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Article

Nonlinear pushover analysis of the mechanical influences under the varied stories and column orientations in RC structures

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Abstract: The natural disaster of earthquakes continues to be a catastrophic issue for urban environments, especially considering the widespread existence of RC (reinforced concrete) buildings in cities around the world. The continuous demand for expanded living spaces has led to the construction of taller structures, which brings an increased vulnerability to seismic events. The dilemma lies in the profound challenges that earthquakes pose to the structural integrity of these tall RC buildings, causing significant human and economic losses. Over the past decades, numerous analytical methods have been developed to evaluate and improve structural performance under seismic conditions. Notably, nonlinear pushover analysis has become prominent for its practicality and efficient stress calculations. This research aims to disclose the complex dynamics of seismic performance in the context of RC structures. Specifically, 10 distinct RC frame structures have been classified into two groups based on different column orientations. The overall goal is to examine and understand the mechanical influences of different stories and column orientations on the seismic resistance of RC buildings. By applying nonlinear pushover analysis, this research intends to offer valuable insights into the structural behavior of these various RC frame structures, contributing to a deeper understanding of seismic vulnerabilities and effective mitigation strategies.

Keywords: seismic analysis; nonlinear pushover analysis; RC frame; column orientations

1. Introduction

The increasing frequency of earthquake events in recent decades has led to significant economic losses and human casualties. As a result, there has been a growing emphasis on ensuring the dwelling safety of buildings during seismic activities. To improve the performance of RC frame structures in earthquake-prone areas, numerous researchers have developed various analytical methods [1–4]. These include techniques such as column jacketing and the implementation of bracing systems, all aimed at enhancing the resilience of RC structures.

Over the past few decades, numerous dedicated researchers have enforced refining structural analytical methods, taking into account various structural considerations and seismic activities. To systematically assess and compare the effectiveness of each method of structural analysis in RC frame structures, simulation analysis has emerged as a pivotal tool. Simulation analysis allows researchers to replicate earthquake behaviors, providing a virtual environment to evaluate how different structural analytical methods perform under stress and identify the most effective strategies for enhancing structural resilience [2]. As a result, the approach of structural simulation plays a significant role in advancing the aspect of structural analysis and ensuring the development of robust and earthquake-resistant building practices.

The seismic assessment of a building involves analyzing the structural nonlinear force-displacement response, which is achieved through a meticulous process known as nonlinear pushover analysis, also recognized as nonlinear dynamic analysis. During this analytical procedure, the structure undergoes examination under gradually increasing lateral displacement based on the increasing structural velocity [3]. The distinctive feature of nonlinear pushover analysis lies in its ability to consider and incorporate nonlinear structural behavior throughout the analysis [5–7]. This is achieved by updating the stiffness matrix at each load increment, providing a comprehensive understanding of the structural response to seismic forces. The practical application of nonlinear pushover analysis has been significantly facilitated by the availability of numerous computer programs, allowing researchers to implement this methodology effectively in real-world seismic activities.

The primary objective is to develop and validate a simplified nonlinear pushover analysis procedure specifically tailored for moment-resisting frame structures as outlined by Sullivan et al. [1]. This methodology aims to function as a practical tool for confirming the results obtained from computer-based nonlinear pushover analysis. The significance of this approach to nonlinear pushover analysis lies in its capacity to independently verify outputs from structural analysis software, providing researchers with a valuable means of cross-checking and validating their findings. Furthermore, the simplified nonlinear pushover analysis procedure is not only designed to validate results but also to offer researchers a deeper understanding of the key characteristics of the structural system under assessment. By adopting this approach, researchers can gain insights into the behavior of moment-resisting frame structures, enabling the structural designer to make informed decisions about structural performance and safety under seismic events.

In addition to the validation and insight provided, the research of Sullivan et al. [1] involves a meticulous calculation of strain-energy proportions and values of story stiffness as below:

$$\theta_{y,sys,i} = \frac{\sum M_{j,i}\theta_{y,i} + \sum M_{j,i-1}\theta_{y,i-1}}{\sum M_{j,i} + \sum M_{j,i-1}} \tag{1}$$

where $\theta_{y,sys,i}$ is the story drift required to yield story i, $M_{j,i}$ and $M_{j,i-1}$ are the total flexural resistances (for the governing mechanism) provided at joint centers, and $\theta_{y,i}$ and $\theta_{y,i-1}$ are the drifts at yield at levels i and $i-1$ respectively.

$$k_{y,i} = \frac{V_{R,i}}{\theta_{y,i}h_{s,i}} \tag{2}$$

where $k_{y,i}$ is the story stiffness required to yield story i, $V_{R,i}$ is the story shear resistance associated with a column shear failure, $\theta_{y,i}$ is the drifts at yield at levels i, and $h_{s,i}$ is the story height (between floor centerlines). These parameters contribute to a comprehensive assessment of the structural system, offering information that goes beyond the traditional scope of analyses.

Employing an innovative approach to structural analysis, the simplified nonlinear pushover analysis method is utilized to examine the behavior of one of several RC frames in the Italian city of L’Aquila. These frames notably incorporate unreinforced masonry partitions and infill walls, making them a critical subject for seismic evaluation as emphasized by Sullivan et al. [1].

The research findings demonstrate a significant similarity between the displacement results obtained from the traditional nonlinear pushover analysis and the innovative simplified nonlinear pushover analysis method as illustrated in **Figure 1**. This notable congruence suggests that the simplified nonlinear pushover analysis developed in this research produces results that closely align with established traditional methods. The implications of this similarity are far-reaching, indicating that the simplified approach is a reliable and effective alternative for assessing the seismic performance of reinforced concrete frames with unreinforced masonry partitions and infill walls. This research not only contributes to the advancement of analytical methodologies but also to the practical application of simplified nonlinear pushover analysis in seismic engineering practices [1].

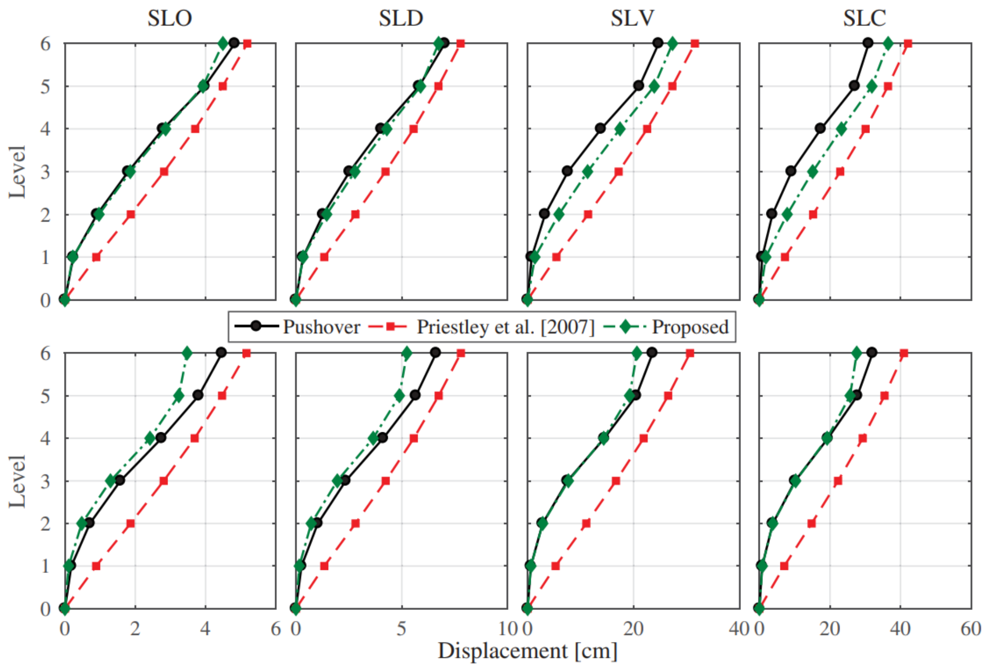


Figure 1. Normalized displacement profiles with different methodologies.

Note: SL (limit state) [SLO (operational), SLD (damage control), SLV (life safety), and SLC (collapse prevention)].

Furthermore, Chrysanidis et al. [8] conducted research in which they simulated a five-story RC building with a standard rectangular floor plan per story using SAP 2000. The purpose of the simulation was to determine whether the construction cost of the load-bearing body of an RC building is affected by the area of earthquake hazard. This was achieved through a comparative analytical estimation of construction costs based on the earthquake hazard zones of Greece. Following the discussions, the research of Chrysanidis et al. [8] also emphasizes the significance of earthquake damage to RC buildings.

In order to mitigate seismic damage in RC buildings, Chrysanidis and Tegos [9] discuss the axial and transverse strengthening of RC circular columns. The researchers identify conventional and new types of steel and hybrid jackets using high-strength mortar through analysis of nine test specimens. These specimens model reinforced concrete columns with a circular cross-section, which have been constructed and tested under either a transverse load or an axial load history.

In this research, a total of ten distinct RC frame structures have been categorized into two groups based on differing column orientations for structural analysis under nonlinear pushover analysis. The research aims to investigate and compare the analytical results obtained from the nonlinear pushover analyses, with a focus on understanding how different column orientations impact the response of various stories within the structure. By utilizing ETABS, a widely utilized structural analysis and design software, this research seeks to offer valuable insights into the behavior of columns with varying orientations.

The use of nonlinear pushover analysis allows for a detailed examination of the structural response to lateral forces, providing a more comprehensive understanding of how different column orientations affect the overall performance of RC frame structures. The primary objective is to examine and comprehend the influences of different stories and column orientations on the seismic resilience of RC buildings. In summary, this research aims to contribute to structural analysis by elucidating the influences of variations in column orientation on the seismic performance of RC buildings.

2. Structure description and analysis design

2.1. Structure description

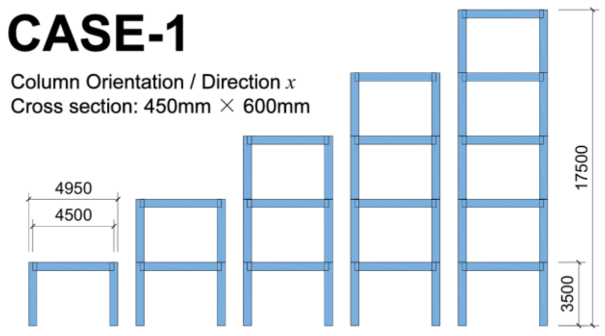
Choosing 2D frame structures for nonlinear pushover analysis instead of full 3D building models offers several benefits, particularly in terms of simplicity, computational efficiency, and clarity of results.

Analyzing a 2D frame structure is significantly simpler than a full 3D model, and this simplification helps in understanding the fundamental behavior of individual frames without the added complexity of three-dimensional interactions. Additionally, 2D models require fewer computational resources in terms of processing power and memory. This is particularly beneficial when performing multiple iterations or analyses, as it allows for faster computations and quicker results.

Moreover, using 2D frames enables researchers to focus on specific frames or parts of the structure. This targeted approach helps in identifying critical elements and understanding the detailed behavior of key structural components under lateral loads. Furthermore, results from 2D analyses are often easier to interpret, as they provide clear and direct insights into the performance of individual frames. This clarity helps in identifying failure mechanisms, understanding load paths, and making informed design decisions.

In conclusion, while 3D models provide a comprehensive understanding of structural behavior, 2D models serve as a practical and effective under the nonlinear pushover analysis.

In this research, the target structure of investigation is the RC frame structure of an educational building known as No. 401, which dates back to the 1970s. This building is located within the School of Architectural Engineering at Kyungpook National University in Daegu Metropolitan City, Republic of Korea, and this RC building serves as the specific RC frame structure for nonlinear pushover analysis. The analysis covers five distinct structures, each corresponding to a different story of the educational building, as visually depicted in **Figure 2**.



(a) **(b)**

Figure 2. Target RC frame structure specimens. **(a)** CASE-1 (Column: 450 mm × 600 mm); **(b)** CASE-2 (Column: 600 mm × 450 mm).

A significant aspect of this research involves the examination of two cases, each with distinct column orientations. This intentional variation in column orientation aims to investigate how different column orientations impact the structural response under the nonlinear pushover analysis. It is worth noting that the height of each RC frame structure remains consistent at 3500 mm per story, ensuring uniformity across the analyzed structural design. Additionally, all the RC frame structures also have an identical width of 4950 mm.

This research design enables a detailed exploration of how variations in column orientations impact the seismic performance of typical educational buildings in the Republic of Korea. By specifically selecting a structure from the 1970s, the research also considers the implications of the historical design of the RC buildings on the response to lateral loads.

The systematic analysis of various stories and diverse column orientations provides valuable insights into the understanding of structural behavior under the nonlinear pushover analysis. The results also inform potential retrofitting or design considerations for similar existing RC buildings.

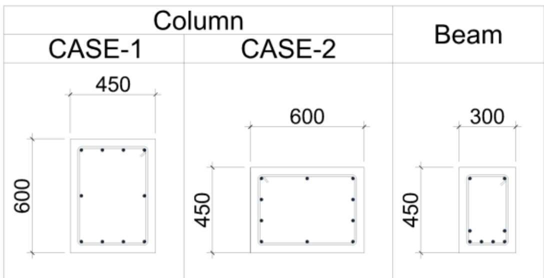


Figure 3. Sections of column and beam.

As illustrated in **Figure 3**, the columns with a typical cross-sectional area of 270,000 mm^2 play a crucial role in understanding the structural considerations in this research. The columns are systematically categorized into two cases: CASE-1 and CASE-2, each characterized by specific column orientations of direction *x* and direction *y*. In CASE-1, aligned with direction *x*, the columns measure 450 mm × 600 mm, while in CASE-2, aligned with direction *y*, the dimensions are reversed to 600 mm × 450 mm. Both CASE-1 and CASE-2 columns incorporate ten longitudinal rebars of D19 (Diameter: 19 mm). Additionally, hoop rebars of D10 (Diameter: 10 mm) are integrated into the design at regular intervals of 300 mm. This configuration of reinforcing elements is essential for enhancing the structural integrity and load-bearing capacity of the columns under consideration. Furthermore, the design adheres to concrete covering depth standards outlined in KDS 14 20 50: 2022. According to these standards, a concrete covering depth of 40 mm is maintained to ensure compliance with industry regulations and promote the durability and protective qualities of the structural elements.

The beam has a cross-sectional area of 135,000 mm^2, resulting from its dimensions of 300 mm in width and 450 mm in height. These dimensions are crucial in determining the beam's resistance to external forces and its overall structural performance. Additionally, the reinforcement strategy plays a vital role in enhancing the beam's ability to withstand loads. In this configuration, the beam is reinforced with a total of eight longitudinal rebars. Two D16 (Diameter: 16 mm) rebars are placed at the top to provide additional strength to the upper section, while six D16 (Diameter: 16 mm) rebars are positioned at the bottom as tensile utilization, reinforcing the lower portion and contributing to overall structural integrity. To further enhance the resilience of the beam, hoop rebars are incorporated at regular intervals. Specifically, D10 (Diameter: 10 mm) hoop rebars are placed at 300 mm intervals along the length of the beam. This arrangement serves to confine and strengthen concrete, improving its ability to withstand lateral forces and deformations.

Similar to the section designs of the column, the concrete cover depth of the beam complies with the guidelines outlined in KDS 14 20 50: 2022. The concrete cover depth is set at 40 mm, aligning with established standards and providing a protective layer for the reinforcement, and this contributes to the durability and long-term performance of the beam.

In summary, the detailed specifications of the column and beam, including dimensions, types of reinforcement, and adherence to standards, collectively contribute to the structural robustness. The designs of the column and beam are crucial for accurately simulating and analyzing structural behavior, particularly in the context of nonlinear pushover analysis. By carefully adjusting column dimensions and reinforcement configurations, researchers are enabled to investigate how the varies column orientations impact the seismic performance of the structure.

Ensuring the quality of the concrete is of utmost importance in the structural considerations of this research. The concrete utilized in this research conforms to the standards outlined in KS F 4009: 2021, which are specifically designed for ready-mixed concrete. Adhering to these standards is crucial to ensure that the concrete meets the necessary criteria for structural performance, durability, and safety.

The compressive strength of concrete is a critical parameter in determining its ability to withstand loads. Referring to **Table 1**, in accordance with design guidelines established for educational buildings in the 1980s by the Republic of Korea's Ministry of Education, the specified compressive strength is denoted as F_{ck} = 15.12 MPa, indicating the compressive strength at 28 days of the concrete. This value represents the characteristic compressive strength of the concrete and provides insight into its performance under standard conditions. In addition to the specified compressive strength, there is an anticipated compressive strength outlined as F_{ek} = 18.14 MPa as

Table 1 illustrates. The expected strength value represents the expected performance of the concrete under realistic conditions, accounting for variations in materials and construction processes after 28 days. Both the specified and expected compressive strength values are crucial for nonlinear pushover analysis, offering a comprehensive understanding of the concrete capacity to resist compressive forces.

Table 1. Material property.

Concrete	Weight per unit volume	23,540 N/m^3
	Mass per unit volume	2400 kg/m^3
	Modulus of elasticity (E)	22,334 MPa
	Poisson (U)	0.1667
	Coefficient of thermal expansion (A)	1.100×10^{-5}
	Specified compressive strength (F_{ck})	15.12 MPa
	Expected compressive strength (F_{ek})	18.14 MPa
Rebar	Weight per unit volume	77,000 N/m^3
	Mass per unit volume	7850 kg/m^3
	Modulus of elasticity (E)	200,000 MPa
	Poisson (U)	0.3
	Coefficient of thermal expansion (A)	1.170×10^{-5}
	Minimum yield stress (F_y)	240 MPa
	Expected yield stress (F_{ey})	300 MPa

Note: Specified compressive strength (F_{ck}) means specified compressive strength indicates the concrete compressive strength at 28 days.

In accordance with the guidelines outlined in KS D 3504: 2021, which regulate the utilization of rebars for RC structure, and in line with the design criteria established by the Ministry of Education of the Republic of Korea for educational buildings in the 1980s, the strength of the rebars in this research is specified. This is a critical step in ensuring the structural integrity and performance of the entire system.

As indicated in **Table 1**, the minimum yield stress of the rebar is established at F_y = 240 MPa. This value, representing the yield strength of the rebar, is a critical parameter for understanding its ability to withstand applied loads without undergoing permanent deformation. It is a fundamental characteristic that influences the overall behavior and capacity of RC structures. In addition to the specified yield strength, the expected yield stress is determined and identified as F_{ey} = 300 MPa. This expected stress also provides insights into the expected performance of the rebars under realistic conditions, considering factors such as variations in material properties and construction processes.

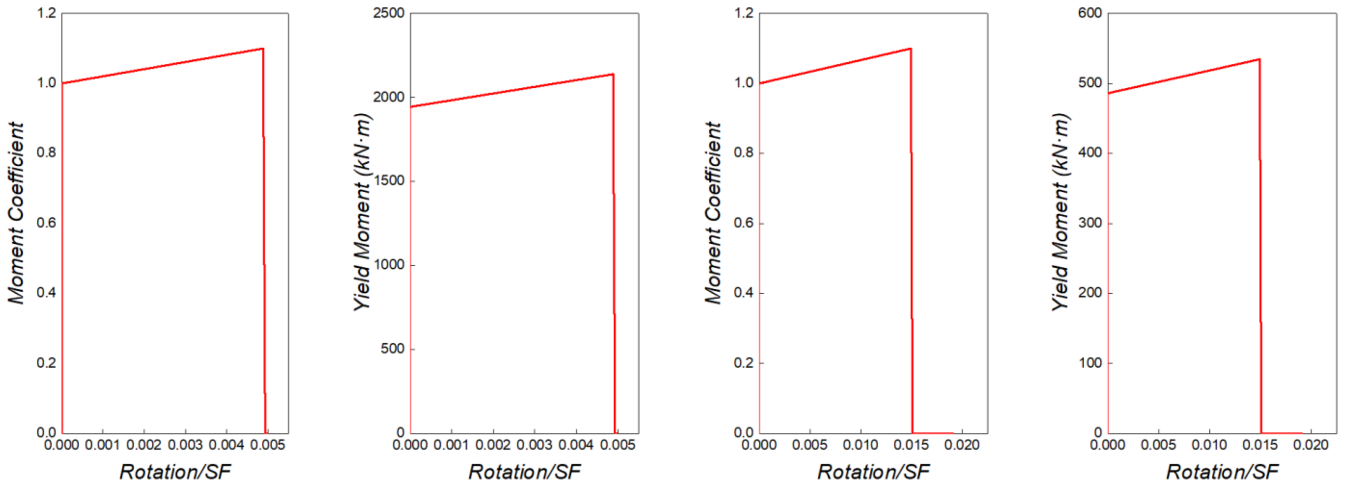
2.2. Plastic hinges design

To meet the simulation requirements specified by ETABS, it is essential to assign plastic hinge properties to each structural component. This entails defining specific characteristics for plastic hinges, with the criteria for determining these properties outlined in ASCE 41-13, a standard endorsed and supported by ETABS. ASCE 41-13 offers comprehensive guidelines for the seismic evaluation and retrofitting of existing

RC buildings, and its adoption within ETABS ensures a standardized and reliable approach to attributing plastic hinge properties in structural analysis and design. The incorporation of the plastic hinge properties is crucial for accurately simulating and assessing the behavior of structural elements, particularly in the context of seismic analysis where the response of components to plastic deformation is a critical consideration. Adhering to established standards enhances the reliability and consistency of the RC structural analysis results in this research, contributing to the overall effectiveness of the structural design process in ETABS.

The representation of plastic hinges for the column section is modeled in accordance with the established ASCE 41-13 standards. Specifically, these modeling decisions are guided by the parameters and criteria outlined in Table 10-8, which is dedicated to Reinforced Concrete Columns in nonlinear procedures. The plastic hinges are designed for Condition ii-Flexure/Shear, with degrees of freedom encompassing axial forces, bending moments of the M2 axis, and bending moments of the M3 axis.

As illustrated in **Figure 4**, the plastic hinge properties for column sections are distinctly characterized by axial forces, with values set at 1944 kN·m for the M2 axis and 486 kN·m for the M3 axis. These values play a critical role in defining how the columns respond under different loading conditions, particularly in the context of seismic events.



(a) **(b)** **(c)** **(d)**

Figure 4. Plastic hinge property of columns. **(a)** Coefficient of M2; **(b)** Yield Moment of M2; **(c)** Coefficient of M3; **(d)** Yield Moment of M3.

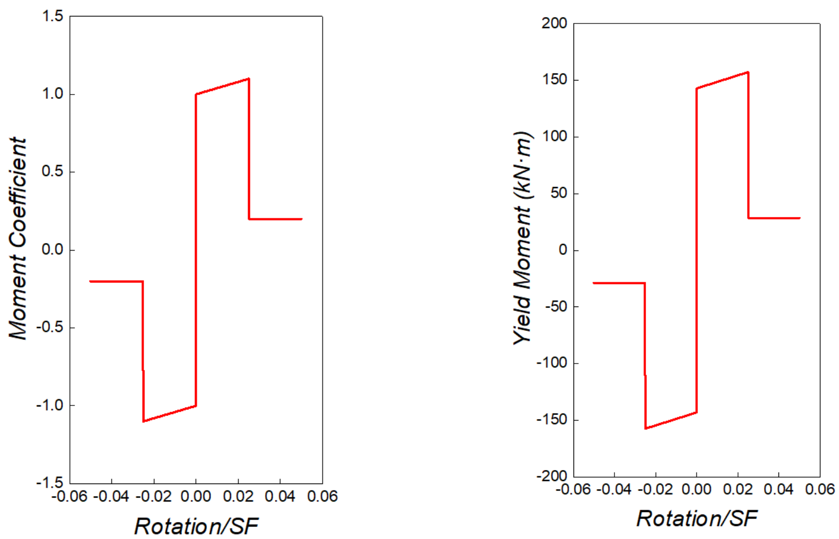
Further elaborating on the plastic hinge properties of the column, **Table 2** presents comprehensive information for M2 and M3. For M2, the IO (Immediate Occupancy) is specified at 1948.174 kN·m, LS (Life Safety) at 1951.547 kN·m, and CP (Collapse Prevention) at 1953.491 kN·m. Meanwhile, for M3, the corresponding values are 488.43 kN·m (IO), 493.36 kN·m (LS), and 495.2607 kN·m (CP). These values indicate the capacity of the plastic hinges to withstand bending moments and axial forces at various levels of structural performance ranging from immediate occupancy to collapse prevention.

Table 2. Plastic hinges on column.

Acceptance criteria	Yield moment	Coefficient	M2	Yield moment	Coefficient	M3
	kN·m		kN·m	kN·m		kN·m
IO	1944	0.002147	1948.17	486	0.005	488.43
LS	1944	0.003882	1951.55	486	0.015144	493.36
CP	1944	0.004882	1953.49	486	0.019055	495.26

The plastic hinge modeling for the beam section is designed according to the comprehensive ASCE 41-13 standard. These guidelines are specifically detailed in Table 10-7, which serves as a dedicated resource for reinforced concrete beams within nonlinear procedures. The focus here is on capturing the behavior of the beam section, with particular emphasis on the M3 degree of freedom as a critical aspect in understanding the response to lateral forces and deformations.

In **Figure 5**, the properties of the plastic hinges for the beam section are visually illustrated. The key parameter is quantified at 143.0132 kN·m which is known as the yield moment. This value represents the moment at which the plastic hinges in the beam section initiate yielding, providing critical information about the structural response under loading conditions.



(a) **(b)**

Figure 5. Plastic hinge property of beams. **(a)** Coefficient of M2; **(b)** yield moment of M2.

For a more comprehensive understanding, **Table 3** provides detailed plastic hinge properties for the beam. The values include the yield moments corresponding to different performance levels. At IO (immediate occupancy), the yield moment is specified at 144.4433 kN·m, reflecting the capacity of the beam under initial loading conditions. The LS (life safety) level indicates a yield moment of 146.5885 kN·m, representing a higher level of structural performance. Finally, the CP (collapse prevention) condition is characterized by a yield moment of 150.1639 kN·m, indicating the maximum capacity of the beam to resist collapse under severe loading conditions.

Table 3. Plastic hinges on beam.

Acceptance criteria	Yield moment	Coefficient	M2
	kN·m		kN·m
IO	143.0132	0.01	144.4433
LS	143.0132	0.025	146.5885
CP	143.0132	0.05	150.1639

The plastic hinge properties play a crucial role in accurately simulating the behavior of the beam and column in this research, particularly in nonlinear pushover analysis where plastic deformation becomes a critical consideration.

2.3. Load design

According to the guidelines outlined in KDS 41 10 15: 2019, specific dead load and live load values are provided for a school building intended for educational purposes. In accordance with the standard of KDS 41 10 15: 2019, the Dead Load is specified as 4.3 kN/m^2, representing the weight of permanent elements such as the structure and finishes, while the Live Load is designated as 3 kN/m^2, indicating the variable load imposed by occupants, furniture, and other transient factors. These values are derived from Table 3.2-1 within the documentation of KDS 41 10 15: 2019, providing a reference for load considerations in educational structures.

To tailor these load values to the specific dimensions of the room under scrutiny in this research, specific calculations are applied. The dead load and live load are determined using dedicated formulas that account for the width and length of the room as below:

$$P_D = \left(\frac{1}{2} \times W \times \frac{W}{2}\right) \times DL \tag{3}$$

$$\omega_D = \frac{P_D}{L} \tag{4}$$

$$P_L = \left(\frac{1}{2} \times W \times \frac{W}{2}\right) \times LL \tag{5}$$

$$\omega_L = \frac{P_L}{L} \tag{6}$$

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. W is the width of the specific room for this research, DL and LL are dead load and live load separately.

Upon performing calculations and following the load design principles outlined in KDS 41 10 15: 2019, this research has determined specific values for the dead load and live load for the nonlinear pushover analysis. These values are crucial for analyzing the structural response of the building and have been quantified as 4.83751 kN/m for the dead load and 3.375 kN/m for the live load.

In the realm of pushover analysis, the consideration of load combinations is a critical aspect that significantly influences the structural assessment. The evaluation code for the structural seismic performance by KISTEC (Korea Institute of Science and Technology Evaluation and Planning) in 2021 highlights the crucial role of load combinations in structural analyses. It also provides a systematic method for determining the appropriate combinations of loads, emphasizing their significance in ensuring structural integrity and safety as the equation shows below:

$$LC = 1.0 \times DL + 0.25 \times LL \quad (7)$$

where LC is load combinations, DL and LL are dead load and live load separately.

The nonlinear pushover analysis is intricately designed to utilize a displacement control system, where the control is implemented through conjugate displacement. Furthermore, the pushover analysis is organized with a plan consisting of a total of 100 analytical steps. Each analytical step is systematically formulated to accommodate different displacements, providing a comprehensive range of data points throughout the analysis process. This designed variation in displacement levels allows for a detailed exploration of the structural response under progressively increasing lateral loads. The 100-step design ensures a thorough examination of the structural behavior, capturing the evolution of deformations and identifying critical points in the load-displacement relationship.

3. Results and discussion

3.1. Performance point

The analysis includes the presentation of critical data in **Tables 4** and **5**, offering a comprehensive overview of the performance points associated with CASE-1 and CASE-2 in this research. These points are derived based on the plot definition outlined in FEMA 440 EL, which serves as a guideline for assessing structural performance under seismic conditions.

To further enrich the analysis in this research, the computation of S_a (spectral acceleration) is undertaken. By utilizing the demand spectrum specified in ASCE 7-10 General and incorporating considerations from KDS 41 17 00: 2022, the calculations focus on two key spectral accelerations for 1-sec and 0.2-sec as follows:

$$S_{D1} = S \times F_V \times \frac{2}{3} \quad (8)$$

$$S_{DS} = S \times 2.5 \times F_a \times \frac{2}{3} \quad (9)$$

where S represents the effective ground acceleration value for a 2400-year return period earthquake, as referenced in KDS 41 17 00: 2022. Additionally, the factors F_a and F_v denote the acceleration-based site coefficient and velocity-based site coefficient respectively, which can be found in Table 4.2-1 and Table 4.2-2 according to KDS 41 17 00: 2022.

By applying seismic parameters and equations derived from ASCE 7–10 General, the calculations produce critical values that characterize the dynamic response of the specific RC frame structure under consideration. These calculations yield two significant results: S_{D1}, representing the 1-second spectral acceleration, and S_{DS}, representing the 0.2-second spectral acceleration.

Based on KDS 41 17 00: 2022, the process involves careful consideration of the site-specific conditions, denoted as site-class S4, with a specific long period of 8 seconds. The equations provided by ASCE 7–10 General are applied to compute the acceleration values S_a and S_1. As a result of the calculations, S_a is determined to be 1 g, indicating the acceleration experienced by the structure over a 1-second period. Simultaneously, S_1 is computed as 0.4 g, representing the acceleration during a shorter 0.2-second interval. These acceleration values are crucial indicators of the structural ability to withstand seismic loading and are integral to understanding its dynamic behavior under different seismic conditions. Importantly, these computed values directly impact the determination of performance points for the specific RC frame structure analyzed in this research.

The performance points result, as shown in **Tables 4** and **5**, reveal a discernible pattern in the behavior of the RC frame structure. The findings demonstrate a consistent trend of decreasing base shear forces as the number of stories increases. This trend is evident across two distinct column orientations, differentiating between CASE-1 and CASE-2. However, there is a shift in dynamics when analyzing the 1st floor, which stands out due to its singular modal behavior. In contrast to the multi-modal nature of the higher floors, the base shear of the 1st floor behavior differs significantly, reflecting its unique structural characteristics and response to lateral forces.

Table 4. Performance point (CASE-1).

FL	Shear	Displ.	S_a	S_d	*T* secant	*T* effective	Ductility ratio	Damping ratio	Modification factor
	kN	mm	g	mm	sec	sec	-	Beff	M
1F	36.976	1.320	1.095	1.320	0.065	0.072	1.816	0.063	1.251
2F	112.006	32.322	1.607	25.031	0.250	0.385	10.460	0.201	2.455
3F	81.456	94.592	0.748	68.378	0.606	0.638	8.956	0.205	1.118
4F	65.232	154.935	0.432	107.030	0.998	1.017	11.273	0.199	1.044
5F	51.992	245.265	0.274	165.874	1.561	1.560	15.914	0.185	1.001

Note: Displ. indicates structural lateral displacement.

Table 5. Performance point (CASE-2).

FL	Shear	Displ.	S_a	S_d	*T* secant	*T* effective	Ductility ratio	Damping Ratio	Modification Factor
	kN	mm	g	mm	sec	sec	-	Beff	M
1F	49.691	1.025	1.473	1.016	0.049	0.064	2.132	0.061	1.758
2F	150.522	25.098	2.161	19.265	0.189	0.344	12.282	0.194	3.449
3F	108.326	66.870	0.991	47.529	0.438	0.544	9.071	0.202	1.719
4F	87.647	126.271	0.586	87.032	0.773	0.811	8.463	0.206	1.099
5F	71.007	207.242	0.381	140.828	1.219	1.299	12.448	0.196	1.163

Note: Displ. indicates structural lateral displacement.

A more detailed exploration through the floors from the 2nd to the 5th reveals intriguing findings that indicate the multi-modal analysis indicates that the smallest base shear force is encountered on the 5th floor while the largest base shear force is observed on the 2nd floor. This observation aligns with the general trend of decreasing base shear forces with an increasing number of stories, emphasizing how verticality (number of stories) influences seismic response within this structure.

When assessing the seismic performance of a specific RC frame structure in this research, a comprehensive analysis should consider not only the results of base shear forces but also the displacement results at each performance point [10–16]. Unlike base shear forces, the displacement of the RC frame structure is not affected by modal behavior during the analysis. Despite being independent from modal influence, the displacement results consistently show an increasing trend. This trend is significant as it suggests that the structure experiences greater deformations with each additional story, regardless of the specific column orientation (CASE-1 or CASE-2).

In further exploring the seismic characteristics of the specific RC frame structure in this research, an examination of the trends in S_a (spectral acceleration) and S_d (spectral displacement) offers valuable insights. This analysis not only considers the base shear force and displacement results independently but also aims to establish interrelationships among the critical parameters of S_a and S_d. The trends in S_a and S_d at each performance point are linked to the behavior of base shear forces and displacements of the RC frame structure in this research and this approach allows for a more comprehensive evaluation, taking into account both the intensity and duration of ground shaking as well as the resulting structural deformations. Of particular significance is the explicit relationship observed between S_d and the analytical results of displacement. This finding emphasizes the reliability and relevance of S_d as a key metric for characterizing the structural response to seismic forces. As S_d is inherently connected to the amplitude and frequency content of ground motions, its explicit relationship with analytical displacement results further validates its usefulness in seismic assessments [14–16].

The comparative analysis of different column orientations as presented in **Tables 4** and **5**, reveals intriguing trends in the seismic performance of the RC frame structure in this research. The results notably demonstrate distinct behaviors in base shear forces and displacements between CASE-1 and CASE-2, providing valuable insights into the influence of column orientations on structural response.

Specifically, referring to the results of CASE-2, a larger base shear force is exhibited compared to CASE-1. This phenomenon suggests that longer column sections aligned with the load direction demonstrate superiority in resisting lateral forces, resulting in larger base shear forces. This finding aligns with the expectation that longer column sections contribute to increased stiffness and resistance to lateral loads. Conversely, CASE-1 appears longer displacements. This phenomenon suggests that shorter column sections aligned with the load direction cannot demonstrate superiority in resisting lateral forces, resulting in smaller base shear forces. This finding aligns with the expectation that shorter column sections lead to decreased stiffness and resistance to lateral loads.

Furthermore, this phenomenon also applies to the results of S_a and S_d. The interaction between column orientations, base shear forces, and displacements is evident in the seismic characteristics, highlighting the importance of a comprehensive understanding of structural response under different column orientations. Additionally, the period of specific RC frame structures shows an increasing trend with the growing number of stories, as observed in both CASE-1 and CASE-2 performance points following **Tables 5** and **6**. Moreover, a comparison between CASE-1 and CASE-2 indicates that longer column sections aligned with the load direction exhibit shorter periods in pushover analysis, while shorter column sections in the same alignment demonstrate longer periods.

3.2. Capacity curve

The assessment of structural performance through nonlinear pushover analysis significantly relies on the results obtained from the capacity curve [17,18]. The capacity curve is a crucial element in comprehending how the structure reacts to incremental lateral loads and provides valuable insights into its overall seismic performance [17–23]. In this research, **Figure 6** presents a visual representation of the capacity curves for each specific RC frame structure under nonlinear pushover analysis. The black curves represent the capacity curves of CASE-1, focusing on the specimen from the 1st floor to the 5th floor, while the red curves illustrate the capacity curves of CASE-2, providing a comparable analysis for the same range of stories.

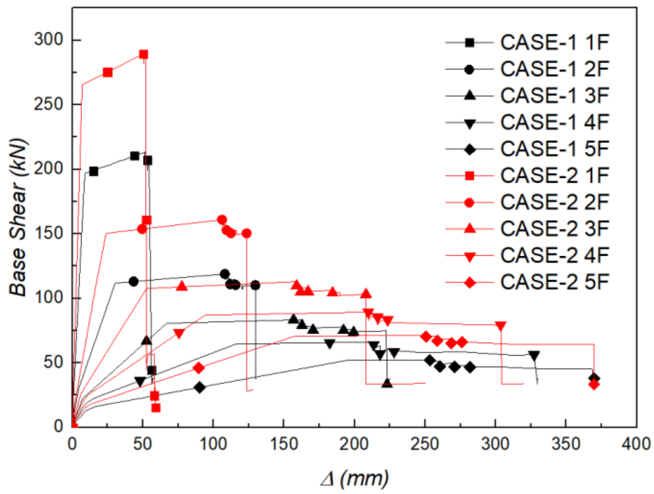
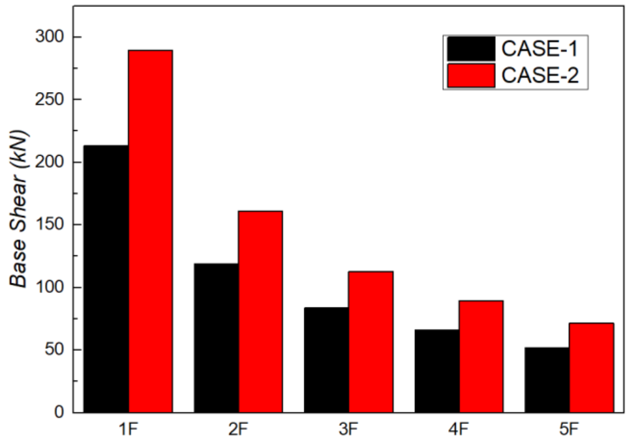


Figure 6. Capacity curve.

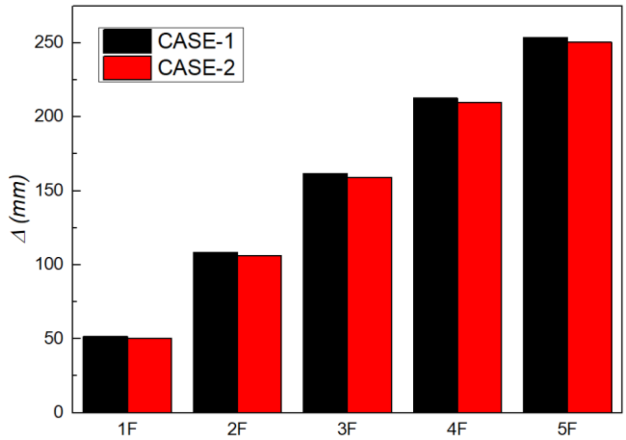
The analysis of the capacity curves as shown in **Figure 6**, offers valuable insights into the seismic behavior of the specific RC frame structures. The trends observed in the capacity curves shed light on how various factors, such as the number of stories and column orientations, influence the response of the structure to lateral loads under nonlinear pushover analysis.

The capacity curves reveal a significant correlation between the number of stories and the structural response. As the number of stories increases, there is a noticeable decrease in the base shear force and a simultaneous increase in displacement. Furthermore, when comparing different column orientations, the results of capacity curves emphasize the influence of column orientations. Longer column sections aligned with the load direction exhibit larger base shear forces and shorter displacements. Conversely, shorter column sections aligned with the load direction display smaller base shear forces and shorter displacements.

The analysis presented in **Figure 7** provides a detailed comparison of the maximum base shear force and the corresponding displacement for different column orientations within specific RC frame structures in this research. The discussion regarding maximum base shear and structural lateral displacement under the maximum base shear is expected to offer valuable insights into the influence of varying column orientations on structural seismic performance.



(a)



(b)

Figure 7. Maximum base shear and corresponding displacement. **(a)** Maximum base shear; **(b)** displacement under the maximum base shear.

The results unequivocally demonstrate that longer column sections that are represented by CASE-2 and aligned with the load direction led to larger base shear forces and shorter displacements. This finding is in accordance with the principles of structural mechanics, emphasizing the influence of column section length on the overall stiffness and resistance of the structure to lateral loads. In addition to comparing the displacement and base shear force values, **Figure 7** also provides a critical perspective on the collapse points of each specific RC frame structure in this research as the properties of plastic hinges play a pivotal role in the nonlinear pushover analysis. The maximum values of base shear force with the corresponding displacement signify the collapse points, indicating the structural limit under seismic loading conditions.

The investigation into the slope of the elastic zone in plastic hinges within RC frames is of significant importance for this research. It serves as a crucial reference that reflects the structural behavior before entering the plastic zone for nonlinear pushover analysis [21–23]. The value of the slope of the elastic zone is a critical indicator of structural performance under seismic forces and plays a significant role in assessing the seismic safety of RC frame structures.

Table 6 presents a comprehensive overview of the slope values of the elastic zone for all different specific RC frame structures in this research. The data reveals a consistent trend as the number of stories increases, the slope of the elastic zone experiences a decline. This observation holds true for all different column orientations, whether CASE-1 or CASE-2 and emphasizes a fundamental aspect of structural behavior with increasing structure height.

Table 6. Slope value in the elastic zone.

Types	1F	2F	3F	4F	5F
CASE-1	33.374	9.0864	4.5697	2.9252	1.9352
CASE-2	49.922	12.12	5.7235	3.5246	2.2396
Ratio	49.58%	33.39%	25.25%	20.49%	15.73%

Furthermore, the comparison between different column orientations in CASE-1 and CASE-2 reveals a significant finding as CASE-2 consistently exhibits a larger slope than CASE-1. The ratio of slopes increases from CASE-1 to CASE-2, indicating a clear correlation between the different column orientations and the slope of the elastic zone. This aligns with the earlier discussion regarding the capacity curve, reinforcing the discussion that longer column sections aligned with the load direction result in a larger slope of the elastic zone, while shorter column sections exhibit a smaller slope.

On the other hand, the observed decrease in the slope ratio between CASE-1 and CASE-2 as the number of stories increases highlights a significant impact of the number of stories on the structural performance within the elastic zone of RC frame structures in this research. This phenomenon suggests that the response of structures to seismic forces, especially within the elastic zone, is distinctly influenced by the vertical dimension of the structure. Conversely, as the number of stories increases, there are notable changes in structural behavior within the elastic zone. The decreasing slope ratio indicates a diminishing influence of different column orientations (CASE-1 and CASE-2) on structural response with increasing height of the RC frame structure. Essentially, as the vertical scale of RC frame structures increases, structural performance in the elastic zone becomes less sensitive to variations in column orientation.

3.3. Capacity spectrum

In evaluating the seismic performance of the RC frame structures in this research, the capacity spectrum method is instrumental in determining the performance level of the structures [2,15,16]. This method involves establishing a target displacement and conducting a graphical comparison between the structural capacity and the seismic demand. The key feature of the capacity spectrum method is its ability to provide a visual representation of the capacity of the structure and its response to seismic forces.

The capacity spectrum under nonlinear pushover analysis is a graphical representation of the structural lateral resisting capacity, illustrating how the structure responds as lateral loads increase incrementally. The curve of the capacity spectrum is a crucial component of the analysis, depicting the nonlinear behavior of the structure and capturing the maximum lateral displacement it can withstand. Concurrently, this curve represents both seismic demand on and distribution across different structural spectral displacements for structural spectral acceleration.

The process of converting the capacity curve to the capacity spectrum involves calculating the modal participation factor (MPF_1) and the modal mass coefficient (a) through the specific equations below:

$$\mathrm{MPF}_1 = \frac{\sum m_i \phi_{i1}}{\sum m_i \phi_{i1}^2} \tag{10}$$

$$a = \frac{\left[\sum m_i \phi_{i1}\right]^2}{\left[\sum_{i=1}^{N} \frac{w_i}{g}\right] \cdot \left[\sum_{i=1}^{N} m_i \phi_{i1}^2\right]} \tag{11}$$

where $\frac{w_i}{g}$ is mass assigned to level i, φ_{i1} is the amplitude of model 1 at level i, and N is level N.

The values of S_a (spectral acceleration) and S_d (spectral displacement) are computed for each point along the capacity curve using specific equations below:

$$\frac{S_a}{g} = \frac{V_b}{w} \cdot \frac{1}{a} \tag{12}$$

$$S_d = \frac{\Delta_{\text{roof}}}{\text{MPF}_1 \cdot \phi_{\text{roof}_1}} \tag{13}$$

where V_b is base shear force, w is building load weight and Δ_{roof} is roof displacement.

$$S_d = \frac{T^2 S_a}{4\pi^2} \tag{14}$$

To transform a demand spectrum from S_a (spectral acceleration) and T (period) format to ADRS (Acceleration Displacement Response Spectrum) format, it is necessary to compute the value of S_d (spectral displacement) for each point on the curve using the specific equation above.

The performance point is determined by overlaying the demand spectrum onto the capacity curve in spectral coordinates or ADRS format. This process is facilitated by the built-in capacity spectrum method within the ETABS program.

The results of the capacity spectrum analysis for various specific RC frame structures are visually presented in **Figure 8**. The considered structures have different column orientations, which are systematically categorized into two cases: CASE-1 and CASE-2. These cases are depicted in two different colors black and red as **Figure 8** illustrates.

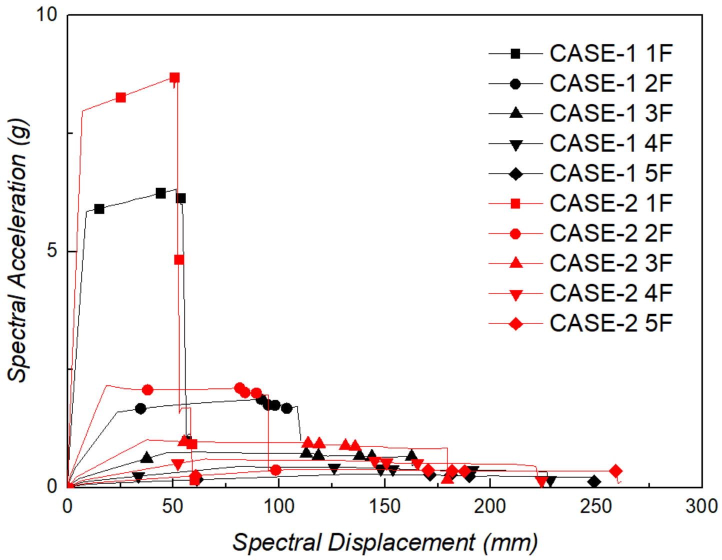


Figure 8. Spectral acceleration and spectral displacement.

In a parallel observation to the capacity curve comparison, **Figure 8** illustrates a consistent pattern as the number of stories increases in both CASE-1 and CASE-2 where the results emphasize a noticeable trend of decreasing spectral acceleration and increasing spectral displacement. Additionally, a comparison between CASE-1 and CASE-2 in **Figure 8** unveils distinct characteristics based on the different column orientations. Notably, CASE-2 exhibits larger spectral acceleration than CASE-1 for structures with the same number of stories. Simultaneously, despite the larger spectral acceleration, CASE-2 exhibits slightly shorter displacements compared to CASE-1.

This comparison emphasizes the influence of different column orientations on the dynamic response of the structures.

3.4. Layer shear force

The layer shear in a specific RC frame serves as a comprehensive indicator, revealing the distribution of shear forces across each story of the entire structure. The results of layer shear are instrumental in understanding how shear forces vary along the vertical axis of the structure, offering valuable insights into the structural performance under seismic loading conditions [21–25]. Analyzing the layer shear force at different stories becomes a pivotal aspect in evaluating the structural capacity to withstand lateral forces, and it serves as a key point of assessment in nonlinear pushover analysis, a widely used method in seismic performance evaluation.

Based on the collapse point of the plastic hinge through nonlinear pushover analysis in this research, **Figure 9** visually depicts the layer shear force for various specific RC frame structures, each characterized by different column orientations as CASE-1 and CASE-2 shown in **Figure 9**. Moreover, the stories of the structure are clearly delineated along with the height of the RC frame structure, providing a visual representation of how layer shear forces vary from one story to the next.

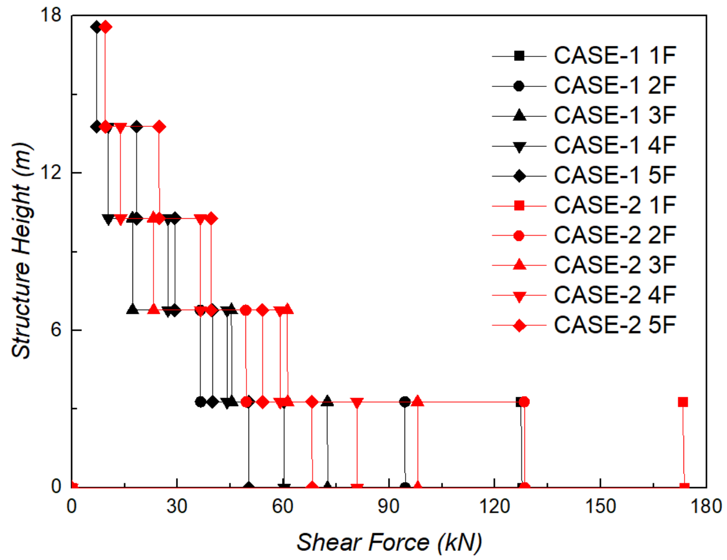


Figure 9. Layer shear force.

The analysis of layer shear force in **Figure 9** provides insightful findings regarding the behavior of the specific RC frame structures. Notably, the number of stories in the RC frame structures emerges as a significant factor influencing the magnitude of the layer shear force. As the number of stories increases, there is a consistent trend of smaller layer shear forces for both column orientations (CASE-1 and CASE-2), indicating a significant relationship between structural height and shear force distribution. This trend holds true for both column orientations, suggesting a universal influence of the number of stories on layer shear force.

In addition to considering the influence of the number of stories, a comparative analysis between CASE-1 and CASE-2 reveals the influence of different column orientations in this research. The findings indicate that column orientation plays a crucial role in determining layer shear force values. It is worth noting that for structures with the same number of stories, CASE-2 consistently shows larger layer shear forces than CASE-1 across every story of the specific RC frame structure. This observation supports the discussion on base shear force and emphasizes the significance of column orientation in influencing shear force distribution.

Based on the insights gained from the discussion on the layer shear force, a definitive conclusion can be drawn. The findings indicate that longer column sections when aligned with the load direction, contribute to a greater layer shear force within the specific RC structure in this research. Conversely, the structures featuring shorter column sections aligned with the load direction exhibit smaller layer shear forces.

3.5. Layer displacement and drift ratio

The investigation of layer displacement is a central focus in the aspect of nonlinear pushover analysis in this research, where the structural response to lateral forces is systematically evaluated. Layer displacement offers valuable insights into the behavior of each individual story within the RC frame structures as a crucial metric [24,25]. The assessment of layer displacement becomes particularly relevant when considering the collapse points identified during the plastic hinge stage through nonlinear pushover analysis. **Figure 10** provides a visual representation of the layer displacement results, offering a comprehensive view of the structural response across different stories in the specific RC frame structures. **Figure 10a,b** illustrate the layer displacement results obtained from nonlinear pushover analysis. The collapse point at the plastic hinge state in RC frame structures is a critical juncture in structural response and also plays a pivotal role in seismic performance evaluation. By discussing layer displacement at the collapse point, it is possible to gain insights into the structural ability to withstand lateral forces and the overall effectiveness of design in ensuring structural integrity under nonlinear pushover analysis for seismic activities.

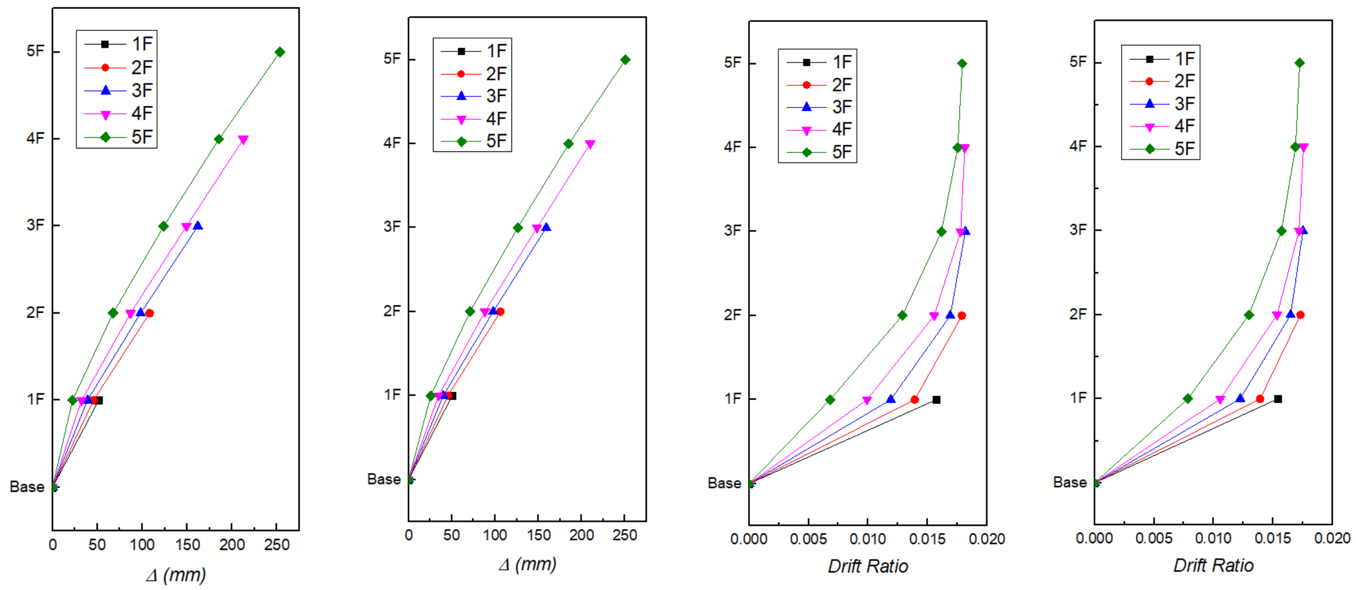
Furthermore, the drift ratio is a crucial factor in assessing structural performance under the nonlinear pushover analysis, as it reflects the response of the structure to seismic activities. Therefore, this research also includes a discussion on drift ratio as depicted in in **Figure 10c,d**. Specifically, the drift ratio for each individual story within the specific RC frame structures is calculated under both layer displacement and story height. This calculation involves evaluating the ratio of layer displacement to story height using the following equations:

$$\mathit{\Delta} = \delta_x - \delta_{x-1} \tag{15}$$

$$\mathit{\Delta}_{\mathrm{ratio}} = \frac{\mathit{\Delta}}{h} \tag{16}$$

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

The drift ratio plays a crucial role in the evaluation of seismic performance, as it represents the relationship between lateral displacement and vertical height for each story within the RC frame structures [24,25]. The examination of drift ratios as depicted in **Figure 10c,d**, provides valuable insights into the structural behavior of specific RC frame structures in this research. These visual representations offer a comparative analysis of different cases corresponding to varied column orientations, showcasing the influence of column orientations on the entire structure. The cases under consideration include orientations where longer or shorter columns are aligned with the load direction, contributing to an understanding of different drift ratio patterns. Analyzing these variations helps in comprehending how changes in column orientations impact the distribution of lateral displacements throughout the structure.



(a) **(b)** **(c)** **(d)**

Figure 10. Layer displacement and drift ratio. **(a)** CASE-1 (Layer Displacement); **(b)** CASE-2 (Layer Displacement); **(c)** CASE-1 (Layer Drift Ratio); **(d)** CASE-2 (Layer Drift Ratio).

The analysis of layer displacement in specific RC frame structures becomes more insightful when considering the influences of different column orientations. **Figure 10** focuses on CASE-1 and CASE-2 with different column orientations, revealing key patterns in the layer displacement results. Notably, **Figure 10a,b** both demonstrate how the number of stories in the RC frame structure distinctly influences layer displacement for different column orientations of CASE-1 and CASE-2. As the number of stories increases, there is a noticeable reduction in layer displacement, indicating a correlation between structural height and lateral displacement.

Furthermore, the detailed analysis presented in **Table 7** enhances the understanding of the influences due to different column orientations by directly comparing the layer displacement between CASE-1 and CASE-2. The consistent observation is that CASE-1 consistently exhibits slightly longer layer displacements compared to CASE-2. This finding aligns with the notion that longer column sections, such as those in CASE-2 aligned with the load direction, contribute to shorter layer displacements. Conversely, shorter column sections aligned with the load direction in CASE-1 result in longer layer displacements. The observed phenomenon emphasizes the importance of column orientations in influencing the lateral behavior of the RC frame structure. Longer column sections prove effective in limiting layer displacements, while shorter column sections contribute to more extensive layer displacements.

Table 7. Layer displacement.

Story	CASE-1	CASE-2	CASE-1	CASE-2	CASE-1	CASE-2	CASE-1	CASE-2	CASE-1	CASE-2
	Displ.	Displ.	Displ.	Displ.	Displ.	Displ.	Displ.	Displ.	Displ.	Displ.
	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm
Base	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Story 1	51.515	50.395	45.574	45.547	38.982	40.079	32.452	34.604	22.291	25.660
Story 2	-	-	108.139	106.097	98.123	97.709	86.884	88.253	67.331	71.055
Story 3	-	-	-	-	161.711	158.975	149.062	148.347	123.897	125.985
Story 4	-	-	-	-	-	-	212.482	209.780	185.224	185.056

Note: Displ. indicates structural lateral displacement.

The analysis of drift ratios when considering different column orientations (CASE-1 and CASE-2) provides valuable insights into the seismic behavior of specific RC frame structures under nonlinear pushover analysis. **Figure 10c,d** highlight how the number of stories influences the drift ratio. The results demonstrate a discernible trend: regardless of the different column orientations as illustrated by CASE-1 and CASE-2, an increase in the number of stories in the RC frame structure leads to a notable reduction in the drift ratio for each corresponding story. This observation underscores the significance of structural height in mitigating lateral displacements during seismic events.

The detailed comparison presented in **Table 8** enhances the comprehension of the influences resulting from different column orientations by directly comparing the drift ratios between CASE-1 and CASE-2. It is consistently observed that CASE-1 exhibits a slightly larger drift ratio than CASE-2. This recurring pattern suggests that longer column sections, as seen in CASE-2 and aligned with the load direction, contribute to smaller drift ratios. In contrast, the shorter column sections aligned with the load direction in CASE-1 result in larger drift ratios.

Table 8. Layer drift ratio.

Story	CASE-1	CASE-2	CASE-1	CASE-2	CASE-1	CASE-2	CASE-1	CASE-2	CASE-1	CASE-2
	Drift	Drift	Drift	Drift	Drift	Drift	Drift	Drift	Drift	Drift
Base	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Story 1	0.01573	0.01539	0.01392	0.01391	0.01190	0.01224	0.00991	0.01057	0.00681	0.00784
Story 2	-	-	0.01788	0.01730	0.01690	0.01647	0.01555	0.01533	0.01287	0.01297
Story 3	-	-	-	-	0.01817	0.01751	0.01777	0.01717	0.01616	0.01569
Story 4	-	-	-	-	-	-	0.01812	0.01755	0.01752	0.01688
Story 5	-	-	-	-	-	-	-	-	0.01791	0.01724

This discussion holds particular significance in the context of seismic design considerations. The capacity of longer column sections to restrict drift ratios can contribute to enhanced structural resilience against lateral forces. Conversely, structures with shorter column sections may experience larger drift ratios, necessitating additional design measures to improve seismic performance.

4. Discussion

The assessment of structural performance under seismic conditions is a crucial aspect of ensuring the resilience and safety of RC buildings. In current practice, a variety of methods are employed for this purpose, with particular emphasis on pushover analysis as a primary nonlinear approach. This analytical method involves simulating the structural response to incremental lateral loads, providing valuable insights into the nonlinear behavior of structures under seismic forces. The increasing societal concern resulting from significant seismic damage experienced by existing buildings over decades has heightened the need for comprehensive assessments. This situation has prompted researchers to undertake a dual mandate: first, rigorously evaluating the safety of newly constructed designs, and second, actively enhancing the seismic performance of RC structures that have been in existence for extended periods.

This research focuses on the comprehensive simulation and analysis of 10 distinct RC frame structures, utilizing the nonlinear pushover analysis methodology within the ETABS structural analysis software. The investigation includes a thorough examination of performance points, capacity curves, capacity spectrum, layer displacement, and layer drift ratio to discern the intricate nuances of structural behavior under the nonlinear pushover analysis.

In this research, the RC frame structure with one floor demonstrates a maximum base shear force of 213.33 kN for CASE-1 when the column orientation is aligned to direction x and 289.47 kN for CASE-2 when the column orientation is aligned to direction y. These findings closely resemble the real experimental results reported by Zhou et al. [26]. Additionally, the hysteresis diagram test results for SPW1 in the research of Karimi and TahamouliRoudsari [27] appear to have similar results as the nonlinear pushover analytical results of the RC frame structure with one floor in this study. Based on the previous experimental research, two different real experimental results validate the analytical results obtained through nonlinear pushover analysis in this research.

1) In reference to the discussion on the performance point and the capacity curve, this research emphasizes the significant role of the number of stories in the RC frame structure. As the number of stories increases, there is a noticeable decrease in both base shear force and S_a (spectral acceleration). At the same time, there is an increase in displacement length and S_d (spectral displacement). Consequently, a noteworthy conclusion drawn from this research is that structures with fewer stories demonstrate superior performance characteristics under seismic activities as the structures may exhibit larger base shear forces and shorter displacements, indicating improved stability and resilience when subject to seismic forces. This insight can provide valuable references for structural design considerations, highlighting the benefits of constructing buildings with a limited number of stories for enhanced seismic performance.
2) Based on the discussions of the performance point and capacity curve, a comparative analysis of different column orientations (represented by CASE-1 and CASE-2) reveals significant insights. The analysis highlights that longer column sections aligned with the load direction outperform their shorter counterparts. Specifically, longer columns aligned with the load direction

demonstrate larger base shear forces, shorter displacements, a higher value of S_a, and a lower value of S_d. These advantageous structural properties contribute to the resistance of seismic damage.

The investigation delves into a detailed analysis of layer shear force, layer displacement, and layer drift ratio concerning the collapse points based on the plastic hinge analysis in diverse specific RC frame structures in this research. Through the discussions of the results, it becomes evident that the structural performance is notably influenced by the number of stories and the different column orientations.

3) In terms of the number of stories, it is crucial to observe that an increasing number of stories in the RC frame structure leads to distinct changes in performance metrics. Specifically, there is a noticeable reduction in layer shear forces, accompanied by an increase in the length of layer displacement. Additionally, a subtle rise in the drift ratio is also observed. The findings illuminate the dynamic response of RC frame structures and underscore the significance of the number of stories in shaping the structural response to seismic forces. This suggests that having a lower story in the RC frame may be advantageous for resisting seismic activities.
4) The comparison analysis of the structural performance of different column orientations reveals that the longer column aligned with the load direction demonstrates superior performance characteristics. These longer columns display larger layer shear forces, shorter layer displacements, and slightly smaller drift ratios compared to their shorter counterparts under the nonlinear pushover analysis in this research. This suggests that emphasizing longer columns aligned with the load direction may be advantageous for RC structures in resisting seismic damage, as indicated by the performance point and capacity curve mentioned above.

In essence, this research offers a comprehensive exploration of specific RC frame structures characterized by diverse column orientations. It provides valuable insights for designing and assessing the seismic performance of RC frame structures, with an emphasis on the significant structural mechanical influences of the number of stories and column orientations. The findings are expected to serve as a valuable reference for newly constructed designs of RC buildings and reinforced projects for existing RC buildings. Additionally, this research is also anticipated to be a valuable reference for future studies in this aspect.

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References

1. Sullivan TJ, Saborio-Romano D, O'Reilly GJ, et al. Simplified Pushover Analysis of Moment Resisting Frame Structures.

Journal of Earthquake Engineering. 2018; 25(4): 621-648. doi: 10.1080/13632469.2018.1528911

2. Hakim RA, Alama MSA, Ashour SA. Seismic Assessment of an RC Building Using Pushover Analysis. Engineering, Technology & Applied Science Research. 2014; 4(3): 631-635. doi: 10.48084/etasr.428
3. Bergami AV, Forte A, Lavorato D, et al. Proposal of an Incremental Modal Pushover Analysis (IMPA). Earthquakes and Structures. 2017; 13(6): 539-549. doi: 10.12989/EAS.2017.13.6.539
4. Habibi A, Saffari H, Izadpanah M. Optimal lateral load pattern for pushover analysis of building structures. Steel and Composite Structures. 2019; 32(1): 67-77. doi: 10.12989/SCS.2019.32.1.067
5. Gholipour M, Alinia MM. Considerations on the Pushover Analysis of Multi-Story Steel Plate Shear Wall Structures. Periodica Polytechnica Civil Engineering. 2016; 60(1): 113-126. doi: 10.3311/ppci.7706
6. Endo Y, Pelà L, Roca P. Review of Different Pushover Analysis Methods Applied to Masonry Buildings and Comparison with Nonlinear Dynamic Analysis. Journal of Earthquake Engineering. 2016; 21(8): 1234-1255. doi: 10.1080/13632469.2016.1210055
7. Liu J, Wang W, Dasgupta G. Pushover analysis of underground structures: Method and application. Science China Technological Sciences. 2014; 57(2): 423-437. doi: 10.1007/s11431-013-5430-z
8. Chrysanidis T, Mousama D, Tzatzo E, et al. Study of the Effect of a Seismic Zone to the Construction Cost of a Five-Story Reinforced Concrete Building. Sustainability. 2022; 14(16): 10076. doi: 10.3390/su141610076
9. Chrysanidis T, Tegos I. Axial and transverse strengthening of R/C circular columns: Conventional and new type of steel and hybrid jackets using high-strength mortar. Journal of Building Engineering. 2020; 30: 101236. doi: 10.1016/j.jobe.2020.101236
10. Hsiao FP, Oktavianus Y, Ou YC. A pushover seismic analysis method for asymmetric and tall buildings. Journal of the Chinese Institute of Engineers. 2015; 38(8): 991-1001. doi: 10.1080/02533839.2015.1056553
11. Shakeri K, Tarbali K, Mohebbi M. Pushover analysis of asymmetric-plan buildings based on distribution of the combined modal story shear and torsional moment. Earthquake Engineering and Engineering Vibration. 2014; 13(4): 707-716. doi: 10.1007/s11803-014-0274-5
12. Fujii K. Prediction of the largest peak nonlinear seismic response of asymmetric buildings under bi-directional excitation using pushover analyses. Bulletin of Earthquake Engineering. 2013; 12(2): 909-938. doi: 10.1007/s10518-013-9557-x
13. Dya AFC, Oretaa AWC. Seismic Vulnerability Assessment of Soft Story Irregular Buildings Using Pushover Analysis. Procedia Engineering. 2015; 125: 925-932. doi: 10.1016/j.proeng.2015.11.103
14. Rofooei FR, Mirjalili MR. Dynamic-based pushover analysis for one-way plan-asymmetric buildings. Engineering Structures. 2018; 163: 332-346. doi: 10.1016/j.engstruct.2018.02.052
15. Hassan WM, Reyes JC. Assessment of modal pushover analysis for mid-rise concrete buildings with and without viscous dampers. Journal of Building Engineering. 2020; 29: 101103. doi: 10.1016/j.jobe.2019.101103
16. Bakalis AP, Makarios TK. Seismic Assessment of Asymmetric Single-Story RC Buildings by Modified Pushover Analysis Using the “Capable Near Collapse Centre of Stiffness”: Validation of the Method. Journal of Earthquake Engineering. 2019; 26(2): 980-1009. doi: 10.1080/13632469.2019.1698477
17. Handana, M. A. P., Karolina, R. Performance evaluation of existing building structure with pushover analysis. In IOP Conference Series: Materials Science and Engineering, 2018; 309(1): 012039. doi: 10.1088/1757-899X/309/1/012039
18. Liu Y, Kuang JS. Spectrum-based pushover analysis for estimating seismic demand of tall buildings. Bulletin of Earthquake Engineering. 2017; 15(10): 4193-4214. doi: 10.1007/s10518-017-0132-8
19. Soleimani S, Aziminejad A, Moghadam AS. Extending the concept of energy-based pushover analysis to assess seismic demands of asymmetric-plan buildings. Soil Dynamics and Earthquake Engineering. 2017; 93: 29-41. doi: 10.1016/j.soildyn.2016.11.014
20. Kuria KK, Kegyes-Brassai OK. Pushover Analysis in Seismic Engineering: A Detailed Chronology and Review of Techniques for Structural Assessment. Applied Sciences. 2023; 14(1): 151. doi: 10.3390/app14010151
21. Reyes, J. C., Chopra, A. K. Three-dimensional modal pushover analysis of buildings subjected to two components of ground motion, including its evaluation for tall buildings. Earthquake Engineering & Structural Dynamics. 2011; 40(7): 789-806. doi: 10.1002/eqe.1060
22. Liu, S. W., Liu, Y. P., Chan, S. L. Pushover analysis by one element per member for performance-based seismic design. International Journal of Structural Stability and Dynamics. 2010; 10(01): 111-126. doi: 10.1142/S0219455410003385
23. Poursha, M., & Amini, M. A. A single-run multi-mode pushover analysis to account for the effect of higher modes in

estimating the seismic demands of tall buildings. Bulletin of Earthquake Engineering. 2015; 13: 2347-2365. doi: 10.1007/s10518-014-9721-y

24. Mwafy A, Elnashai AS. Static pushover versus dynamic collapse analysis of RC buildings. Engineering Structures. 2001; 23(5): 407-424. doi: 10.1016/S0141-0296(00)00068-7
25. Azizi-Bondarabadi H, Mendes N, Lourenço PB. Higher Mode Effects in Pushover Analysis of Irregular Masonry Buildings. Journal of Earthquake Engineering. 2019; 25(8): 1459-1493. doi: 10.1080/13632469.2019.1579770
26. Zhou X, Kou X, Peng Q, et al. Influence of Infill Wall Configuration on Failure Modes of RC Frames. Russo S, ed. Shock and Vibration. 2018; 2018(1). doi: 10.1155/2018/6582817
27. Karimi R, TahamouliRoudsari M. Quasi-static cyclic testing of RC frames retrofitted using steel plate shear walls and diagonal tensile mesh. Asian Journal of Civil Engineering. 2021; 22(7): 1301-1318. doi: 10.1007/s42107-021-00382-z