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Comparative Study for Seismic Response of Various Seismic Force-Resisting Systems Employed in New Buildings in Erbil City

Ali H. Omar*, Ghafur H. Ahmed

Highway & Bridge Engineering Department, Erbil Technical Engineering College, Erbil Polytechnic University,
120m Ring Road, Erbil, Iraq
E-mail: Ali.H.Omar@Outlook.com

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Abstract: Tall buildings (TBs) are becoming increasingly prevalent in urban areas, posing unique challenges for their structural design and seismic performance. In Erbil city, flat slab construction with special reinforced concrete shear walls is commonly used in TBs, although it may not comply with international standards like ASCE7 and IBC without validation through nonlinear analysis. This study investigates the seismic performance of various seismic force-resisting systems employed in tall buildings in Erbil city, utilizing ACI318 for the design of the reinforced concrete structures and ETABS software for the analysis. Four structural systems were analyzed: Dual Systems with Special Moment Frames, Special Reinforced Concrete Moment Frames, Reinforced Concrete Ductile Coupled Walls, and Special Reinforced Concrete Shear Walls. Key structural responses, including stiffness, fundamental period of vibration, mass participation ratio, story displacement, inter-story drift ratio, story shear, and overturning moment, were examined. Dual Systems and Special Moment Frames demonstrated superior management of these parameters, thereby enhancing overall structural performance. The study underscores the importance of selecting appropriate seismic systems based on building height, with particular attention to the limitations posed by ductility and stability in taller structures.

Keywords: Tall buildings; Seismic force resisting system; Erbil city; Seismic response; Dynamic analysis.

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1. Introduction

Tall buildings have become increasingly prevalent in urban areas worldwide, serving as icons of modernity and urbanization. However, their unique structural design and seismic performance pose significant challenges, particularly in regions prone to seismic activity [1]. The seismic response of buildings is a critical area of research, particularly in regions prone to seismic activity, such as Erbil City in Iraq. This city located in a seismically active region [2], in recent years city has witnessed a rapid growth in tall buildings, with a common construction practice of flat slab systems with special reinforced concrete shear walls. However, concerns have been raised about the compliance of these systems with building codes and standards, particularly the [3] code, without validation through nonlinear analysis.

Most of the new pleasant constructed or under construction tall building projects in Erbil city has been shown in the Figure 1. Which made the city more modernized and shine in entire region. Reinforced concrete structures are engineered to endure seismic forces by utilizing various seismic force-resisting systems. These systems are crucial in enhancing the resilience of buildings during earthquakes, ensuring they remain stable and functional. Among the most effective systems are dual systems, special reinforced concrete moment frames, reinforced concrete ductile coupled walls, and special reinforced concrete shear walls. Each of these systems contributes uniquely to the structural performance, offering distinct advantages and facing specific challenges in seismic design and construction.

Dual systems, which incorporate both shear walls and special moment frames, are widely utilized in reinforced concrete structures to combat lateral forces [4-7]. In this configuration, moment frames contribute flexibility and ductility, while shear walls enhance stiffness and strength. The interplay between these components is critical, as design codes like [3] generally require moment frames to resist at least 25% of the total base shear. The main benefit of this system is its ability to provide increased lateral stability and superior energy dissipation during seismic events. However, designing and constructing dual systems can be challenging due to the complex interaction between components, particularly at beam-column joints, where high stress concentrations necessitate meticulous detailing and careful execution.

Brayati Towers
2# Towers 52 Floors / Under Construction

One Tower
48 Floors / Completed - Tallest Building in Iraq

Justice Tower
40 Floors / Completed

Qaiwan Mirador
9# Towers 29 – 40 Floors / Under Construction

Candle Residence Towers
4# Towers 40 Floors / Under Construction

Tulip Towers
4# Towers 38 Floors / Under Construction

Sky Towers
4# Towers 38 Floors / Completed

Sky View Towers
6# Towers 38 Floors / Under Construction

VAR Park Towers
4# Towers 36 Floors / Under Construction

Zagros Towers
3# Towers 35 Floors / Under Construction

English Tower
1# Tower 35 Floors / Under Construction

Rona Towers
4# Towers 26-35 Floors / Under Construction

Roya Tower
32 Floors / Completed

Ramy Towers
10# Towers 31 Floors / Under Construction

Bakhtiary Twin Towers
2# Towers 31 Floors / Under Construction

Eskan Towers
7# Towers 30 Floors / Completed

Empire world Wings
4# Towers 30 Floors / Completed

Florence Towers
2# Towers 27 Floors / Under Construction

Business Towers
5# Towers 27 Floors / Under Construction

Rona Towers
2# Towers 26 Floors / Under Construction

ASCO International City
12# Towers 20-26 Floors / Under Construction

4 Seasons Park
4# Towers 16 – 26 Floors / Under Construction

World Trade Center
2# Towers 25 Floors / Completed

Diamond Towers
3# Towers 23-25 Floors / Completed

Figure 1. Some of the Erbil Towers constructed or under construction.

Special reinforced concrete moment frames (SMRF) [8-10] are specifically designed to absorb seismic forces by flexural action within the beams and columns. Thanks to detailed reinforcement that enhances ductility, these frames are capable of undergoing substantial deformations without losing structural stability. The rigid beam-column connections facilitate effective load transfer during seismic activity, making SMRF a highly ductile system that efficiently dissipates energy. Despite its adaptability to various architectural designs due to the open space it allows, SMRF can be expensive to construct, requiring skilled labor to ensure that complex connections are executed correctly.

Reinforced concrete ductile coupled walls [11-14] consist of multiple shear walls connected by coupling beams, which help improve lateral resistance and allow for controlled deformation under seismic stress. The coupling beams distribute loads between the walls, enhancing overall performance. This system offers greater lateral stiffness than isolated shear walls and dissipates energy through controlled yielding in the coupling beams. Nevertheless, designing ductile coupled walls requires careful planning to ensure that the loads are evenly shared, necessitating advanced modeling to accurately predict the interaction between the walls and beams under seismic conditions.

Special reinforced concrete shear walls [15-18] are another crucial system for resisting seismic forces. These walls are typically placed strategically within a building to maximize lateral resistance, and they are reinforced to improve both ductility and strength under seismic loads. Shear walls are highly effective in resisting both wind and seismic forces, reducing building sway and enhancing the overall stability of the structure. However, the inclusion of shear walls in a building's design may limit interior space due to their size and placement. Additionally, maintaining adequate slenderness is vital for their optimal performance under extreme loads.

Several advanced structural systems, such as base isolation and viscous dampers, have been extensively researched for their contributions to seismic performance and structural resilience [19-22]. One study used the endurance time method to evaluate the vulnerability of tall isolated steel buildings, revealing how these structures can be optimized to withstand varying levels of earthquake hazards. Another investigation highlighted the effective range of base isolation design parameters, focusing on optimizing them to enhance a building's resilience to both near- and far-fault earthquakes. Research on the effects of unexpected earthquake severity and the placement of dampers further underscores the importance of strategic design in reducing seismic pounding. Additionally, the role of structural flexibility in minimizing the risk of pounding between adjacent isolated buildings has been emphasized, pointing to the need for flexible design solutions to mitigate earthquake damage. Collectively, these studies provide valuable insights into the seismic design of isolated structures, particularly in earthquake-prone regions.

Research conducted by [23] and [24] has provided comprehensive analyses of lateral load-resisting systems in tall buildings, focusing on their ability to withstand both seismic and wind forces while also considering economic feasibility. [23] identified structural systems such as outriggers, belt trusses, diagrids, and fluid viscous dampers as key in improving the stiffness of tall buildings. Among these, fluid viscous dampers were noted for being the most cost-effective method of maintaining stability under lateral loads. Meanwhile, [24] expanded on this by reviewing a broader spectrum of systems, including shear walls, reinforced concrete frames with bracings, and frame tube systems, to determine the most efficient and cost-effective solutions for resisting lateral forces. These studies provide critical insights into selecting lateral load-resisting systems, emphasizing the need for a balance between structural performance and economic viability in designing resilient tall buildings.

The discussion of seismic force-resisting systems is essential to ensure the structural integrity and safety of tall buildings [25], especially in seismically active regions. These systems are engineered to resist lateral forces generated by earthquakes, with performance varying based on material selection, geometry, and structural configuration. Comparative studies on concrete slab systems—such as flat slabs, ribbed slabs, and panelled beam systems—reveal significant differences in their suitability for high-rise construction. While flat slabs offer flexibility in design and ease of construction, they may underperform under lateral seismic loads. Ribbed slabs, strengthened by reinforced beams, provide higher strength and stiffness, making them more effective in resisting both gravity and lateral forces. In contrast, panelled beam systems exhibit varying degrees of seismic performance depending on their specific design and connections. For high-rise structures in seismically active areas, ribbed slab-column frames are recommended as the optimal system for resisting gravity loads, due to their superior capacity for handling both vertical and lateral forces. Overall, selecting the right seismic force-resisting system is crucial for designing structures that can endure earthquakes while maintaining safety and functionality.

This study aims to assess and compare the seismic performance of various seismic force-resisting systems employed in tall buildings in Erbil city. Its objectives include (1) evaluating the seismic behavior of different force-resisting systems used in tall buildings in Erbil, (2) investigating current practices and identifying potential shortcomings in structural systems, including flat slab construction with reinforced concrete shear walls, (3) analyzing the compliance of these systems with both local and international building codes, (4) examining the specific seismic parameters of Erbil and how they impact tall building performance, and (5) offering recommendations for design professionals, researchers, and stakeholders to improve the seismic resilience of buildings.

Despite significant advances in structural design and seismic analysis, challenges remain in ensuring the safety and performance of tall buildings, particularly in regions prone to seismic activity. Numerous studies have investigated the behavior of various structural systems under seismic loading; however, research tailored to the local conditions of Erbil City is notably scarce. While the current practice in Erbil heavily relies on flat slab systems coupled with shear walls, concerns about their seismic adequacy persist, especially regarding compliance with international codes such as ASCE 7. These systems, though efficient in certain aspects, may not provide the required ductility and energy dissipation for tall buildings in high-risk seismic zones. Furthermore, previous research often focuses on evaluations of the current buildings, leaving a critical gap in the comparative evaluation of multiple seismic force-resisting systems under real-world constraints.

This study addresses these gaps by conducting a comprehensive investigation of four widely used seismic force-resisting systems in Erbil's tall buildings. The selection of these systems—dual systems with special moment frames, special reinforced concrete moment frames, reinforced concrete ductile coupled walls, and special reinforced concrete shear walls—is justified by their frequent use in high-rise construction across the city. These systems are commonly employed in the region due to their effectiveness in resisting lateral forces and their adaptability to the architectural demands of tall buildings. However, local designers often apply these systems without fully considering their height limitations or conducting the necessary nonlinear validations required by international codes such as ASCE 7 and ACI 318. This practice can lead to potential vulnerabilities in the seismic performance of tall buildings, particularly in a seismically active region like Erbil. Each system offers distinct advantages in terms of stiffness, ductility, and energy dissipation, which are key to managing seismic forces effectively. By evaluating and comparing these systems under the same geometric and seismic parameters, this research aims to provide valuable insights for both design professionals and policymakers. The findings will highlight the importance of adhering to height restrictions and conducting nonlinear analyses, contributing to safer and more resilient urban development in Erbil.

2. Research methodology and Scope

2.1 Scope and methodology

The primary objective as described before, it is for evaluation the seismic performance of four different seismic force-resisting systems that are commonly employed in high-rise buildings in Erbil city. These systems include Dual Systems with Special Moment Frames (Model 1), Special Reinforced Concrete Moment Frames (Model 2), Reinforced Concrete Ductile Coupled Walls (Model 3), and Special Reinforced Concrete Shear Walls (Model 4). The configuration of these models, as detailed in Table 1 and illustrated in Figure 2, represents typical structural systems used in the region, allowing for a comparative analysis of their efficacy in resisting seismic loads.

Table 1. List of Models [27].

Model No.	Seismic Force-Resisting System	Response Modification Coefficient, R	Overstrength Factor, Ω0	Deflection Amplification Factor, Cd	Hight Limit ASCE7
1	Dual Systems With Special Moment Frames	7	2.5	5.5	Not Limited
2	Special reinforced concrete moment frames	8	3	5.5	Not Limited
3	Reinforced concrete ductile coupled walls	8	2.5	8	160ft
4	Special reinforced concrete shear walls	5	2.5	5	160ft

The analysis is conducted using ETABS version 21.0.1 [26], a finite element-based commercial software widely recognized for its accuracy in structural analysis. For seismic loading and load combinations, the study adheres to the ASCE 7 standard [27], ensuring compliance with established guidelines. The design of the concrete structure follows the ACI 318-19 code [28], providing the necessary criteria for member sizing and reinforcement detailing. After a comprehensive analysis, members were designed and sized to meet both the minimum code requirements and the structural demands imposed by the seismic loads. Moreover, modal analysis been run on the ultimate model with stiffness modifiers according to ACI318 [28] for shear walls and columns 0.7 used, for beams 0.35 used, and for the slab 0.25 used.

A key consideration across all models is the uniformity of building geometry and seismic input, facilitating a direct comparison of the performance of different seismic force-resisting systems. The models share the same building length, width, height, and seismic force parameters, which are depicted in the design response spectrum shown in Figure 3. This approach ensures that the observed differences in seismic performance are attributable to the structural systems themselves rather than variations in building size or seismic intensity.

The building under consideration has 35 stories, with an 6-story podium. At the podium level, the building measures 66 meters in length and 41 meters in width, while the tower section measures 54 meters in length and 29 meters in width. The height of each story is 3.2 meters. In terms of material properties, the structure uses concrete with a compressive strength of 60 MPa and reinforcement steel with a tensile strength of 420 MPa. While the study assumes fixed material properties for concrete and reinforcement steel across all models for consistency, real-world conditions often introduce variability in these properties. Factors such as variations in local procurement, environmental exposure, and quality control during construction can significantly affect the mechanical performance of materials. In regions like Erbil, where construction practices and material sourcing may vary, understanding the potential impact of these variations is crucial. Fluctuations in concrete compressive strength or steel yield strength could influence key structural parameters, including stiffness, ductility, and energy dissipation capacity, ultimately affecting the seismic resilience of tall buildings. Future investigations could focus on sensitivity analyses to evaluate how variations in material properties might alter the seismic behavior of different force-resisting systems. Such studies would provide more realistic insights into structural performance under practical conditions and aid in developing design guidelines that account for local material variability. Incorporating probabilistic approaches and considering a range of material properties could further enhance the robustness of seismic design in Erbil's rapidly expanding skyline.

Seismic analysis is carried out using two widely accepted methodologies: the Equivalent Lateral Force Procedure (ELFP) and Modal Response Spectrum Analysis (MRSA). The seismic parameters for Erbil city are considered, including a short period spectral acceleration (Ss) value of 0.6 and a one-second period spectral acceleration (S1) value of 0.2, based on soil type D (stiff soil). These parameters result in a seismic design category D, which demands specific attention to design, detailing, and construction to ensure adequate seismic resilience. Buildings compared for the parameters like fundamental period of vibration, mass participation ratio, stiffness, tower displacement, and inter story drift ratio. Despite the seismic force 2 and 2.5 kN/m2 used as super imposed deadload and live load on the slabs respectively.

The seismic analysis in this study employs two widely recognized methods: the Equivalent Lateral Force Procedure (ELFP) and the Modal Response Spectrum Analysis (MRSA). ELFP, also known as the static method, is commonly used in seismic design due to its simplicity and ease of application. It involves applying a set of lateral forces to the structure, proportional to the building's mass and distribution along its height, based on a design response spectrum. This method is suitable for regular, low to medium-rise buildings but may produce conservative results for taller, irregular structures where higher-mode effects become significant. ELFP provides a straightforward means to estimate seismic base shear and distribute it along the height of the building in a manner consistent with code provisions such as ASCE 7 [3]. In contrast, MRSA is a dynamic analysis method that considers the contributions of multiple vibration modes, making it more suitable for tall or irregular buildings where higher modes significantly influence the response. The method calculates the dynamic response of a structure by combining the modal responses obtained from a design response spectrum. MRSA provides a more refined estimation of parameters such as base shear, story drift, and displacement compared to ELFP, resulting in more accurate predictions of seismic behavior. Because MRSA accounts for dynamic effects and varying modal contributions, it is frequently used in the design of high-rise and complex structures in seismic-prone regions [33]. The use of both methods in this study ensures a comprehensive analysis, allowing for the comparison of static and dynamic results under consistent seismic input. References to ASCE 7 [3] and established structural analysis guidelines [29-33] provide the basis for selecting these methods and interpreting the results.

The structural members are sized in accordance with the ACI 318 code [28], supplemented by industry best practices and "rule-of-thumb" guidelines for core and shear wall dimensions, which were applied before running the analysis.

While this study provides a detailed analytical investigation of seismic performance using well-established codes and guidelines (ASCE 7 and ACI 318), it is acknowledged that the absence of real-world data or experimental validation introduces limitations regarding the accuracy of the results. Calibration of analytical models against experimental or field data is critical for ensuring that the assumptions, boundary conditions, and material behaviors accurately reflect real-world performance. However, due to the unavailability of comprehensive experimental data specific to Erbil's seismic conditions and structural systems, direct validation was not feasible within the scope of this research. Future work should include experimental testing on scaled physical models or monitoring of actual tall buildings during seismic events to validate and refine the analytical models. Such efforts could enhance confidence in the modeling process by providing a basis for comparison, ensuring that the simulated results reliably represent the behavior of real structures. Additionally, collaboration with local construction and research institutions could facilitate data collection and foster further studies focused on structural health monitoring and post-seismic performance assessments in Erbil's rapidly evolving urban environment.

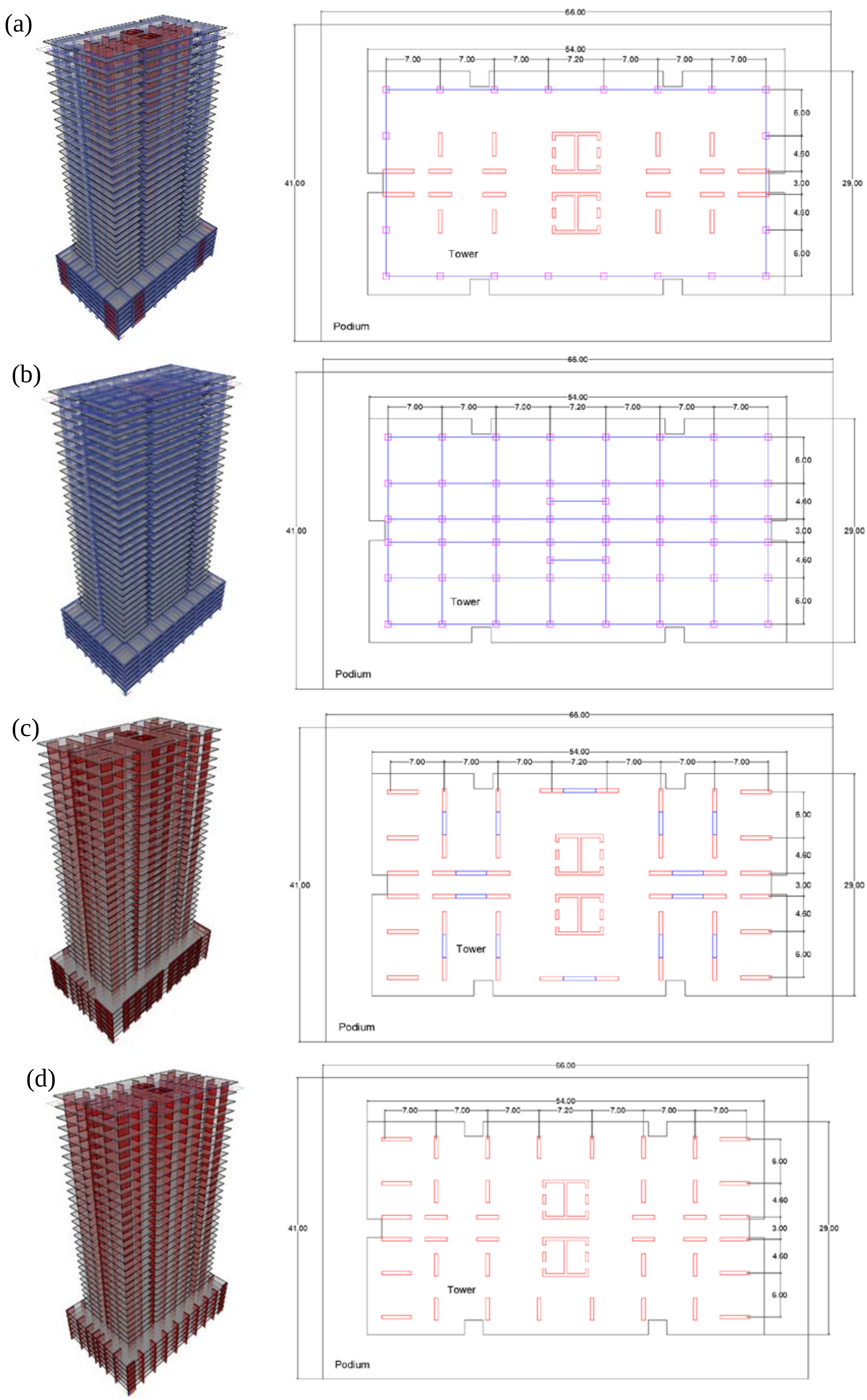


Figure 2. 3D View & Layouts, (a) Model 1, (b) Model 2, (c) Model 3, and (d) Model 4.

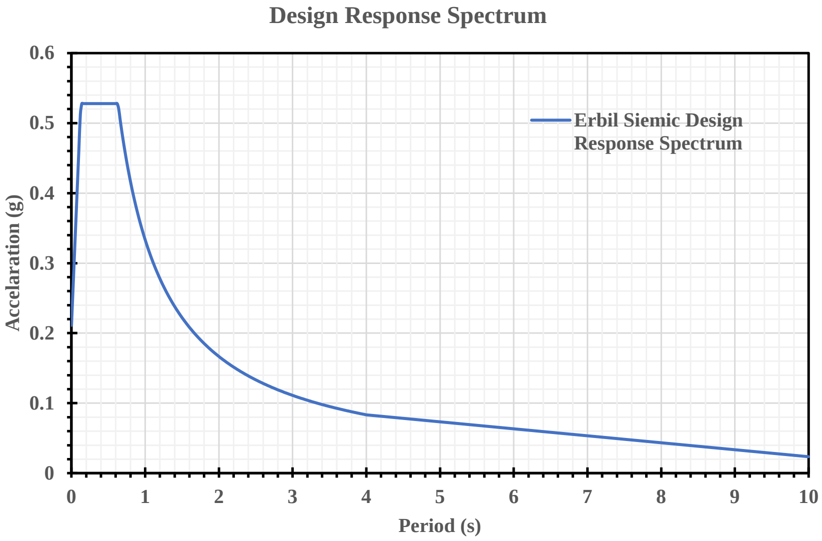


Figure 3. Erbil City Design Response Spectrum.

2.2 Model descriptions

In model 1 Dual Systems with Special Moment Frames (SMFS), the seismic load is resisted by a combination of shear walls and SMFS. According to the design requirements, at least 25% of the base shear generated by the earthquake is resisted by the SMFS, while the rest is carried by the shear walls. At the podium level the perimeter at the podium level consists of square columns with a side length of 1000mm, along with eight shear walls, each 600mm thick. These shear walls are connected by beams that measure 800mm in width and 1000mm in depth. At the tower level: The tower perimeter is supported by SMFS, with columns at the corners having square sections of 1200mm side length. Along the building’s length, columns from the 1st to the 25th story have a square section of 1000mm, while from the 26th to the 35th story, the column size reduces to 800mm. Columns along the building’s width are rectangular, with dimensions of 800mm in width and 1200mm in length. These columns are interconnected by beams that are 800mm wide and 1000mm deep. Inside the tower, shear walls are placed strategically to provide lateral support, with two core walls running through the entire height of the building, each with a thickness of 400mm.

In model 2 Special Reinforced Concrete Moment Frames , only beams and columns are used to resist both gravity and lateral loads without any shear walls. At the podium level the perimeter is made up of square columns with 1000mm side lengths, connected by beams with a width of 800mm and a depth of 1000mm. At the tower level the perimeter columns in the tower have a square section of 1200mm side length at the lower levels. From the 1st to the 6th story, rectangular columns are used, with dimensions of 1200mm by 800mm. From the 7th to the 25th story, the column size transitions to 1000mm square sections, and from the 26th to the 35th story, they reduce further to 800mm square sections. Along the width of the tower, rectangular columns of 800mm by 1200mm are maintained throughout the full building height. Internally, the tower has square columns of 1000mm from the 1st to the 25th story, which reduce to 800mm in the upper stories. All columns are interconnected with beams of 800mm width and 1000mm depth.

In model 3 Reinforced Concrete Ductile Coupled Wall system, seismic and gravity loads are resisted primarily by shear walls connected by coupling beams. At the podium level the perimeter shear walls at the podium level are 600mm thick, with coupling beams matching the wall thickness. At the tower level the tower contains coupled shear walls on both the north and south sides, each with a thickness of 600mm from the 1st to the 6th story. The thickness of the remaining shear walls reduces to 400mm from the 1st to the 35th story, while the core wall maintains a constant thickness of 600mm throughout the tower height. The coupling beams that link the shear walls have the same thickness as the walls, with a depth of 1200mm, enhancing the system's ductility and energy dissipation during seismic events.

In model 4 Special Reinforced Concrete Shear Walls uses only reinforced concrete shear walls to carry both gravity and lateral loads. At the podium level shear walls at the podium level have a thickness of 600mm, ensuring adequate lateral resistance. At the tower level the thickness of the shear walls varies with height. From the 1st to the 15th story, the walls are 600mm thick. From the 16th to the 25th story, the thickness reduces to 500mm, and from the 26th to the 35th story, the walls are further reduced to 400mm thick. The core wall remains at 600mm thickness throughout the entire height of the tower, providing robust resistance to lateral forces.

A critical aspect of seismic performance in tall buildings lies in the design and detailing of connections between structural elements. Proper detailing of beam-column joints, coupling beam-wall connections, and core wall reinforcements is essential to ensure ductility, energy dissipation, and overall stability during seismic events. In this study, each connection type was modeled and designed according to the provisions of ACI 318-19 and ETABS default design parameters, with particular attention to critical zones that are prone to high stress concentrations during seismic loading.

In moment-resisting frames, beam-column joints play a vital role in transferring moments and shear forces. These joints were detailed with special reinforcement to enhance their ductility and prevent premature failure. Confining reinforcement was provided around the joint core to resist shear forces induced by seismic loads and ensure stable behavior. The reinforcement detailing was based on seismic provisions, ensuring that the joints could sustain large deformations without significant degradation of strength or stiffness. In models incorporating coupled walls, coupling beams serve a dual purpose: they transfer lateral forces between adjacent walls and provide significant energy dissipation through controlled yielding. To ensure adequate ductility, the coupling beams were reinforced with diagonal bars, as recommended for high-seismic regions. This configuration allows the beams to undergo plastic deformations during seismic loading, thereby enhancing the system's ability to dissipate energy. The wall-beam interface was designed to ensure proper anchorage of the diagonal reinforcement into the walls, minimizing the risk of joint failure. Core walls, which provide the primary lateral resistance in certain models, were detailed with boundary elements at critical regions where high compressive and tensile stresses are expected during seismic events. Boundary elements were reinforced with closely spaced ties to prevent buckling of longitudinal reinforcement and ensure sufficient confinement. At the base of the core walls, where seismic demands are highest, additional reinforcement was provided to resist overturning moments and shear forces.

By incorporating these detailed connection designs, the models aim to replicate real-world structural behavior under seismic conditions. Future experimental validation of these connections would provide further insights into their performance and reliability, contributing to the development of more resilient seismic designs.

2.3 Study motivation

The motivation for this research arises from the prevalent use of flat slab construction with special reinforced concrete shear walls in high-rise buildings in Erbil city. Despite its widespread adoption, this construction method may not fully comply with the ASCE 7 code without thorough validation through nonlinear analysis. Nonlinear analysis is a method used to assess the behavior of structures under loads that may cause nonlinear responses. Unlike linear analysis, which assumes that the relationship between loads and displacements is proportional and constant, nonlinear analysis considers changes in stiffness, strength, and geometry of the structure as it deforms. This is particularly important for structures subjected to large deformations or in materials that exhibit nonlinear behavior. By conducting a comprehensive analysis of these different seismic force-resisting systems, the study aims to provide critical insights into their structural performance, particularly in relation to the specific seismic conditions of Erbil. The findings of this research will provide crucial insights for design professionals and stakeholders, aiding in the informed selection and design of suitable seismic force-resisting systems for tall buildings in earthquake-prone areas. These insights will contribute to enhancing the structural resilience and safety of buildings, ensuring better preparedness and performance during seismic events.

In Erbil and Iraq, there are no updated local building codes, and the previous regulations are outdated. As a result, it is common practice for construction projects to follow international standards such as ASCE 7 and ACI 318, which are widely recognized for their robustness and reliability in seismic design. Academic studies and engineering education in the region are also primarily based on these international codes, further reinforcing their adoption in professional practice. This study is aligned with this common practice, as it uses ASCE 7 and ACI 318 as the basis for seismic analysis and design. By evaluating the seismic performance of commonly used structural systems under these standards, the findings of this study are directly applicable to local construction practices in Erbil and Iraq, contributing to safer and more resilient urban development in the region.

2.4 Modeling assumptions and limitations

The ETABS models used in this study were based on several key assumptions, which are consistent with common engineering practices but may influence the results:

1) Material Nonlinearity:

The analysis assumed linear elastic material behavior for concrete and reinforcement steel, as defined by the ACI 318-19 code. While this simplification allows for a straightforward comparison of the seismic performance of the four systems, it does not account for the energy dissipation and ductility that occur during inelastic deformations under seismic loading. As a result, the analysis may provide conservative estimates of displacements and forces.

2) Damping Ratios:

A damping ratio of 5% was assumed for all models, which is a typical value for reinforced concrete structures under seismic loading, as recommended by ASCE 7. This assumption is based on the expected energy dissipation characteristics of reinforced concrete systems. However, the actual damping ratio may vary depending on factors such as cracking, material degradation, and nonstructural elements. A sensitivity analysis could be conducted in future work to evaluate the impact of varying damping ratios on the seismic response.

3) Connections Between Shear Walls and Slabs:

The connections between shear walls and slabs were modeled as rigid, assuming full composite action between the two elements. This assumption simplifies the modeling process and is generally conservative for seismic design. However, in reality, the connection behavior may exhibit some flexibility, which could influence the distribution of forces and the overall seismic performance. Future studies could explore the effects of semi-rigid or flexible connections to better understand their impact on the results.

These assumptions were made to align with common engineering practices and simplify the analysis. However, they may influence the results in the following ways:

1) The linear elastic material assumption may underestimate the energy dissipation capacity of the structures, leading to conservative estimates of displacements and forces.

2) The assumed damping ratio of 5% may not fully capture the energy dissipation characteristics of the structures under severe seismic loading, potentially affecting the accuracy of the dynamic response.

3) The rigid connection assumption between shear walls and slabs may overestimate the stiffness of the system, leading to lower displacement and drift values compared to a more flexible connection model.

While these assumptions provide a reasonable basis for comparing the seismic performance of the four systems, future work could incorporate nonlinear material models, sensitivity analyses for damping ratios, and more detailed connection modeling to further refine the results.

The seismic analysis in this study was conducted using soil type D (stiff soil), as defined by ASCE 7. This assumption is based on the general characteristics of soil conditions in regions where site-specific geotechnical data are not readily available. While this provides a reasonable basis for the analysis, we acknowledge that Erbil-specific soil characteristics were not explicitly considered due to the lack of detailed geotechnical data for the region.

The omission of Erbil-specific soil conditions may impact the findings in the following ways:

1) Site Amplification Effects: Different soil types can amplify or deamplify seismic waves, affecting the intensity of ground motion experienced by the structure. If the actual soil conditions in Erbil differ significantly from the assumed soil type D, the seismic demands on the structure could be either overestimated or underestimated.

2) Foundation Behavior: Soil-structure interaction (SSI) effects, which are influenced by local soil conditions, can alter the dynamic response of the structure. The rigid base assumption used in this study may not fully capture the flexibility and energy dissipation characteristics of the foundation system, potentially affecting the accuracy of the results.

To address these limitations, future studies could incorporate site-specific geotechnical data and consider soil-structure interaction effects to provide a more accurate representation of the seismic performance of tall buildings in Erbil. This would enhance the applicability of the findings to the local context and improve the overall reliability of the analysis.

In this study, a "tall" building was defined as a 35-story structure with a total height of approximately 112 meters, assuming a typical story height of 3.2 meters. All four models were evaluated at the same height to ensure a direct comparison of their seismic performance under identical geometric and loading conditions. This approach allows for a clear assessment of the relative strengths and weaknesses of each system in managing seismic forces for tall buildings.

While the results of this study are specific to 35-story buildings, they can provide insights into the performance of the systems for buildings of slightly different heights:

1) Shorter Buildings (e.g., 10–20 stories): For shorter buildings, systems such as special reinforced concrete shear walls (Model 4) or reinforced concrete ductile coupled walls (Model 3) may become more viable due to their lower cost and sufficient stiffness for low- to mid-rise structures. The seismic demands on shorter buildings are generally lower, which may reduce the need for the enhanced ductility and energy dissipation provided by dual systems (Model 1).

2) Exceptionally Tall Buildings (e.g., >40 stories): For exceptionally tall buildings, dual systems (Model 1) remain the most reliable option due to their ability to manage higher-mode effects and large lateral displacements. However, additional design considerations, such as the use of outriggers or belt trusses, may be necessary to further enhance stability and reduce drift.

The findings of this study are most applicable to buildings within the studied height range, but they can be extended to buildings of slightly different heights with appropriate adjustments. Future studies could explore the performance of these systems for a wider range of building heights to provide more comprehensive guidance.

3. Results and discussion

3.1 Stiffness

The comparative analysis of the four seismic force-resisting systems highlights the significant differences in base stiffness and how they relate to the structural height limitations as specified in ASCE 7. Figure 4 showing the stiffness change according to the height of the tower. Additionally, the base stiffness comparison for all models is depicted in Figure 5. Model 1, which represents Dual Systems with Special Moment Frames, demonstrates the highest base stiffness in both the X and Y directions, measured at 62.7×10^6 and 72.1×10^6, respectively. This elevated stiffness is primarily due to the combined contribution of moment frames and shear walls, which effectively control lateral displacements and enhance energy dissipation. The integration of special moment frames adds significant ductility to the system, enabling it to withstand greater inelastic deformations during seismic events. As a result, Model 1 is not restricted by height limitations under ASCE 7, owing to the system's high redundancy and ductility, ensuring stability and resilience even for tall buildings.

In contrast, Model 2, which represents Special Reinforced Concrete Moment Frames, shows the lowest base stiffness values, with 18.0×10^6 in the X direction and 20.9×10^6 in the Y direction. Despite the reduced stiffness compared to Model 1, Model 2 is also exempt from height restrictions under ASCE 7, primarily due to the significant ductility of moment frames. These frames are capable of undergoing large deformations without compromising their load-bearing capacity. Their flexibility allows for effective control of lateral drifts, making them well-suited for high-rise buildings. Moreover, moment frames excel at managing higher-mode effects, which are critical in taller buildings, further validating the lack of height restrictions.

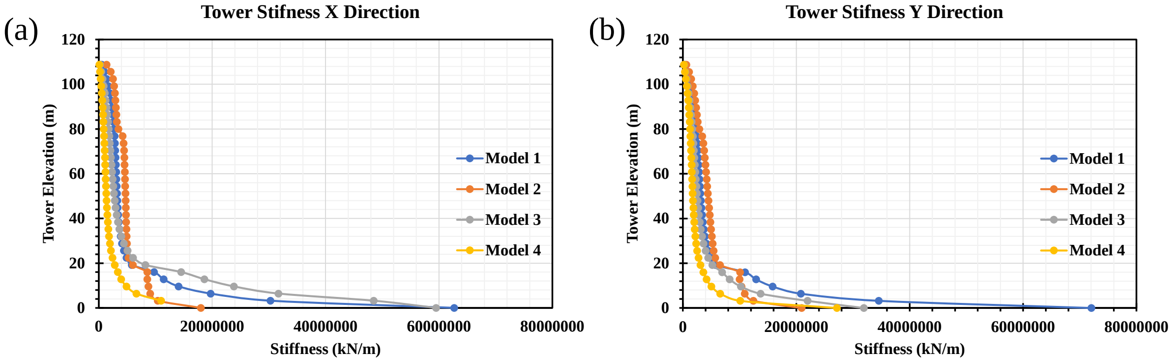


Figure 4. Tower Stiffness, (a) X-Direction, and (b) Y-Direction.

Model 3, representing Reinforced Concrete Ductile Coupled Walls, exhibits intermediate stiffness values of 59.5×10^6 in the X direction and 31.9×10^6 in the Y direction. While coupled walls provide reasonable stiffness, they do not match the energy dissipation capacity of dual systems or moment frames. The system’s dependence on stiffness for controlling lateral displacements restricts its ability to handle higher-mode effects and large drifts in taller structures. This limitation leads to the 160 ft height restriction imposed by ASCE 7. Additionally, the increased shear demand and the need for enhanced reinforcement in taller buildings make it challenging for this system to be employed beyond that height.

Finally, Model 4, representing Special Reinforced Concrete Shear Walls, has lower stiffness values of 27.6×10^6 in the X direction and 27.2×10^6 in the Y direction. Though shear walls are effective for resisting lateral forces in shorter buildings, this system is also constrained by the 160 ft height limit under ASCE 7. Compared to moment frames, shear walls offer reduced ductility and energy dissipation, making them less suitable for taller structures. Furthermore, their reliance on stiffness for controlling displacements in tall buildings increases the risk of excessive P-delta effects, which could cause structural instability during significant seismic events. The shear demand and reinforcement requirements also increase in taller buildings, complicating design and construction for heights beyond the specified limit.

As a result, the height limitations imposed by ASCE 7 on Models 3 and 4 are directly related to their lower redundancy, energy dissipation and ductility compared to Models 1 and 2. Dual Systems with Special Moment Frames and Special Reinforced Concrete Moment Frames are not subject to height restrictions due to their high seismic performance, which includes better handling of lateral displacements, higher-mode effects, and P-delta effects, making them ideal for use in tall buildings.

The lower ductility of shear walls (Model 4) compared to other systems is primarily due to their inherent structural behavior and design characteristics, rather than material choices. Shear walls are designed to provide high stiffness and lateral resistance, which makes them effective in controlling lateral displacements and reducing building sway. However, this high stiffness comes at the cost of reduced ductility, as shear walls are less capable of undergoing large inelastic deformations without significant loss of strength.

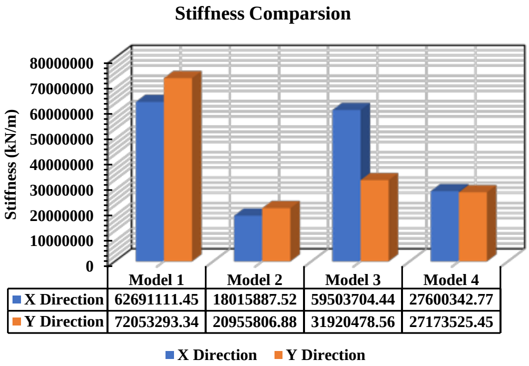


Figure 5. Tower Stiffness Comparison.

3.2 Modal structural analysis

The modal analysis results of the four seismic force-resisting systems provide valuable insights into their dynamic characteristics as illustrated in Table 2 and Figure 6, particularly the fundamental periods of vibration and mass participation ratios across the first three modes. Model 1 and Model 2, which correspond to dual systems with special moment frames and special reinforced concrete moment frames, respectively, exhibit relatively short fundamental periods, with values of 3.15s and 3.11s for the first mode. At first glance, these short periods suggest stiffer behavior, as structures with shorter periods are typically more resistant to deformation under dynamic loads. However, this assumption doesn't hold entirely true for Model 2. Despite having the shortest fundamental period, Model 2 demonstrates the lowest stiffness, indicating that the fundamental period of vibration is influenced not only by stiffness but also by factors such as member sizes, mass distribution, and structural configuration. This finding highlights that stiffness alone is not a direct indicator of the fundamental period.

Table 2. Modal Analysis Results.

Mode			1	2	3
Model 1	Period		3.15	3.08	2.00
	Mass Participation Ratio	UX	0%	58%	0%
		UY	57%	0%	0%
		RZ	0%	0%	45%
Model 2	Period		3.11	3.08	2.72
	Mass Participation Ratio	UX	0%	68%	0%
		UY	64%	0%	0%
		RZ	0%	0%	55%
Model 3	Period		3.59	3.33	2.84
	Mass Participation Ratio	UX	0%	55%	0%
		UY	58%	0%	0%
		RZ	0%	0%	47%
Model 4	Period		4.95	4.36	3.68
	Mass Participation Ratio	UX	58%	0%	0%
		UY	0%	61%	0%
		RZ	0%	0%	56%

In contrast, Model 4, which utilizes special reinforced concrete shear walls, demonstrates the longest fundamental period at 4.95s, indicating a more flexible structural behavior, as expected from a system with lower stiffness values. The fundamental period of Model 3, associated with reinforced concrete ductile coupled walls, falls between the stiffer Model 1 and the more flexible Model 4, with a period of 3.59s for the first mode, reflecting an intermediate balance of stiffness and flexibility.

The mass participation ratios further illustrate the differences in structural behavior among the models. In Mode 1, Models 1, 2, and 3 show dominant participation in the UY direction, with values ranging from 57% to 64%, indicating that lateral movement in the transverse direction governs the dynamic response of these systems. Conversely, Model 4 exhibits significant participation in the UX direction (58%) for Mode 1, suggesting that lateral motion in the longitudinal direction is the primary mode of response for this system. This distinction in mass participation ratios underscores the varying distribution of dynamic loads among the systems. Models 1 through 3 are predominantly influenced by transverse lateral forces in the early modes, which highlights their reliance on lateral stiffness to control displacements. In contrast, Model 4 is more susceptible to longitudinal movements, indicating that its dynamic response is governed by different modes of vibration. This difference affects how each system manages seismic forces, with Models 1 through 3 better suited for controlling lateral drifts, while Model 4 may require additional considerations for longitudinal stability under seismic loading.

In Mode 2, Model 2 exhibits the highest UX participation (68%), closely followed by Model 1 and Model 3 at 58% and 55%, respectively. This indicates that in the second mode, horizontal motion along the UX direction is the dominant dynamic response in these systems. However, Model 4 once again deviates, showing significant UY participation (61%) rather than UX. This suggests that while Models 1, 2, and 3 experience more uniform dynamic behavior with high UX participation in both the second and third modes, Model 4 exhibits distinct behavior, with its second mode dominated by UY motion. The differences in mass participation ratios between UX and UY across the models indicate that each system will respond differently under seismic excitation, depending on the direction of the applied forces.

In the third mode, all models show substantial rotational mass participation in the RZ direction. Models 1 and 3 exhibit RZ participation ratios of 45% and 47%, respectively, while Model 2 and Model 4 reach even higher values of 55% and 56%. This indicates that rotational modes become increasingly dominant as the systems progress through higher modes. The elevated rotational response in Model 4, combined with its longer periods, suggests a more flexible and potentially torsionally active structure compared to the other systems. The findings highlight the importance of accounting for both lateral and rotational responses when assessing seismic force-resisting systems, particularly since models with higher RZ participation in higher modes may be prone to significant torsional effects during seismic activity. Model 4 (special reinforced concrete shear walls) stands out as the most flexible, exhibiting the longest periods and distinctive mass participation in both the UX and RZ directions. This flexibility contrasts with Models 1, 2, and 3, which are generally stiffer and have shorter periods. However, Model 2 presents an intriguing exception—despite its lower stiffness, its period does not significantly increase, suggesting that factors such as mass and member sizing also play a key role in the dynamic response.

This comparison underscores the diverse dynamic behaviors of different seismic force-resisting systems, with each model offering unique advantages depending on the structural objectives and the seismic demands of a given project. The results of this analysis have important implications for seismic performance, particularly in selecting the most suitable system based on design priorities such as flexibility, stiffness, and torsional resistance.

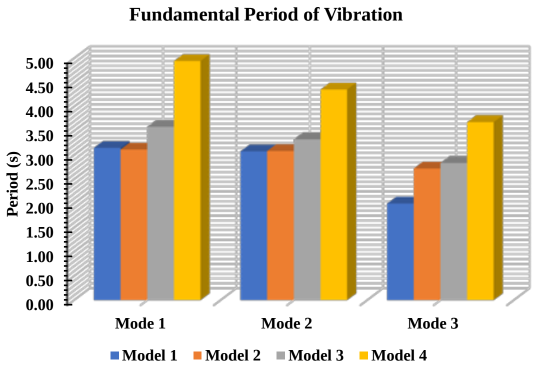


Figure 6. Fundamental Period of Vibration chart for all models.

3.3 Top story displacement and inter-story drift ratios

The tower displacement analysis offers valuable insights into the seismic performance of the studied models in both the X and Y directions, as illustrated in Figures 7 and 8.

This evaluation focuses on the top story displacements and inter-story drift ratios of the four structural models, analyzed using both Modal Response Spectrum Analysis (MRSA) and the Equivalent Lateral Force Procedure (ELFP). These metrics are essential for assessing the seismic resilience of each model and understanding how different analytical approaches impact structural behavior. The maximum displacement values obtained from ELFP and MRSA highlight each model's capacity to mitigate displacement during seismic events. These results, depicted in Figure 9, provide crucial information on the models' overall performance under seismic loads, particularly in terms of lateral displacement and drift.

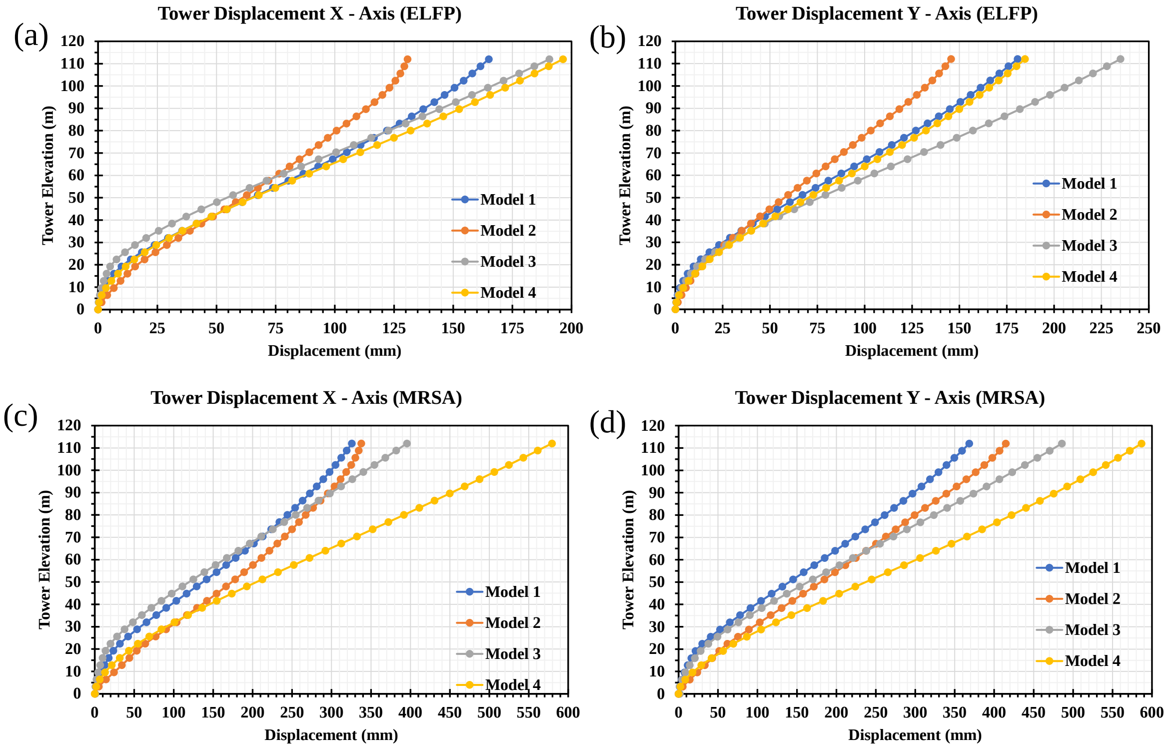


Figure 7. Tower Displacement, (a) EFLP-X, (b) ELFP-Y, (c) MRSA-X, and (d) MRSA-Y.

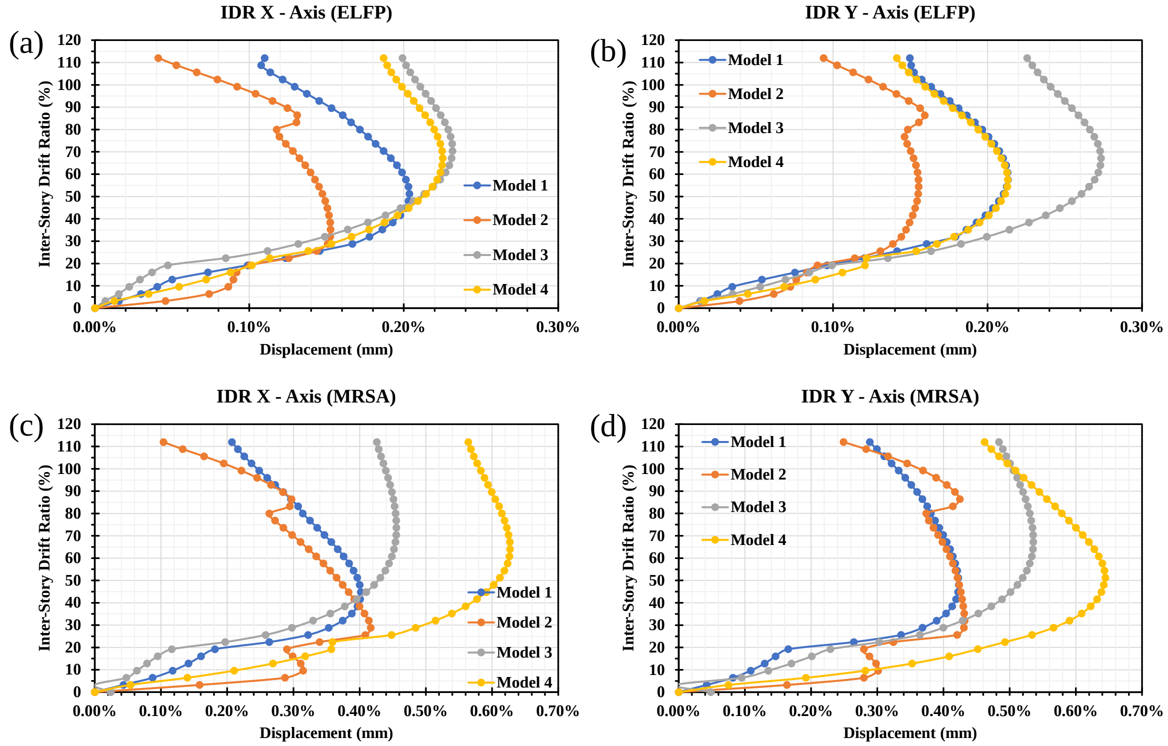
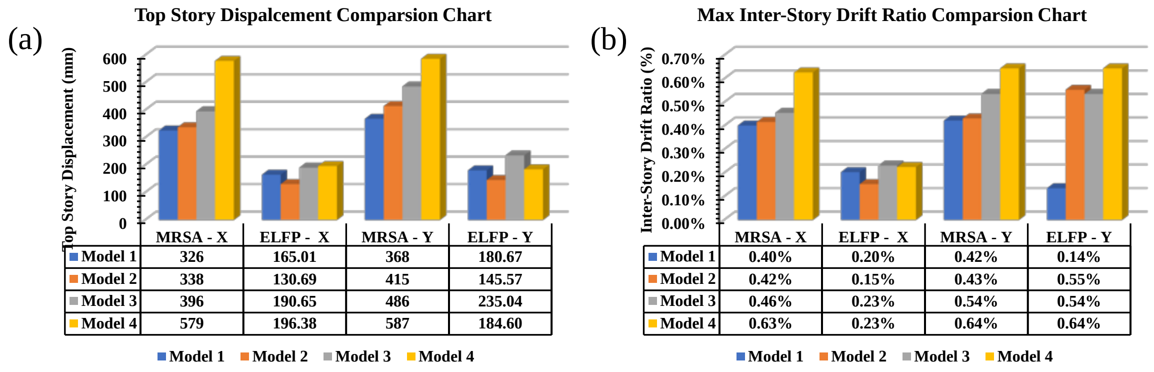


Figure 8. Inter-Story Drift Ratio, (a) EFLP-X, (b) ELFP-Y, (c) MRSA-X, and (d) MRSA-Y.

A significant finding is the notable differences between the two analysis methods. Model 1, for example, experiences a top story displacement of 326 mm in the X direction and 368 mm in the Y direction under MRSA, while under ELFP, these values are substantially lower—165.01 mm and 180.67 mm, respectively. This discrepancy indicates that MRSA tends to yield more conservative estimates of displacement, possibly revealing greater vulnerability to seismic forces when compared to ELFP. This difference underscores the importance of selecting the appropriate analysis method to accurately capture the seismic response of tall buildings. Model 2 shows a similar pattern, with MRSA predicting a displacement of 338 mm in the X direction, 415mm in the Y direction, while ELFP records significantly lower values of 130.69 mm (X) and 145.57 mm (Y). The pronounced difference in displacement predictions between the two methods emphasizes the critical impact of the chosen analytical approach on the perceived seismic response of the structure. For Model 3, the MRSA results of 396 mm (X) and 486 mm (Y) further highlight the trend, contrasting with the ELFP displacements of 190.65 mm (X) and 235.04 mm (Y). Model 4 reveals the highest displacements across all models, with MRSA indicating 579 mm (X) and 587 mm (Y), while ELFP reports 196.38 mm (X) and 184.60 mm (Y). The significant differences in predictions underscore the importance of analysis method choice in assessing the seismic performance of structure.

When comparing the results despite the ELFP in Y direction, displacement results showing the pattern that that displacement in minimum for the Model 1 then Model 2 and it is increased until Model 4 in sequence, which is showing the performance of the systems as described in ASCE7. As the result Model 1 have better performance in mitigating displacement during seismic events in both directions compared to the other models. Model 4 shows higher maximum displacement values in both directions, indicating that it is more susceptible to displacement under seismic loads compared to Model 3.

Inter-story drift ratios remain crucial for evaluating structural integrity under seismic loads. All models demonstrate compliance with ASCE 7 limits. For Model 1, the inter-story drift ratios are 0.40% (MRSA - X), 0.20% (ELFP - X), 0.42% (MRSA - Y), and 0.14% (ELFP - Y). In Model 2, the ratios are 0.42% (MRSA - X), 0.15% (ELFP - X), and 0.43% (MRSA - Y), with a notably higher ELFP ratio of 0.55% in the Y direction. For Model 3, inter-story drift ratios of 0.46% (MRSA - X), 0.23% (ELFP - X), and 0.54% (both MRSA and ELFP - Y). Model 4 presents the highest ratios at 0.63% (MRSA - X) and 0.64% (ELFP - Y), while the ELFP value for the X direction and the MRSA value for the Y direction are both 0.23%. Despite the observed variance between MRSA and ELFP displacement values, all results remain within acceptable limits as defined by relevant seismic design codes, affirming the robustness of the structural design. The top story displacements and inter-story drift ratios for all models comply with the thresholds established in ASCE 7 and other applicable standards, ensuring the structural integrity of the buildings under anticipated seismic loads. This compliance reinforces the effectiveness of the selected seismic force-resisting systems in controlling displacements, mitigating drift, and maintaining overall stability during seismic events, ultimately contributing to the safety and resilience of the structures.



	MRSA - X	ELFP - X	MRSA - Y	ELFP - Y
Model 1	326	165.01	368	180.67
Model 2	338	130.69	415	145.57
Model 3	396	190.65	486	235.04
Model 4	579	196.38	587	184.60

	MRSA - X	ELFP - X	MRSA - Y	ELFP - Y
Model 1	0.40%	0.20%	0.42%	0.14%
Model 2	0.42%	0.15%	0.43%	0.55%
Model 3	0.46%	0.23%	0.54%	0.54%
Model 4	0.63%	0.23%	0.64%	0.64%

Figure 9. (a) Maximum Top Story Displacement, and (b) Maximum Inter-Story Drift Ratio.

The results of the tower displacement and inter-story drift ratio analysis highlight the varying performance of the studied models in mitigating displacement under seismic loads in both the X and Y directions. Model 1 and Model 2 generally exhibit lower maximum displacement values, suggesting better performance in mitigating displacement, while Model 3 and Model 4 show higher maximum displacement values, indicating relatively poorer performance, moreover dynamic analysis shows that Model 1 have best performance for seismic analysis that is why made him allowable by most of the codes and standards for using in tall buildings. These findings are important in understanding the behavior and performance of each model under seismic loads and can assist in making informed decisions for designing earthquake-resistant tall buildings. It is crucial to consider these displacement results, along with other structural performance indicators, in the design and selection of appropriate seismic force-resisting systems to ensure the safety and stability of tall buildings during seismic events.

3.4 Story shear and overturning moment

The seismic performance of the structures is directly influenced by the design configurations and structural systems employed, which significantly shape their responses to seismic loads. In this study, the distinct structural configurations of the four models offer valuable insights into their ability to resist seismic forces. A comparative analysis of base shear (Figure 10) and overturning moment (Figure 11) reveals important distinctions between the systems, highlighting their relative strengths and weaknesses.

Model 1 features a dual system that combines the advantages of special reinforced concrete moment frames and shear walls. This configuration provides both enhanced ductility and high lateral stiffness, which enables the structure to dissipate seismic energy effectively. The results show that Model 1 has a base shear of 23,852.14 kN in the X direction and 23,853.04 kN in the Y direction under the Equivalent Lateral Force Procedure (ELFP), while the Modal Response Spectrum Analysis (MRSA) produces much higher base shear values of 85,553.77 kN in the X direction and 87,907.88 kN in the Y direction. Similarly, the overturning moments are significantly higher under MRSA, with values of 4,032,930.39 kN·m in the X direction and 3,935,872.27 kN·m in the Y direction. These results underscore the effectiveness of Model 1's dual system in handling high seismic forces through a balanced combination of stiffness and ductility.

Model 2, designed with special reinforced concrete moment frames, demonstrates a different load distribution mechanism that emphasizes flexibility and energy dissipation. The base shear results for Model 2 are 25,188.07 kN in the X direction and 25,149.57 kN in the Y direction under ELFP, while MRSA reveals significantly higher shear forces of 93,510.20 kN in the X direction and 99,082.66 kN in the Y direction. The overturning moments follow a similar pattern, with MRSA indicating values of 5,134,751.63 kN·m in the X direction and 4,962,700.50 kN·m in the Y direction. The results highlight the moment frames' ability to dissipate seismic energy, though they tend to experience higher base shear and overturning moments, which reflect the challenges associated with relying solely on moment frames for seismic resistance. While effective, Model 2 shows a greater susceptibility to increased demand in both base shear and moment forces compared to the dual system used in Model 1.

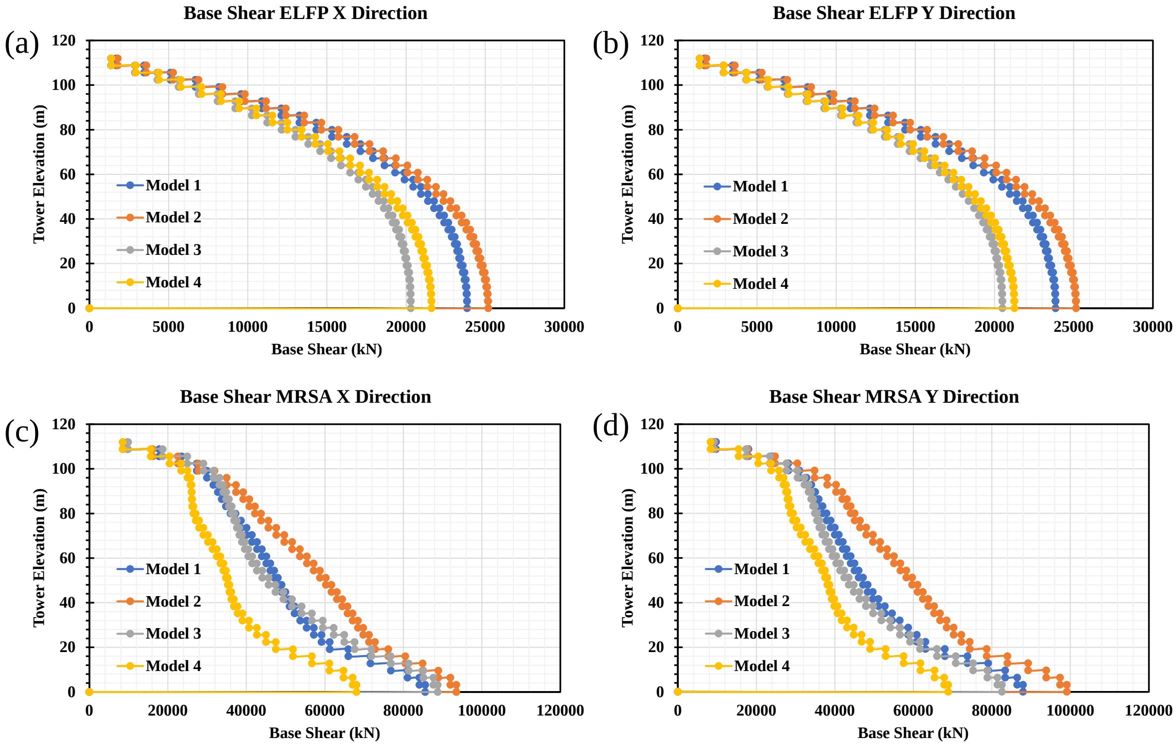


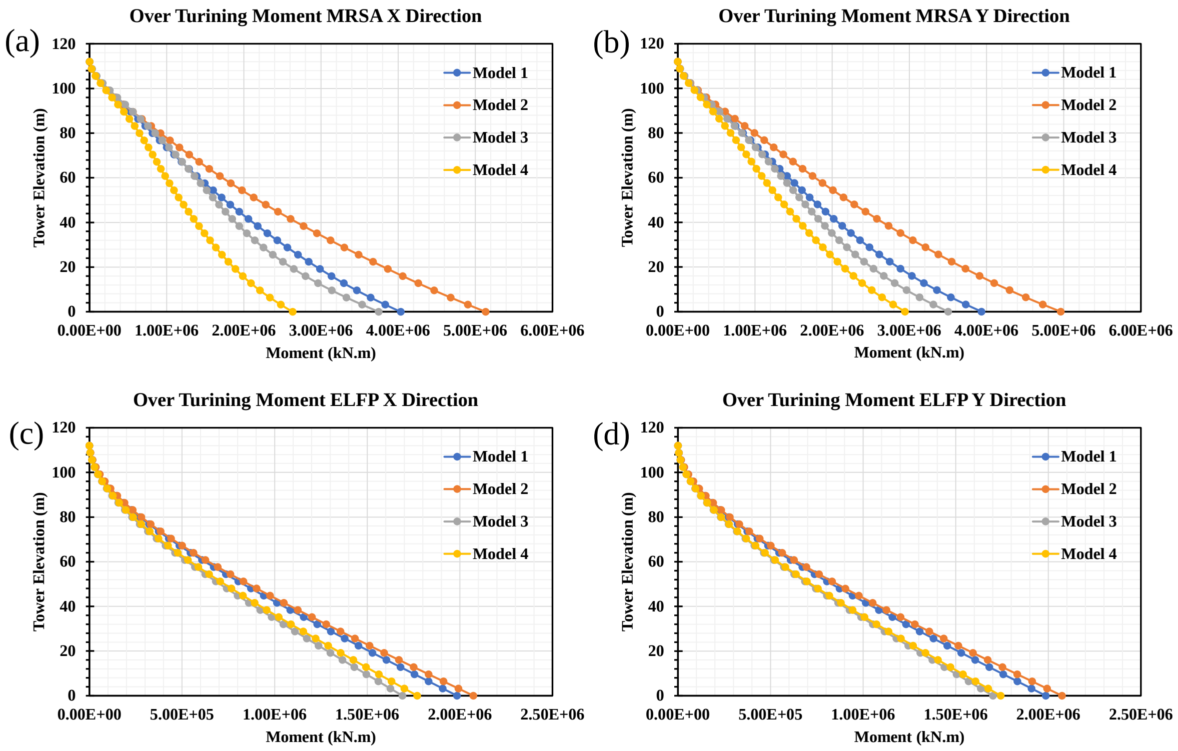
Figure 10. Base Shear, (a) EFLP-X, (b) ELFP-Y, (c) MRSA-X, and (d) MRSA-Y.

In Model 3, the structural system incorporates ductile coupled walls, which enhance lateral load resistance through their stiffness and energy dissipation characteristics. These walls are effective in controlling lateral displacements, which is critical for maintaining stability during seismic events. However, the results indicate lower base shear values compared to the moment frame systems, with ELFP yielding 20,293.61 kN (X) and 20,500.46 kN (Y), while MRSA predicts base shear values of 88,763.90 kN (X) and 82,582.36 kN (Y). The overturning moments are also lower, with MRSA showing 3,747,516.84 kN·m (X) and 3,502,985.86 kN·m (Y). This suggests that while coupled walls provide effective lateral resistance, their overall energy dissipation capacity may not match that of moment frame systems in taller buildings.

Model 4 incorporates special reinforced concrete shear walls, which are intended to provide high stiffness and lateral stability. However, this model encounters challenges at greater heights due to inherent stiffness limitations, resulting in increased lateral drift under seismic loads. The analysis indicates that Model 4 exhibits base shear values of 21,608.05 kN in the X direction and 21,255.09 kN in the Y direction under the Equivalent Lateral Force Procedure (ELFP). Conversely, the Modal Response Spectrum Analysis (MRSA) predicts lower shear forces of 68,062.16 kN in the X direction and 68,851.24 kN in the Y direction. The overturning moments, recorded under MRSA, show values of 2,631,749.32 kN·m in the X direction and 2,944,572.80 kN·m in the Y direction. These findings suggest that while shear walls are effective in resisting lateral forces, they may not perform as efficiently as moment frames or dual systems in scenarios of high seismic demand.

The comparison of structural systems across the four models emphasizes the substantial impact that design choices have on seismic load responses. The dual systems, particularly in Model 1, offer a well-balanced approach to energy dissipation and lateral stability, resulting in favorable performance metrics in terms of both base shear and overturning moment. In contrast, while models relying solely on moment frames (Model 2) or shear walls (Models 3 and 4) exhibit distinct strengths in certain aspects of performance, they also reveal limitations that may compromise their effectiveness during extreme seismic events. These insights highlight the critical importance of selecting appropriate structural systems tailored to anticipated seismic demands, especially for taller buildings situated in high seismic zones. The analysis demonstrates that incorporating a combination of structural elements, such as dual systems, can enhance overall performance and resilience against seismic forces, ensuring that buildings can withstand significant lateral movements and maintain structural integrity.

The evaluation of seismic performance indicates notable distinctions between structural systems that are not limited by height, such as Dual Systems with Special Moment Frames and Special Reinforced Concrete Moment Frames, compared to those that face height restrictions, like Reinforced Concrete Ductile Coupled Walls and Special Reinforced Concrete Shear Walls. The absence of height constraints in the former group can be attributed to several important design advantages and behaviors under seismic loading. These systems are particularly characterized by high ductility, enabling them to endure significant inelastic deformations without considerable loss of strength. This property plays a vital role in effectively dissipating seismic energy, as moment frames can absorb and redistribute forces along their height, which helps reduce the likelihood of brittle failure.


Over Turining Moment MRSA X Direction

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Over Turining Moment ELFP X Direction

Over Turining Moment ELFP Y Direction

Figure 11. Over Turning Moment, (a) EFLP-X, (b) ELFP-Y, (c) MRSA-X, and (d) MRSA-Y.

Moreover, the redundancy found in Dual Systems improves their performance in seismic events. The integration of shear walls and moment frames creates an efficient system for managing lateral displacements, ensuring that if one component fails, others can still uphold the structural integrity. This redundancy not only enhances overall effectiveness but also offers increased architectural versatility, allowing for more extensive open spaces, which are often crucial in contemporary tall building designs. Furthermore, the stringent detailing requirements set forth in standards such as ASCE 7 and ACI 318 bolster the durability of these systems, guaranteeing their effective operation even in regions with high seismic activity.

Conversely, the height limitations applied to Reinforced Concrete Ductile Coupled Walls and Shear Walls arise from issues related to seismic ductility and stability. As structures grow taller, it becomes progressively more difficult to maintain uniform ductility throughout, especially under the increasing demands for lateral displacement. These systems also face significant P-Delta effects, which can induce instability during intense seismic events. Additionally, the effects of higher modes can amplify forces and accelerations, further undermining the ability of shear walls to control lateral movement in taller buildings. Therefore, these considerations necessitate the imposition of height restrictions to ensure safety and maintain structural integrity in high-rise constructions subjected to seismic forces.

4. Conclusions

This research presents a comparative analysis of the seismic performance of four distinct seismic force-resisting systems utilized in tall buildings located in Erbil City. The evaluated systems encompass dual systems with special moment frames, special reinforced concrete moment frames, reinforced concrete ductile coupled walls, and special reinforced concrete shear walls. Each system was modeled and analyzed following the provisions of ASCE 7, taking into account critical parameters such as the response modification coefficient (R), overstrength factor (Ω0), deflection amplification factor (Cd), and height limitations. The analysis indicated notable variations in the seismic responses among the systems, each exhibiting unique performance characteristics. This comparative study focused on aspects of stiffness, dynamic behavior through modal analysis, as well as displacement and inter-story drift ratios under seismic loading scenarios. The results highlight essential differences in stiffness, modal characteristics, and displacement control across the systems, emphasizing their suitability for tall structures in regions susceptible to seismic activity like Erbil City.

1) Stiffness Analysis: Model 1, representing Dual Systems with Special Moment Frames, displayed the highest stiffness, rendering it the most effective in managing lateral displacements. The integration of moment frames and shear walls in this model contributed to its superior performance, validating its exemption from height limitations set by ASCE 7. Conversely, Models 3 and 4, which incorporate Reinforced Concrete Ductile Coupled Walls and Special Reinforced Concrete Shear Walls respectively, exhibited lower stiffness, resulting in reduced capacity for energy dissipation and challenges in addressing higher-mode effects.

2) Dynamic Behavior: Modal analysis revealed considerable differences in the fundamental periods and mass participation ratios among the various models. Model 1 had the shortest fundamental period, indicating a stiffer dynamic response, whereas Model 4, characterized by the longest fundamental period, demonstrated increased flexibility, making it less suitable for tall buildings. The rotational mass participation ratios suggested that torsional behavior becomes more significant in taller structures, particularly in more flexible systems such as Model 4.

3) Displacement and Drift Ratios: The examination of top story displacements and inter-story drift ratios further underscored the relative strengths and weaknesses of each model. Model 1 exhibited the lowest displacements under both Modal Response Spectrum Analysis (MRSA) and Equivalent Lateral Force Procedure (ELFP), confirming its effectiveness in controlling seismic displacement. In contrast, Model 4 showed the highest displacement and drift values, indicating its greater vulnerability to lateral movement and torsional effects during seismic events.

4) Story Shear and Overturning Moment: These were critical factors in the seismic analysis. The results revealed that tall buildings experience higher story shears and larger overturning moments, particularly in systems with limited ductility and height restrictions. Dual systems and moment frames, due to their ability to better distribute seismic forces and resist overturning moments, exhibited improved lateral stability, thus minimizing the risk of structural failures. Conversely, buildings utilizing ductile coupled walls and shear walls, which are more susceptible to higher-mode responses, necessitated height limitations to avert excessive lateral displacements and potential instability during intense seismic events.

In conclusion, this study highlights that the selection of a seismic force-resisting system significantly influences the structural performance of high-rise buildings. Dual systems with special moment frames (Model 1) demonstrate the best overall performance, attributed to their superior stiffness, dynamic response, and ability to control displacements, making them appropriate for tall structures without height restrictions. In contrast, systems such as reinforced concrete shear walls (Model 4) require careful consideration of height limitations to ensure safety in taller constructions. These insights provide essential guidance for structural engineers in the design of buildings within seismic zones, contributing to the development of safer and more resilient structures. Observations indicated that systems employing special moment frames afforded greater flexibility and higher response modification coefficients, rendering them more suitable for taller buildings. In contrast, dual systems and ductile coupled walls offered enhanced overstrength and energy dissipation capabilities, proving more effective in mitigating seismic demands. While special reinforced concrete shear walls exhibited solid performance, they presented limitations related to height restrictions and lower ductility.

While this study focused on a 35-story building, the findings can be extended to buildings of slightly different heights, with some considerations. Dual systems with special moment frames and shear walls (Model 1) are highly scalable and can be effectively used for both taller and shorter buildings. Their combination of stiffness, ductility, and energy dissipation makes them suitable for a wide range of building heights. For taller buildings, dual systems can better manage higher-mode effects and lateral displacements, while for shorter buildings, they provide robust seismic performance with minimal risk of overdesign. The suitability of each system depends on the building height and the associated seismic demands. While dual systems are generally the best choice for tall buildings, other systems may become viable for shorter or mid-rise buildings, depending on the specific design requirements and cost constraints. Future studies could explore these thresholds in more detail by analyzing buildings of varying heights to provide more precise guidance.

Although Model 1 (Dual Systems with Special Moment Frames) demonstrated the best overall seismic performance in this study, its adoption in Erbil has been limited due to cost and skill barriers. Dual systems are more expensive to construct compared to simpler systems like special reinforced concrete shear walls, as they require additional materials, labor, and detailing. This increased cost can be a significant deterrent for developers and contractors in Erbil, where cost-effectiveness is often a priority. Additionally, the design and construction of dual systems require a high level of expertise and precision, particularly in detailing and executing the connections between moment frames and shear walls. The local construction industry may lack the specialized skills and experience needed to implement these systems effectively, leading to a preference for simpler and more familiar systems.

To overcome these barriers, capacity building and training programs could be introduced to enhance local expertise in designing and constructing dual systems. Policymakers and stakeholders could also consider incentives or regulations to promote the adoption of more resilient structural systems, even if they come at a higher initial cost. By addressing these challenges, Erbil can improve the seismic resilience of its tall buildings and ensure safer urban development in the future.

This research is confined to analytical modeling and simulations, with no experimental investigations undertaken to validate the numerical models employed. Future studies should consider conducting experimental tests on physical models or collecting structural health monitoring data post-seismic events to verify the accuracy of the analytical findings. Additionally, further investigations could explore the effects of varying seismic intensities and the soil-structure interactions specific to the city to provide a more thorough understanding of these systems' seismic performance under diverse conditions.

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