design for the external elevator pit and RC footing specifies a total section thickness of 250mm. Within this thickness, the design incorporates a concrete cover of 36.35mm to protect the rebar from environmental exposure and potential corrosion. The rebar within this section is arranged in a grid pattern, with two layers of rebar positioned at 0° and 90° angles on both the top and bottom of the section.

As illustrated in Figure 3, the primary structural framework of the external elevator well is constructed using square steel sections. These sections measure 200mm × 200mm, with a wall thickness of 8mm, providing a sturdy and reliable framework. This design is tailored to satisfy the specific requirements of the external elevator project, ensuring that the primary structure is sufficiently robust to handle the operational loads and stresses associated with the external elevator system.

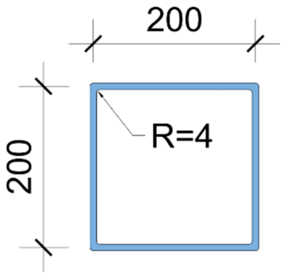


Figure 3. Section of the square steel

The square steel members used in the construction of the external elevator well are fabricated from Q235 steel, which adheres to the standards set by GB/T 700-2006 (Carbon Structural Steels) and GB 50011-2010 (Code for Seismic Design of Buildings). According to Table 3, the Q235 steel specification requires a minimum yield strength of 235 MPa and a minimum tensile strength of 370 MPa. This selection of Q235 steel ensures that the square steel members possess adequate strength and durability to withstand the structural demands and operational stresses encountered by the external elevator system.

Table 3. Square steel property

Weight per unit volume	77000 N/m^3
Mass per unit volume	7850 kg/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 MPa
Minimum Yield Stress (Fy)	235 MPa
Minimum Tensile Stress (Fu)	370 MPa
Expected Yield Stress (Fye)	260 MPa
Expected Tensile Stress (Fue)	410 MPa

In this research, the construction of the external elevator well relies on three primary materials (Q235 square steel, HRB400 rebar, and C30 concrete), which collectively form the structural framework of the external elevator system. These materials have been selected based on their respective properties outlined in Chinese standards, ensuring they satisfy the necessary strength and durability requirements for the structural components. The research methodology includes the application of five different modes of nonlinear pushover analysis, and the primary objective is to evaluate how these analytical modes influence the overall structural integrity and performance of the external elevator well under seismic and operational stresses.

By systematically examining these different analytical modes, the research aims to provide comprehensive insights into the nonlinear behavior of the external elevator system. This investigation is crucial for understanding how variations in analytical approach can influence the predictive accuracy of structural response, aiding in the refinement and optimization of design strategies for external elevator installations in existing RC buildings. Ultimately, the findings are expected to contribute to advancements in structural engineering practices, particularly in the realm of nonlinear pushover analysis applied to retrofit projects involving external elevator systems.

2.3. Description of Load Design

For the specific design of the external elevator well in this project, the passenger load capacity is set at 630kg, in accordance with the GB/T 7588-2020 (Safety Rules for the Construction and Installation of Lifts). Additionally, the self-weight of the elevator cabin is calculated using a scale coefficient, resulting in a weight of 787.5kg. This detailed information is provided in Table 4, ensuring that both the load capacity and the self-weight are accurately accounted for in the design.

Table 4. Load Design

Passenger Load	Cabin Load	Live Load	Dead Load
kg	kg	kN/m	kN/m
630	787.5	1.54	1.93

Furthermore, referring to the Chinese standard GB 50011-2010 (Code for Seismic Design of Buildings), the Dead Load and Live Load for the structure of the external elevator well can be calculated using specific equations as below:

$$\omega_D = \frac{P_D}{L} \tag{1}$$

$$\omega_L = \frac{P_L}{L} \tag{2}$$

where P_D is the force from the Dead Load and ω_D is the uniform load from the Dead Load. On the other hand, P_L is the force from the Live Load and ω_L is the uniform load from the Live Load. Through the calculation above, the value of Dead Load is given in 1.93kN/m, and the value of Live Load is given in 1.54kN/m as Table 4 illustrates.

Accurate load calculations are essential for assessing the loads the external elevator well must support in this research. This accuracy ensures that the design adheres to the required seismic performance criteria, which is vital for the safety and stability of the structure. These calculations play a key role in the structural analysis conducted in this research, particularly using the nonlinear pushover analysis method. The nonlinear pushover analysis evaluates the response of the structure to seismic forces. By thoroughly understanding how the structure behaves under five different analytical modes of nonlinear pushover analysis, this research is expected to enrich the analytical approach to nonlinear pushover analysis.

2.4. Description of Nonlinear Pushover Analysis

To satisfy the requirements for nonlinear pushover analysis, assigning plastic hinge properties to each structural component is crucial. This process involves defining specific characteristics for these plastic hinges, allowing for an accurate simulation of how the components will behave under the five different analytical modes of nonlinear pushover analysis. The code for determining these properties is outlined in ASCE 41-13 which is endorsed and supported by SAP 2000. The definition of the plastic hinges is vital for conducting a thorough and reliable structural analysis, as the characteristics of the plastic hinges enable a detailed understanding of the performance of the structural components under seismic forces.

The plastic hinges for the column section are established according to ASCE 41-13 standards, and this modeling process adheres specifically to the parameters outlined in Table 9-6, which focuses on steel columns in nonlinear procedures. The degree of freedom for the column is set as P-M2-M3, representing the axial force and moments in two directions. This definition of the plastic hinges ensures that the modeling accurately reflects the behavior of the column under various loads and stresses, providing a reliable basis for the nonlinear pushover analysis. On the other hand, the beam section of the external elevator structure utilizes the same square steel as the column section and adheres to Table 9-6 in the ASCE 41-13 guidelines for plastic hinge design. Based on the characteristics of the beam section, the degree of freedom for the beam section is established as M3. By defining the degree of freedom for beams as M3, the modeling process ensures that the plastic hinge accurately represents the behaviors and responses of the beam section under various loads and stresses.

For the nonlinear pushover analysis in this research, considering load combinations is a critical aspect that significantly influences the structural assessment. Referring to Chinese standard GB 50011-2010 (Code for Seismic Design of Buildings) that indicates the pivotal role of load combinations in structural analyses and offers a calculated method to determine the appropriate combinations of loads as below:

$$LC = 1.0 \cdot DL + 0.5 \cdot LL \tag{3}$$

where LC is load combinations, DL and LL are Dead Load and Live Load separately.

Referring to Figure 4, the five different analytical modes for nonlinear pushover analysis are designed to investigate the mechanical behavior of the external elevator well structure. The first mode (Point) applies a mechanical action point with a scale factor of 1.2 at the roof of the entire structure. The second mode (Multipoint Uniform) distributes mechanical action points uniformly across all joints on one side of the structure, each with the same scale factor of 1.2. The third mode (Multipoint Triangle) applies mechanical action points with a decrementing scale factor from 1.2 at the roof to 0 at the ground level. The fourth mode (Line Uniform) involves a mechanical line applied uniformly with a scale factor of 1.2 across all components on one side of the structure. Lastly, the fifth mode (Line Triangle) features a mechanical line with a decrementing scale factor from 1.2 at the roof to 0 at the ground level on one side of the structure. Each of these distinct modes is illustrated in detail on SAP 2000 in Figure 5, showcasing their application within the structural analysis.

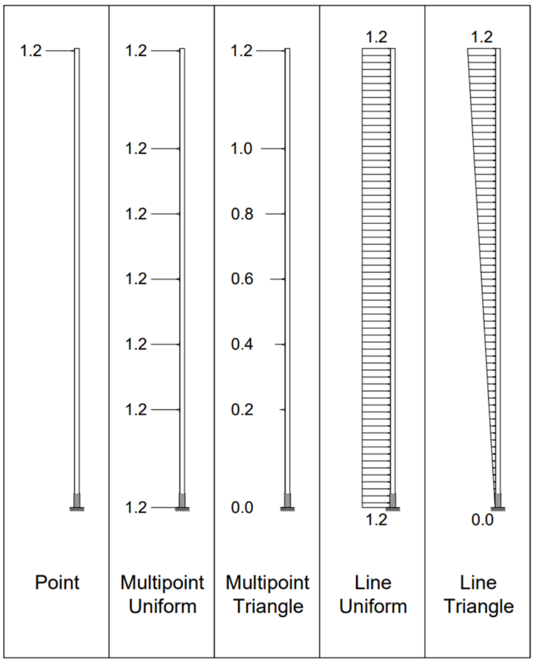
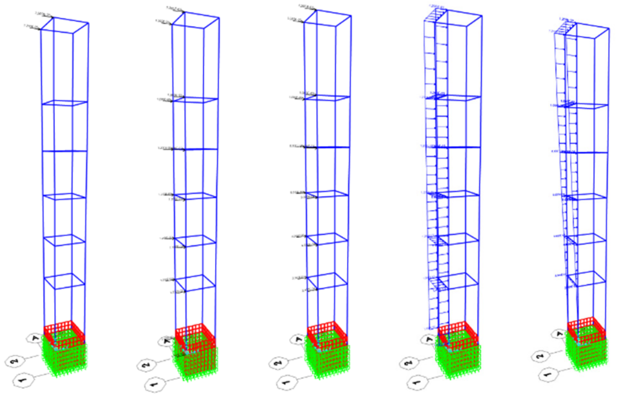


Figure 4. Analytical modes



(a) Point (b) Multipoint Uniform (c) Multipoint Triangle (d) Line Uniform (e) Line Triangle

Figure 5. Analytical modes (SAP 2000)

The nonlinear pushover analysis in this research is designed to employ a displacement control system with the reference point on the roof of the external elevator well structure, ensuring control through conjugate displacement. The analysis is meticulously structured to include 50 steps, each step systematically accounting for different displacement levels, and the comprehensive range of data points enables detailed exploration of the response of the structure to progressively increasing lateral loads. By varying the displacement levels, the analysis thoroughly examines the behavior of the structure, capturing the evolution of deformations and identifying critical points in the load-displacement relationship. This 50-step design is expected to provide a meticulous and thorough assessment of the structural performance under seismic conditions, ensuring that all potential deformation behaviors are examined and critical structural responses are accurately identified.

3. Discussion of Nonlinear Pushover Analysis

3.1. Performance Point

Performance points derived from nonlinear pushover analysis are crucial for assessing structural performance. These points rely on S_a (Spectral Acceleration) and S_d (Spectral Displacement). The methods for calculating S_a and S_d are outlined in *Riza Ainul Hakim et al.* [25], and the relationship between S_a and S_d is detailed in the following equation below:

$$S_d = \frac{T^2 S_a}{4\pi^2} \tag{4}$$

where S_a indicates spectral acceleration, S_d indicates spectral displacement, and T means period.

Moreover, performance points for the external elevator well in this research on Jinzhong Rd, Shanghai City, are determined using a specific spectrum curve. According to Tables 5.1.4-1 and 5.1.4-2 of the Chinese standard GB 50011-2010 (Code for Seismic Design of Buildings), the seismic intensity of this area is classified as 7, with a seismic acceleration of 0.1g. The maximum influence factor is set at 0.12, the characteristic ground period is 0.4, and the period time discount factor is 1. Due to the performance points are calculated using the results of S_a and S_d, Figure 6 displays the capacity spectrum results, and the performance points are extracted based on the intersection with GB 50011-2010 standards, following the guidelines of ACT-40 and FEMA 440, as illustrated in Tables 5 and 6. These performance points are essential for evaluating the seismic resilience of the structure.

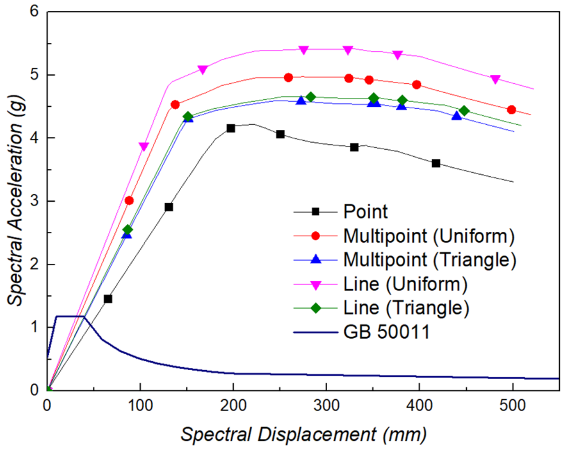


Figure 6. Capacity Spectrum

According to Figure 6, the point analytical mode exhibits the lowest value of S_a and the longest value of S_d. Comparing the multipoint analytical modes, the uniform mode shows a higher S_a and slightly shorter S_d than the triangle mode. This pattern is also observed in the line analytical modes, where the uniform mode again has a larger S_a and slightly shorter S_d than the triangle mode. The larger S_a and slightly shorter S_d values in the uniform modes suggest that the lower stories of the external elevator well structure are weaker. This comparison highlights the structural behavior under different analytical modes, indicating that the uniform modes reveal potential weaknesses in the lower stories of the structure.

Referring to the target response spectrum specified by the Chinese standard GB 50011-2010 (Code for Seismic Design of Buildings) for the external elevator project located on Jinzhong Rd, Shanghai City, Figure 6 illustrates the cross points of each capacity spectrum derived from the five different analytical modes of nonlinear pushover analysis.

The cross points define the performance points under the guidelines of ACT-40 and FEMA 440, as presented in Tables 5 and 6. The analytical results offer a comprehensive overview of the performance points for each of the five analytical modes. The performance points assessed under ACT-40 and FEMA 440 guidelines provide a fundamental framework for evaluating structural performance under seismic events and adhering to the guidelines ensures a detailed and accurate assessment of the structural response to seismic loads.

Table 5. Performance point under ACT-40

Types	BS	Disp.	Sa	Sd	Teff
	kN	mm	g	mm	sec
1	48.731	79.105	1.156	51.475	0.423
2	57.621	47.559	1.199	34.918	0.342
3	55.505	58.147	1.199	41.358	0.373
4	57.887	42.905	1.199	31.819	0.327
5	55.839	56.205	1.199	40.489	0.369

Type 1: Point
Type 2: Multipoint (Uniform) / Type 3: Multipoint (Triangle)
Type 4: Line (Uniform) / Type 5: Line (Triangle)
BS: Base Shear / Disp.: Displacement

The performance points under ACT-40, detailed in Table 5, reveal that the point analytical mode exhibits the lowest base shear and the longest displacement, consistent with the values of S_a and S_d. When comparing the multipoint analytical modes, the uniform mode shows a larger base shear and slightly shorter displacement, which also aligns with the S_a and S_d values. Similarly, the line analytical modes exhibit the same trend as the multipoint modes. These findings suggest that the uniform modes highlight potential weaknesses in the lower stories of the external elevator well structure, which is also evident in the structural period results presented in Table 5.

Table 6. Performance point under FEMA 440

Types	BS	Disp.	Sa	Sd	Teff
	kN	mm	g	mm	sec
1	48.733	79.108	1.157	51.477	0.423
2	57.623	47.561	1.199	34.92	0.342
3	55.507	58.149	1.199	41.36	0.373
4	57.889	42.906	1.199	31.82	0.327
5	55.841	56.207	1.199	40.49	0.369

Type 1: Point
Type 2: Multipoint (Uniform) / Type 3: Multipoint (Triangle)
Type 4: Line (Uniform) / Type 5: Line (Triangle)
BS: Base Shear / Disp.: Displacement

In line with the findings presented in Table 5, the performance points under FEMA 440 as detailed in Table 6 confirm that the point analytical mode demonstrates the lowest base shear and the longest displacement, which are consistent with the results of S_a and S_d values. Additionally, the uniform modes exhibit larger base shear and slightly longer displacement whether in the multipoint or line analytical modes. This trend indicates that the uniform modes highlight potential weaknesses in the lower stories of the external elevator well structure. Furthermore, the comparison of structural periods between ACT-40 and FEMA 440 reinforces these observations. The longest structural period appears in the point analytical mode, while to compare with the analytical results by triangle modes, shorter structural periods are observed in the uniform modes of both multipoint and line analytical modes. This consistency in structural period results further emphasizes that the uniform modes reveal vulnerabilities in the lower stories of the external elevator well structure.

3.2. Capacity Curve

The capacity curve is an essential approach in nonlinear pushover analysis in structural engineering. It delineates the relationship between the base shear force and roof displacement of the structure as lateral loads increase, effectively simulating seismic impacts. This curve is instrumental in identifying key structural performance metrics such as the yield point, ultimate capacity, displacement ductility, and stiffness degradation. In this research, Figure 7 offers a visual representation of the capacity curves for each analytical mode of nonlinear pushover analysis applied to the specific external elevator well. The figure illustrates how the various analytical modes impact the structural response during seismic events. By comparing these capacity curves, it is possible to discern the different ways in which each mode influences the ability of the external elevator well to withstand and respond to seismic forces.

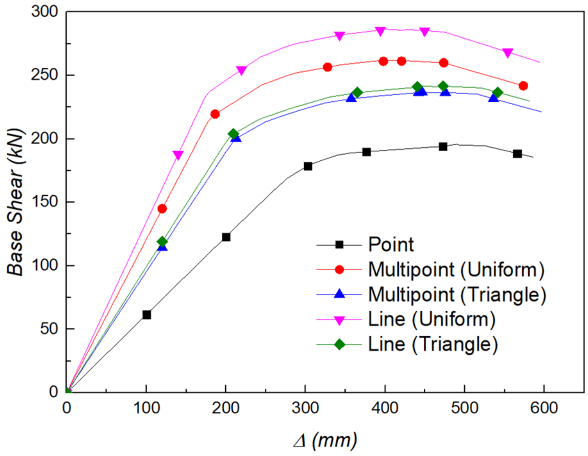


Figure 7. Capacity curves

The results of the capacity curves, as illustrated in Figure 7, demonstrate how the external elevator well structure behaves under five different analytical modes. These findings align with the earlier discussions on the capacity spectrum and performance points. Notably, the point analytical mode shows the smallest base shear forces and longest lateral displacements. In contrast, when comparing the multipoint and line modes, the uniform mode exhibits a larger base shear force and slightly shorter lateral displacement than the triangle mode. These capacity curve results further reinforce the earlier discussions on performance points, emphasizing that the uniform modes reveal potential vulnerabilities in the lower stories of the external elevator well structure.

The slope value of the elastic zone in nonlinear pushover analysis serves as a critical reference for assessing structural performance before any irreversible damage occurs. Table 7 presents the slope values for each different analytical mode. Compared to the point mode, the other four analytical modes exhibit larger slope values. Specifically, whether in the analytical modes of multipoint or line, the uniform mode shows significantly higher slope values with a 96.15% increase for Multipoint (Uniform) and a 117.92% increase for

Line (Uniform) relative to the analytical mode of point. When comparing the uniform and triangle modes, the uniform mode consistently has higher slope values with a 21.11% decrease for Multipoint (Triangle) and a 26.11% decrease for Line (Triangle). These results highlight that uniform modes reveal potential weaknesses in the lower stories of the external elevator well structure.

Table 7. Slope of the elastic zone

Types	Slope	Ratio A	Ratio B	Ratio C
1	0.616	-	-	-
2	1.2083	96.15%	-	-
3	0.9532	54.74%	-21.11%	-
4	1.3424	117.92%	-	11.10%
5	0.9919	61.02%	-26.11%	4.06%

Type 1: Point
Type 2: Multipoint (Uniform) / Type 3: Multipoint (Triangle)
Type 4: Line (Uniform) / Type 5: Line (Triangle)
Ratio A: Ratio to Point
Ratio B: Uniform & Triangle
Ratio C: Multipoint & Line

Moreover, Ratio C in Table 7 compares the slope values between the analytical modes of multipoint and line. The slope value increases by 11.1% in the uniform mode and 4.06% in the triangle mode under the line analysis. This suggests that the line analytical mode exhibits larger base shear and shorter lateral displacement than the analytical mode of multipoint. Consequently, the line mode also indicates potential vulnerabilities in the lower stories of the external elevator well structure.

3.3. Layer Behavior

Plastic hinge states are vital for evaluating structural performance in nonlinear pushover analysis as many previous research emphases. The research of *Vanlong Hoang et al.* [26] highlights their influence on steel frames under static loads, while the research of *Yi Zhou et al.* [27] focuses on welded high-strength steel frames. Both types of research show that analyzing plastic hinges is essential for assessing steel frame resilience and integrity under various loads.

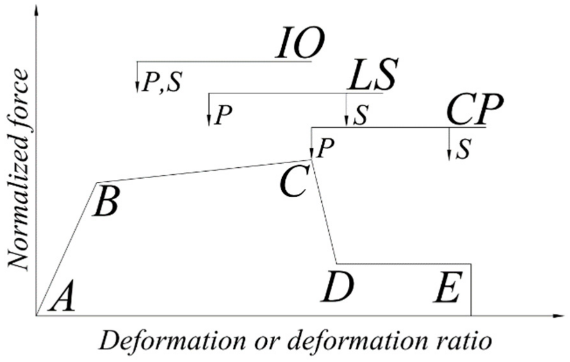
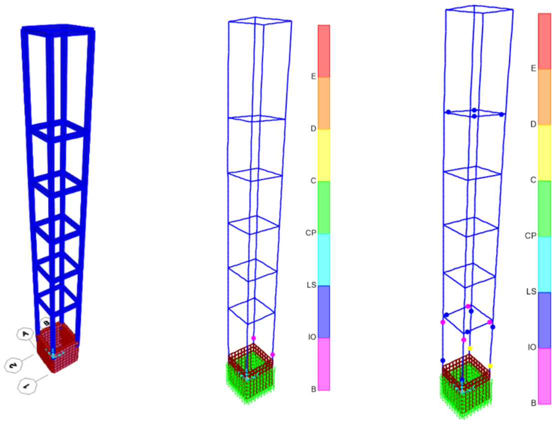


Figure 8. States of the plastic hinge (ASCE 41-13)

The code of ASCE 41-13 used for plastic hinge analysis in SAP 2000 outlines the stages of plastic hinge formation as Figure 8 illustrates. Initially, the element exhibits a linear response from point A (Unloaded Element) to point B (Effective Yield). Between points B and C, the slope is reduced to 0%-10% of the original elastic slope, reflecting strain-hardening effects. Point C marks the beginning of significant strength degradation, which continues until point D. Beyond point D, the strength of the element diminishes further until it reaches point E, where the seismic strength is effectively zero.

The ASCE 41-13 code specifies deformation or deformation ratio criteria for P (Primary components) and S (Secondary components) in the plastic range, linked to target structural performance levels: Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) as depicted in Figure 8. Moreover, according to Figure 8, *Mircea D. Botez et al.* [28] highlights that IO corresponds to a structural state with minimal damage, enabling continued use of the building post-earthquake. LS indicates significant damage has occurred, but there is still a safety margin to prevent partial or total collapse, ensuring the occupants' safety. CP represents a state where the building is on the brink of partial or total collapse, indicating severe structural damage.

Due to layer displacement and layer drift ratio being pivotal analytical results in evaluating the seismic behavior of structures [13-17], this research focuses on these metrics for the external elevator structure in accordance with the principles of nonlinear pushover analysis. Detailed analysis, as illustrated in Figures 9-13, is conducted under the conditions of plastic hinge formation at both states of B (Effective Yield) and CP (Collapse Prevention). These evaluations help understand how the structure performs under seismic stress, highlighting critical points where deformation and potential failure may occur.

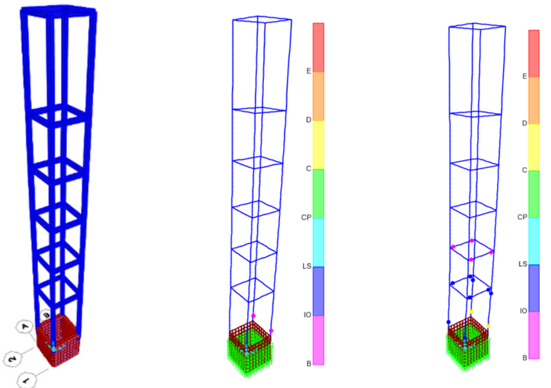


3D Model

B
STEP-13
257.33mm

CP
STEP-18
339.66mm

Figure 9. Plastic hinge states (Point)

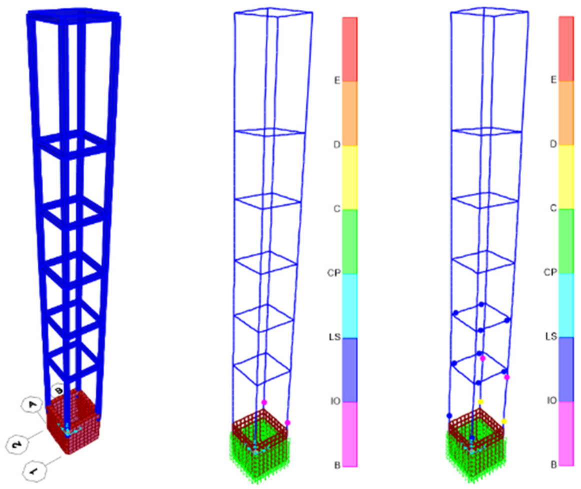


3D Model

B
STEP-8
175.41mm

CP
STEP-13
276.32mm

Figure 10. Plastic hinge states (Multipoint-Uniform)

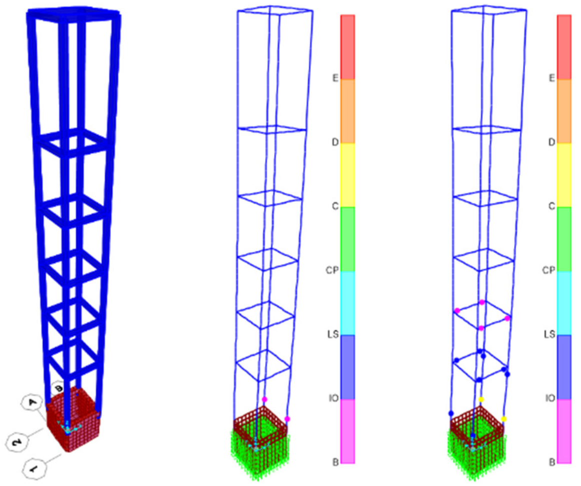


3D Model

B
STEP-8
199.96mm

CP
STEP-13
299.15mm

Figure 11. Plastic hinge states (Multipoint-Triangle)

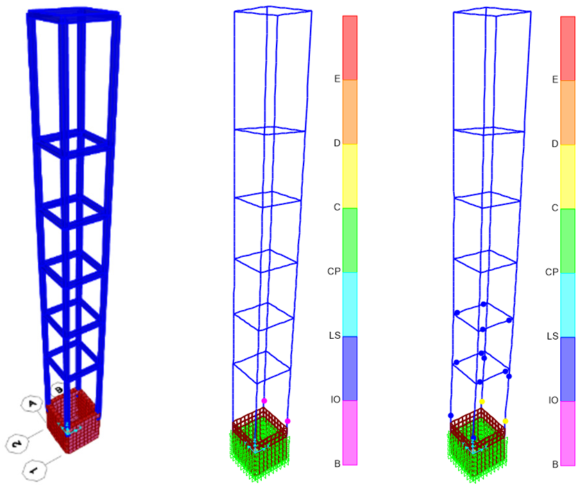


3D Model

B
STEP-7
171.92mm

CP
STEP-12
273.06mm

Figure 12. Plastic hinge states (Line-Uniform)



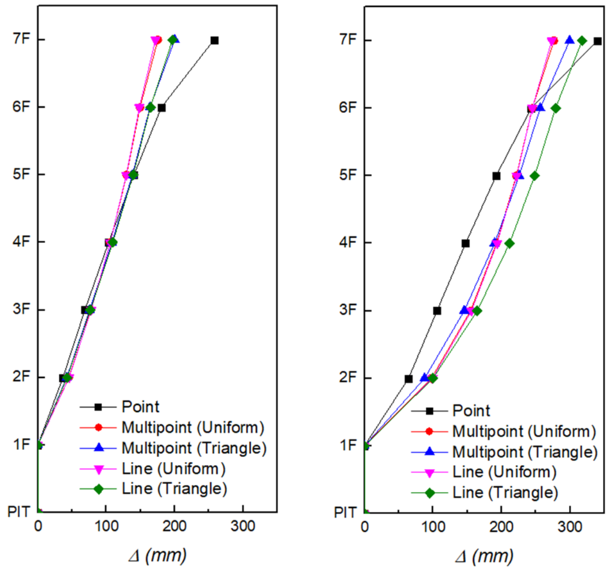
3D Model

B
STEP-8
196.72mm

CP
STEP-13
317.35mm

Figure 13. Plastic hinge states (Line-Triangle)

The analytical results for the external elevator well structure under plastic hinges at both B (Effective Yield) and CP (Collapse Prevention) are illustrated in Figures 9-13. These results align with the discussions of performance points and capacity curves, showing that the analytical mode of point results in the longest lateral displacement whether the plastic hinges reach B or CP. When examining the plastic hinge states at CP, the uniform mode of the nonlinear pushover analysis reveals greater structural damage compared to the triangle mode, regardless of whether the analysis is based on the multipoint or line mode. Specifically, the uniform mode demonstrates shorter lateral displacement but greater overall damage than the triangle mode, highlighting potential vulnerabilities in the lower stories of the structure. These phenomena are further examined through the layer displacement and layer drift ratio results, as detailed in Figures 14-16.



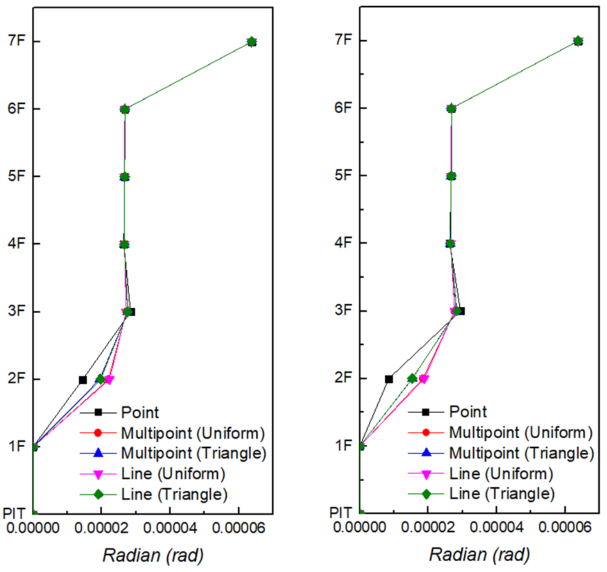
(a) Plastic hinge on B state

(b) Plastic hinge on CP state

Figure 14. Layer displacement

Referring to Figure 14(a), the analysis of layer displacement reveals that the longest structural lateral displacement occurs in the analytical mode of point when the plastic hinge state reaches B. Both analytical modes of multipoint and line display similar structural behavior in uniform mode and triangle mode under nonlinear pushover analysis. When comparing the analytical modes of multipoint and line, the results highlight that uniform mode appears shorter lateral structural displacements than triangle mode, pointing to potential weaknesses in the lower stories of the external elevator well structure. Nevertheless, despite the difference in analytical modes used in the nonlinear pushover analysis, the layer displacement results suggest that there are no substantial differences in the lateral displacement of the lower stories of the structure, and this indicates a consistent behavior in the lower stories regardless of the analytical approach taken before the hinges of the structure be into the plastic zone.

On the other hand, when the plastic hinges reach the state of CP, the impact on the lower stories of the external elevator structure varies depending on the analytical mode of the nonlinear pushover analysis, as shown in Figure 14(b). Similar to Figure 14(a), the analytical mode of point exhibits the longest lateral structural displacement on the roof of the external elevator structure. However, the analytical mode of point has the shortest lateral displacement in the lower stories, suggesting that it does not effectively reveal potential weaknesses in the lower stories of the external elevator well structure. This contrasts with the layer displacement analysis at the B state, where the longest displacement also appeared in the point mode. At the CP state, the triangle mode exhibits longer lateral displacements than the uniform mode in both analytical modes of multipoint and line. This indicates that the uniform mode under nonlinear pushover analysis highlights more potential weaknesses in the lower stories of the external elevator well structure compared to the triangle mode when considering the plastic hinges reaching the CP state.



(a) Plastic hinge on B state

(b) Plastic hinge on CP state

Figure 15. Layer radian

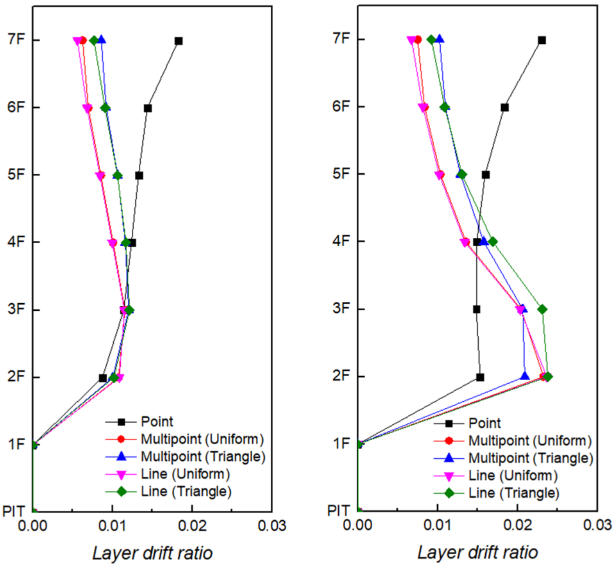
To discuss the influence of different analytical modes in the nonlinear pushover analysis, the findings on layer radian in the lower stories reinforce the discussion on layer displacement, as illustrated in Figure 15. Whether the plastic hinges reach the B state or the CP state, Figures 15(a) and 15(b) show that there are no significant differences in the higher stories of the entire structure of the external elevator well. However, the results of the layer radian indicate that smaller radians appear in the analytical mode of point, whether the plastic hinges reach the B state or the CP state. This emphasizes that the analytical mode of point does not effectively reveal potential weaknesses in the lower stories of the external elevator well structure. When comparing the uniform mode with the triangle mode, both graphs in Figure 15 indicate that the uniform mode exhibits larger layer radians than the triangle mode under nonlinear pushover analysis. This conclusion suggests that the uniform mode effectively highlights potential weaknesses in the lower stories of the external elevator well structure.

In order to reinforce the discussion in this research, the layer drift ratio under each different analytical mode of the nonlinear pushover analysis can be calculated. The layer drift ratio for each distinct story in the external elevator well is determined by calculating the ratio of the structural lateral displacement to the story height. This involves measuring how much each story of the structure displaces laterally compared to its height, providing a detailed understanding of the structural behavior under different seismic loads. In particular, the layer drift ratio involves using the equations below:

$$\Delta = \delta_x - \delta_{x-1} \tag{5}$$

$$\Delta_{ratio} = \frac{\Delta}{h} \tag{6}$$

where δ_x is the displacement at the x floor, δ_{x-1} is the displacement at the $x\text{-}1$ floor, Δ is the drift between the x floor and the $x\text{-}1$ floor, h is the height of the story, and Δ_{ratio} is the drift ratio.



(a) Plastic hinge on B state

(b) Plastic hinge on CP state

Figure 16. Layer drift ratio

Based on the results of layer displacement in Figure 14, the layer drift ratio is calculated using equations (5) and (6), with the results illustrated in Figure 16. Graphs (a) and (b) in Figure 16 show a distinct trend for the analytical mode of point compared to the other four modes. This difference arises because the single point on the roof affects the entire structure differently, resulting in the analytical mode of point displaying the largest layer drift ratio, regardless of whether the plastic hinges reach the B state or the CP state. Reflecting on the discussion of layer displacement, the layer drift ratio in Figure 16 also underscores that the triangle mode of nonlinear pushover analysis allows for a larger layer drift ratio. This indicates that under the triangle mode, larger layer drifts are permitted. This finding emphasizes that the uniform mode reveals more potential weaknesses in the higher stories of the external elevator well structure compared to the triangle mode, irrespective of the plastic hinges reaching the B state or CP state. However, the largest layer drift on the second and third floors shows no significant differences between the uniform and triangle modes under the nonlinear pushover analysis.

Except for the analytical mode of point, the comparison between the layer drift ratios at the B state and CP state as shown in Figure 16 reveals that the second and third floors exhibit a larger layer drift ratio when the plastic hinges reach the CP state, as illustrated in Figure 16(b). However, the analytical mode of point displays completely different structural behavior with the largest layer drift ratio occurring on the roof of the external elevator well structure. This finding underscores that the analytical mode of point fails to highlight potential weaknesses in the lower stories of the external elevator well structure, unlike the other four analytical modes. This is consistent regardless of whether the plastic hinges reach the B state or CP state. This behavior highlights the limitations of the analytical mode of point in accurately assessing structural vulnerabilities in the lower levels of the building.

4. Conclusion

With the rising number of external elevator installations in existing RC buildings, these projects are acknowledged for their role in promoting sustainable development through the reduction of carbon dioxide emissions. However, the seismic performance of external elevators remains underexplored. To fill this gap and provide valuable insights, this research delves into the impacts of five different analytical modes under nonlinear pushover analysis as the nonlinear pushover analysis is the primary method for evaluating structural performance during seismic events. Focusing on an actual external elevator project located on Jinzhong Rd in Shanghai City, this research examines how different analytical modes affect the structural capacity to withstand seismic forces under nonlinear pushover analysis. By doing so, this research aims to offer reference material for future external elevator projects and enhance the methodologies of nonlinear pushover analysis under seismic analysis.

The discussion on the performance point highlights its strong relationship with the capacity spectrum, showing varying structural behaviors under different analytical modes of nonlinear pushover analysis. Notably, the analytical mode of point exhibits the lowest Sa and the longest Sd. Except for the results by the analytical mode of point, the uniform mode uncovers more vulnerabilities in the lower stories of the external elevator well structure than the triangle mode. This conclusion is supported by the findings on base shear, lateral displacement, and structural period.

On the other hand, the discussions on the capacity curve and layer behavior corroborate the findings regarding the performance point. The analytical mode of point consistently exhibits the lowest base shear, the longest lateral displacement, and the largest layer drift ratio, and these observations reinforce the understanding of structural performance under the different analytical modes of the nonlinear pushover analysis. Moreover, the analysis reveals that the uniform mode exposes more vulnerabilities in the lower stories of the external elevator well structure compared to the triangle mode. This is evidenced by the shorter layer displacement and smaller layer drift ratio observed in the uniform mode, whether the plastic hinges are at the B state or CP state. This indicates that the structure under the uniform mode cannot tolerate longer layer displacements and larger layer drift ratios than in the triangle mode.

This research underscores the significant impact that different analytical modes have in nonlinear pushover analysis. It particularly highlights that the differences between the analytical modes of multipoint and line are less pronounced compared to the differences observed between the uniform and triangle modes. The findings in this research emphasize that choosing the appropriate analytical mode in the nonlinear pushover analysis is crucial for accurate structural seismic analysis. To satisfy specific seismic analysis requirements effectively, it is essential to select the analytical mode based on the unique demands of the project.

Referring to the findings in this research, it is anticipated that this research will serve as a valuable reference for future external elevator projects. By providing detailed insights into the impact of different analytical modes on nonlinear pushover analysis, this research contributes to the body of knowledge in structural engineering. The enhanced methodologies presented in this research are expected to enrich the analytical approach used in nonlinear pushover analysis. This will aid in making more informed decisions, ultimately improving the seismic performance and resilience of external elevator structures.

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