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Optimal Structural System Selection and Placement for a High-Rise Concrete Building Affected by Earthquake Loads

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ABSTRACT

Regular earthquakes and wind loads can inflict considerable damage on high-rise buildings. Therefore, various structural systems are utilized to ensure that these structures are safe in terms of lateral stress. To maintain safety during an earthquake, the building elements designed to resist lateral forces must be sufficiently rigid. Achieving high rigidity necessitates larger dimensions for columns and walls, which consequently reduces available floor space. Thus, designing efficient structural systems for this purpose is deemed essential for high-rise buildings. In this research, four structural systems were analyzed and compared using ten models in ETABS: the moment-resisting frame system, the moment-resisting frame system with a shear wall, the moment-resisting frame system with a bracing system, and the moment-resisting frame system with an outrigger system. The analysis reveals that combining concrete shear walls and outrigger systems significantly enhances structural stiffness and minimizes lateral displacements. Furthermore, the placement of these systems influences their performance and effectiveness. The combined use of these systems led to improved seismic performance and stiffness, particularly when the outriggers are located at the midpoint of the building's height. When the outrigger system is positioned at mid-height of the structure, the stiffness enhancement is 18 percent compared to when it is located at the roof level. The implementation of a core shear wall reduced drift by 69 percent compared to using a moment-resisting frame system alone, and the reduction increased to 81 percent with the addition of an outrigger system at mid-height.

Keywords: *Dynamic analysis, Moment resisting frame, Shear wall, Bracing, Outrigger system, ETABS.*

1. Introduction

In the past, when designing high-rise structures, the tendency was to increase the dimensions of structural elements such as beams and columns. However, over time and through research, it was discovered that when designing high-rise buildings exposed to earthquakes, it is preferable to choose the most efficient structural system to reduce earthquake-induced damage. Many structural systems have been developed to enhance a structure's performance under lateral loads, prompting research into which of these systems is most effective at resisting such forces. In a study on earthquake-resistant construction, Mohammadi et al. [1] conducted a comparative analysis of shear wall placement in RC-framed buildings. The study found that the optimal position for a shear wall is at the center and arranged symmetrically. Additionally, combining bracing and shear walls can be a wise strategy for earthquake protection design. Ahmed and Manzoor [2] examined how high-rise structures respond to various structural systems, including shear walls, outrigger-built trusses, and braced frame systems. Their parameters showed that the building with an outrigger core belt truss system performs better than the special moment-resisting frame with shear wall and braced frame systems. This conclusion was determined through dynamic analysis methods, including response spectrum analysis and nonlinear static analysis. To identify the most advantageous structural arrangement involving bracing and shear wall components, Aryan et al. [3] analyzed nine different models. The results indicated that using concrete walls instead of a moment-resisting frame system improves the structure's behavior under lateral loads. P. Gunda and Anthugari [4] conducted a numerical analysis using five models with varying aspect ratios to determine the optimal placement of outriggers relative to building height. They found that for aspect ratios between 0.45 and 0.95, the ideal location for an outrigger truss without a belt truss is between 65% and 80% of the building's height. The effect of outrigger systems in tall buildings was studied by Vellaichamy and Chakkaravarthi [5], who found that adding outrigger trusses to the bottom story significantly reduces drift and increases structural rigidity. Alhaddad et al. [6] examined various outrigger system configurations, components, and types from multiple perspectives, highlighting the system's advantages and disadvantages, performance variables, and behavior under different loading scenarios. Takva et al. [7] investigated the impact of outrigger systems on the structural behavior and cost of high-rise buildings. Their study concluded that outrigger systems enhance lateral rigidity by reducing displacements, especially under lateral loads. This, according to design principles, increases the structure's natural frequency and shortens its vibration period. Shareef et al. [8] developed a dynamic analysis of tall buildings with outrigger structures under lateral loads. The goal was to evaluate the efficiency of outrigger shear walls and determine their optimal placement within high-rise buildings subjected to lateral forces. Marabi et al. [9] proposed the best locations for outriggers in tall structures, also examining the seismic behavior of single-outrigger frame systems. Their findings revealed that the most effective single-outrigger system can reduce the top displacement of the building by approximately 17% more than traditional models (Cap models). Morris [10] studied the influence of belt trusses and outrigger systems on high-rise building performance.

Using nonlinear static pushover analysis, the research assessed how these systems perform under post-elastic seismic conditions, both with and without outriggers and belt trusses. P. Sharma and Singh [11] conducted a dynamic analysis of outrigger systems against lateral loads. They discovered that increasing the number of outriggers improves building performance and that combining belt trusses and shear bands with outriggers yields better results than using outriggers alone. Mohammed et al. [12] investigated how different bracing systems influence seismic responses in high-rise reinforced concrete buildings, especially in soft-story structures. The study found that placing bracings in corner bays results in higher story shear than placements in mid-bays, and V-shaped bracing causes greater shear than X-shaped bracing. Steel braces are highly effective for enhancing structural stability in soft-story buildings.

Basaraboyina et al. [13] analyzed the behavior of high-rise structures with conventional framed, flat slab, and post-tensioned (PT) flat slab systems. Their results showed that the PT flat slab system notably reduces story displacements, story drift, and base shear. Bin Zahid et al. [14] investigated the optimal placement and orientation of shear walls for lateral load resistance. Their findings suggest that incorporating shear walls reduces lateral displacements and story drift while improving overall stiffness. They recommend placing more shear walls along shorter building directions than longer ones. Arvind et al. [15] performed a performance-based seismic analysis of reinforced concrete multi-story framed buildings equipped with dampers. The study found that adding friction and slit dampers can improve seismic performance, with slit dampers providing a greater impact on parameters like top displacement, drift, and energy dissipation, enabling the frame to withstand peak ground acceleration (PGA) levels up to 0.3 g.

2. Aim and Research Significance

Earthquakes are among the most significant natural hazards posing a threat to human safety, making it crucial to design structures that can withstand seismic forces and prevent collapse. This is especially important for tall buildings, which are highly vulnerable to lateral loads generated by ground shaking. Consequently, choosing structural systems that maximize stiffness, strength, and ductility while minimizing lateral displacements is essential. This study aims to evaluate and identify the most effective structural system that provides superior stability, strength, and reduced displacement under seismic lateral loads.

3. Analysis Method

3.1. Description of the Building

The details of the structure and input parameters used in this study are presented in Table 1. The building is located in New York, falls under Risk Category II, and is classified as having stiff soil (Site Class D), with an earthquake priority factor Ie=1.0. The response modification coefficient (R) is 8 for the moment-resisting frame system and 5 for both the moment-resisting frame with shear walls and the moment-resisting frame with bracing systems, by ASCE/SEI 7-16 [17]. The dimensions of the flat slab, columns, beams, and concrete walls were based on the specifications outlined in the American Concrete Institute code (ACI 318-19) [17].

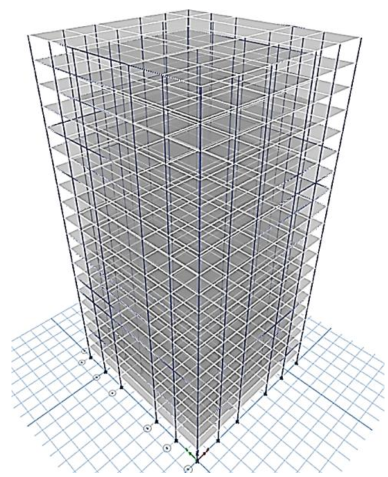
3.2. Modeling and Analysis

For the analysis, four types of structural systems were chosen: the moment-resisting frame, the moment-resisting frame with shear walls, the moment-resisting frame with bracing, and the moment-resisting frame with an outrigger system. Column and beam sections were kept constant along the height of the building. Ten models were used in this study, labeled from (S1) to (S10), as shown in Figure 1. All structural systems were modeled and compared with the (S1) moment-resisting frame model. Bracings, shear walls, and outriggers were added to these models at different locations to incorporate lateral load-resisting components.

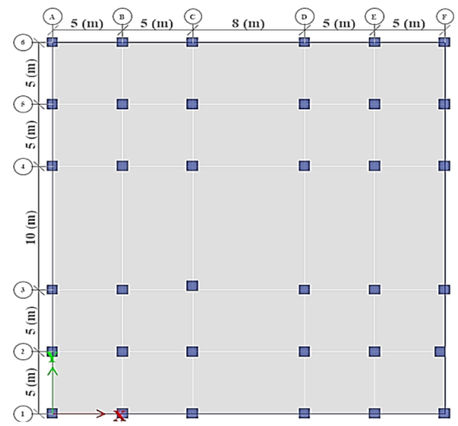
Table 1. Building Details

Building Data	Details
Plan Dimensions	(28 x 30) m
Height of a typical story	3.0 m
Total height of the building	60.0 m
Slab thickness	220 mm
Column size	(800 x 800) mm
Wall thickness	250 mm
Outrigger wall thickness	150 mm
Beam dimensions	(800 x 250) mm
Tie dimensions	(300 x 300) mm
Concrete grade	M30
Steel grade	Fe 415
Density of concrete	$2.5T/m^3$
Damping ratio	5%
Floor Finishes	0.1t/m^2
Live Load	0.3t/m^2
Wall load	1.2t/m^2

Models Description	
S1	Moment-resisting frame
S2	Frame with core shear wall
S3	Moment-resisting frame with bracing at the middle of the perimeter
S4	Moment-resisting frame with a shear wall at the middle of the perimeter
S5	Moment-resisting frame with shear wall at corners
S6	Moment-resisting frame with bracing at corners
S7	Moment-resisting frame with two shear walls in the middle of the perimeter
S8	Moment-resisting frame with two bracings in the middle of the perimeter
S9	Moment-resisting frame with core shear wall and single outrigger at the top of the building
S10	Moment-resisting frame with core shear wall and single outrigger at the middle height of the building

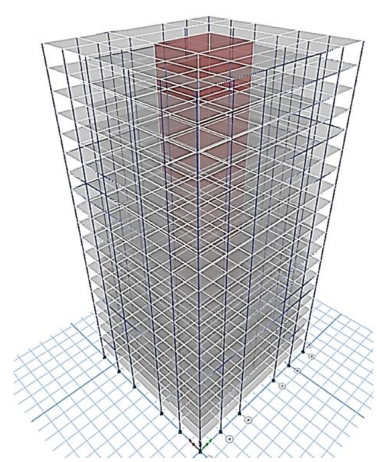


S1

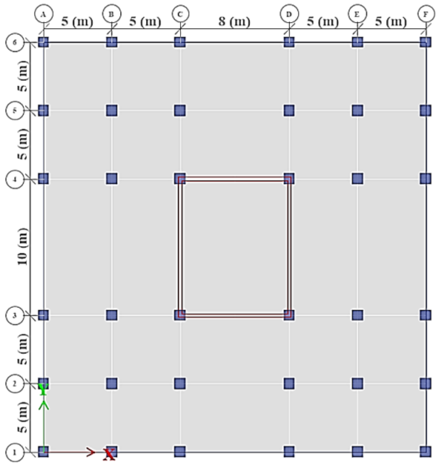


Plan of S1 Model

a) S1 Model

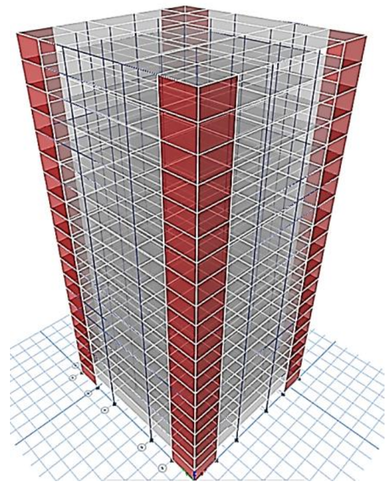


S2

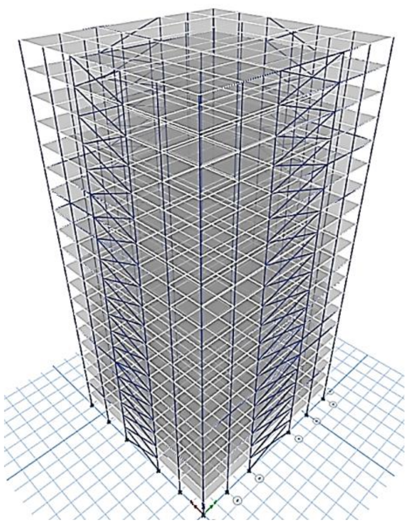


Plan of S2 Model

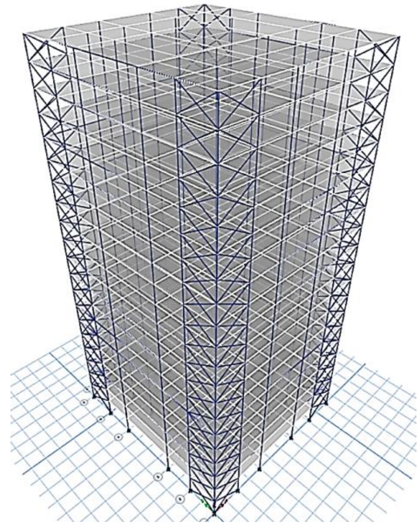
b) S2 Model



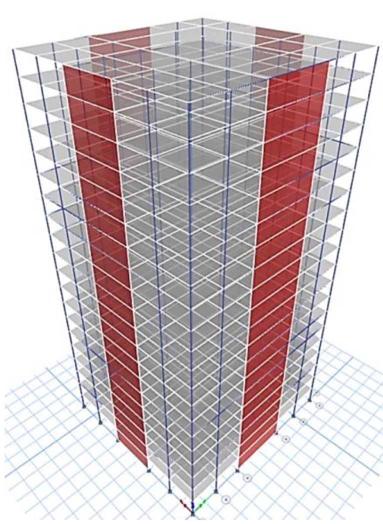
e) S5 Model



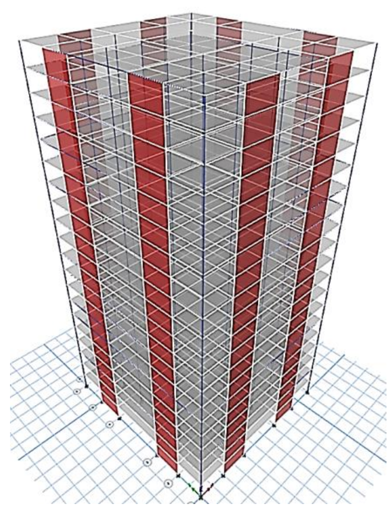
c) S3 Model



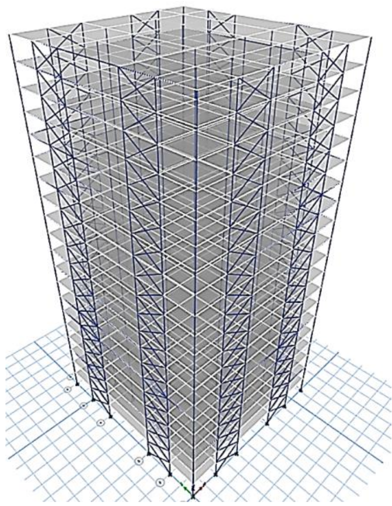
f) S6 Model



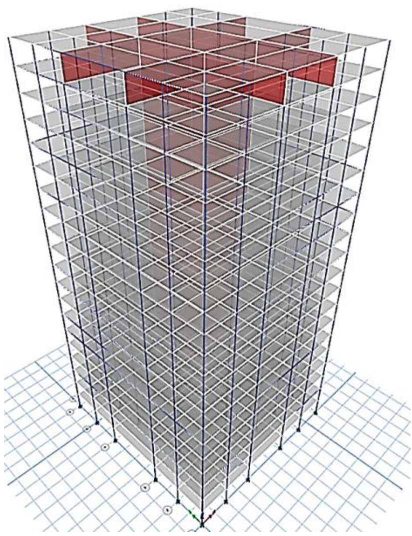
d) S4 Model



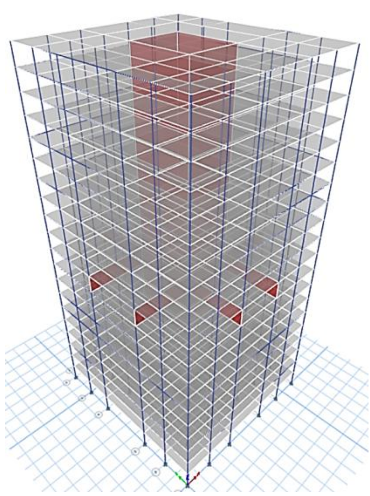
g) S7 Model



h) S8 Model



i) S9 Model



j) S10 Model

Figure 1- Models of Building from S1 to S10

3.3. The Method Selected for Analysis

Two types of analysis were conducted for the earthquake: static analysis and dynamic analysis, using ETABS, a software for modeling and analysis. Modal analysis, combined with the response spectrum function in ETABS, provides an efficient and reliable method for seismic evaluation of structures. The process begins with modal analysis, which determines the structure's natural vibration modes and frequencies. These modes serve as the basis for response spectrum analysis, which applies spectral acceleration curves to estimate maximum seismic responses such as displacements, forces, and stresses by combining the modal results. This approach enables engineers to accurately predict the worst-case scenario responses without requiring extensive time-history simulations, making it both computationally efficient and compliant with seismic design standards. This method offers a clear understanding of the modal analysis and provides concrete results for the design forces of each element in the structure. It also ensures a safe design of the structure under lateral loads. Using the Response Spectrum Method, the dynamic analysis involves extracting a Single Degree of Freedom (SDOF) system subjected to lateral forces to determine the maximum response parameters such as acceleration, velocity, and displacement. This method determines a building's mode shapes, mode frequencies, and mode participation factors through modal analysis. Figure 2 shows the input response spectrum function used for each model. The acceleration response spectra were obtained from the United States Geological Survey (USGS) Seismic Design Maps, based on ASCE/SEI 7-16 Table 1.5-2 [17]. The data used to determine the response spectrum function in the program are shown in Table 2, where:

- S_S is the Spectral Acceleration at Short Period (usually at 0.2 seconds),
- S_1 is Spectral Acceleration at 1 second,
- Fa is the Site Coefficient for Short-Period Spectral Acceleration,
- F_V is the Site Coefficient for 1-Second Spectral Acceleration,
- S_{MS} is the Mapped Spectral Acceleration at Short Period,
- S_{M1} is the Mapped Spectral Acceleration at 1 second,
- S_{DS} is the Design Spectral Acceleration at a short period.

For modal analysis, the load case type is response spectrum, the load type is acceleration, and the Complete Quadratic Combination (CQC) method is used for modal combination.

Table 2- Data used to determine the function of the response spectrum used in the modeling

S_s	0.292	S_{D1}	0.096
S_1	0.06	T_L	6
F_a	1.567	PGA	0.18
F_v	2.4	PGA_M	0.26
S_{MS}	0.457	F_{PGA}	1.439
S_{M1}	0.144	I_e	1
S_{DS}	0.305	C_V	0.883

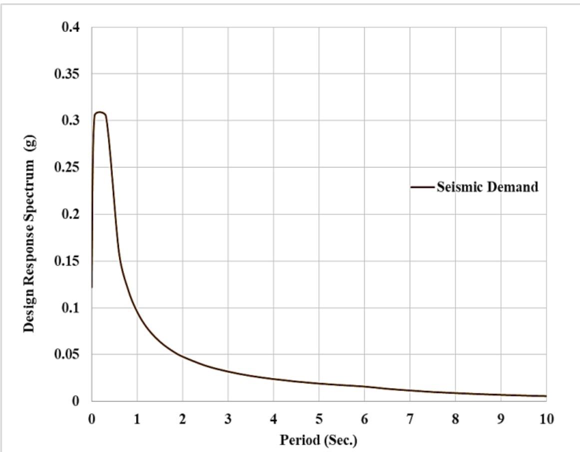


Figure 2- The input response spectrum function for the (S1) model

3.4 Load Combinations

Following the creation of the computational models and the assignment of loads, each load case is examined. For seismic loads, dead loads, and live loads, the internal forces, including axial forces, shear forces, and bending moments, are analyzed by the American Society of Civil Engineers (ASCE/SEI 7-10) standard [16]. For this study, the load combinations according to ASCE/SEI 7-10 [16], listed below, are taken into account.

1. 1.4DL
2. 1.2DL+1.6LL
3. 1.26DL+1LL+1.3[QX+0.3QY]
4. 1.26DL+1LL+1.3[QY+0.3QX]
5. 1.26DL+1LL-1.3[QX+0.3QY]
6. 1.26DL+1LL-1.3[QY+0.3QX]
7. 0.84DL+1.3[QX+0.3QY]
8. 0.84DL+1.3[QY+0.3QX]
9. 0.84DL-1.3[QX+0.3QY]
10. 0.84DL-1.3[QY+0.3QX]

Where, DL is Dead Load, LL is Live Load, QX is Earthquake load (seismic forces) in X direction, and QY is Earthquake load (seismic forces) in Y Direction.

4. Results and Discussion

The results obtained by using Response Spectrum Analysis to analyze the various models in ETABS were as follows.

4.1 Seismic Weight and Base Shear

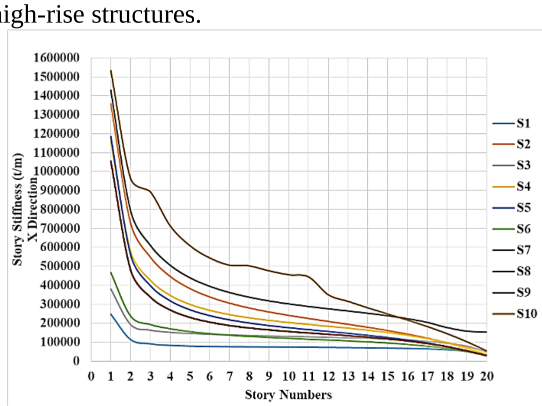
Seismic weight, as defined in ASCE 7, refers to the effective weight of a structure or a portion of it that contributes to its seismic response. According to ASCE 7, seismic weight (Ton) is the total dead load plus a portion of the live load, adjusted for its distribution and the seismic force calculation. Typically, this portion is taken as 25% of the live load. The analysis reveals that the base shear forces across all models are relatively consistent, with variations of no more than 4.0%. This close similarity suggests that, despite differences in structural configurations or system types, the overall seismic resistance, as indicated by base shear, remains comparable among the models. Such uniformity may be attributed to standardized load assumptions, similar material properties, or consistent load distributions applied during the analysis. Comparing these findings with existing literature [3,4] indicates that, in structures with comparable design parameters, variations in base shear tend to be minimal when other key factors are held constant, highlighting the influence of fundamental structural and material properties. The slight differences observed could be due to variations in system stiffness, mass distribution, or connection detailing, which marginally affect the seismic response.

4.2 Fundamental Time Period

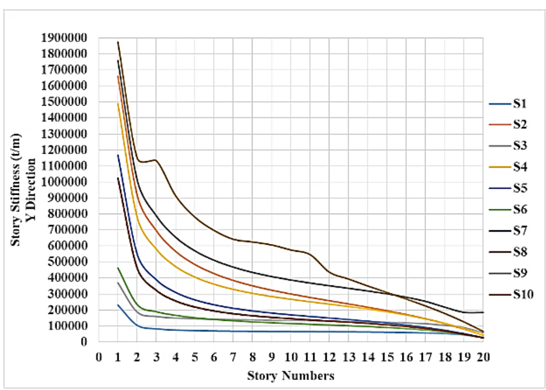
When obtaining the time period from the analysis, it was observed that model S10 (Moment-resisting frame with a single outrigger system at mid-height) has a shorter fundamental time period, as shown in Table 5.

4.3 Story Stiffness

The results indicate that implementing lateral load-resisting systems such as shear walls and outrigger systems significantly enhances the building's lateral story stiffness. Specifically, the introduction of shear walls throughout the structure results in a substantial increase in stiffness, reflecting their high efficiency in resisting lateral forces. In contrast, bracing systems, while providing some structural benefit, exhibit a comparatively smaller improvement in stiffness than that achieved by adding shear walls at various locations within the plan. This discrepancy underscores the greater effectiveness of shear walls in stiffening the structure due to their continuous and robust lateral resistance. The analysis further shows that the incorporation of outrigger systems markedly improves lateral resistance compared to reliance solely on core shear walls. Outriggers act as lateral bracing elements that transfer lateral loads to the core and envelope, thereby distributing forces more effectively and increasing overall stiffness. Notably, placing the outrigger system at mid-height yields better results in terms of stiffness than situating it at the top of the building, as depicted in Figure 3. This optimal positioning allows for a more balanced distribution of lateral forces and enhances stiffness more efficiently, reducing structural deformations under seismic or wind loads. These findings align with existing literature [8,9], which emphasizes the importance of strategic placement of lateral systems to maximize stiffness and stability. The improved performance with mid-height outriggers is attributed to their ability to create a more effective load path, reducing drift and improving overall structural performance. Further analysis of the interaction between these systems and the building's mass and stiffness distribution could provide deeper insights into designing more resilient high-rise structures.



(a) Story Stiffness in X-Direction

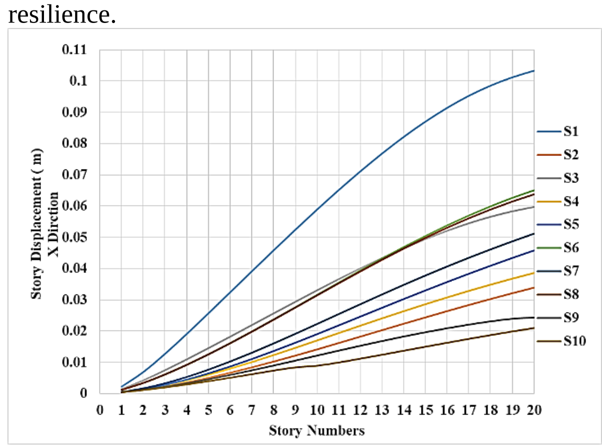


(b) Story Stiffness in Y-Direction

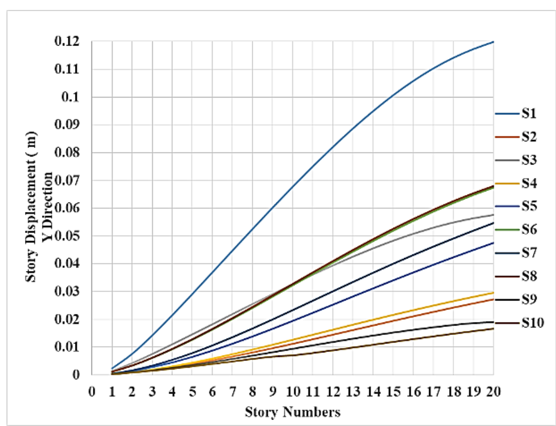
Figure 3- Story Stiffness for all Models

4.4 Story Displacement

The analysis demonstrates a clear inverse relationship between story stiffness and lateral displacement: higher stiffness corresponds with reduced lateral movement at the top story. Specifically, models with enhanced lateral resistance, such as those incorporating shear walls, outriggers, or bracing systems, exhibit significantly lower displacement values, indicating improved structural stability against lateral forces. As illustrated in Figure 4, model S10 shows the lowest lateral displacement at the top story in both directions, reflecting its high stiffness and effective lateral load transfer mechanisms. Conversely, model S1 experiences the greatest lateral displacement, suggesting its relatively lower stiffness and weaker resistance to lateral loads. This correlation underscores the importance of lateral stiffness in controlling story drifts and ensuring structural safety, especially in tall buildings subjected to seismic or wind forces. Lower displacements also imply a reduced likelihood of damage and improved occupant comfort. The findings align with established structural engineering principles that emphasize the need for sufficient lateral stiffness to limit drift and prevent serviceability issues. Further analysis could explore how specific lateral load-resisting systems and placement influence displacement behavior, ultimately guiding optimal design strategies for minimizing story drift and enhancing structural resilience.



(a) Story Displacement in X-direction



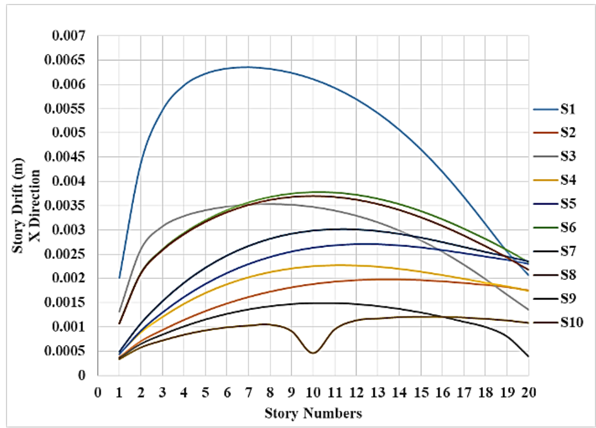
(b) Story Displacement in Y-direction

Figure 4- Story Displacement for all Models

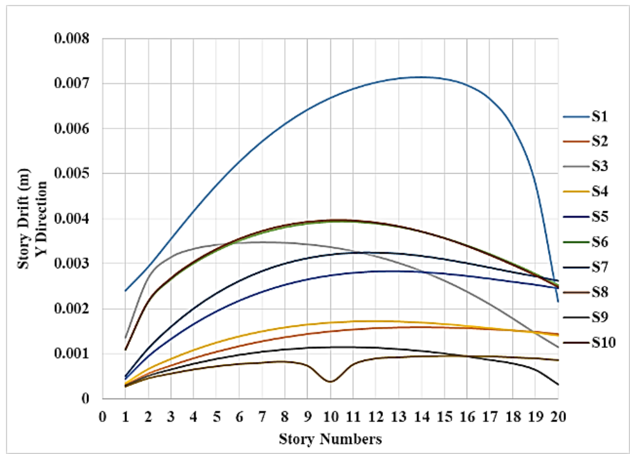
Story Drift

The analysis reveals that story drift tends to be highest at the mid-floor levels of the building, gradually decreasing toward the top floor. This pattern indicates that the mid-height levels experience the greatest lateral displacements, likely due to the combined effects of load distribution and stiffness variations throughout the structure. Model S10 exhibits the lowest story drift values in both directions, reflecting its superior stiffness and effective lateral force resistance, which helps limit deformation and maintain structural integrity under lateral loads, as shown in Figure 5. The introduction of a core shear wall reduces story drift by approximately 69% compared to a simple frame system, demonstrating its effectiveness in enhancing lateral stability.

Additionally, the strategic placement of an outrigger system at mid-height results in a further increase in drift reduction, bringing the decrease to about 81%. This suggests that outriggers positioned at mid-levels can provide a more uniform and efficient transfer of lateral forces, thus further limiting story displacements. These findings are consistent with principles in seismic and wind-resistant design, which emphasize controlling story drift to prevent damage to structural and non-structural elements. Minimizing story drift is critical for ensuring serviceability, occupant comfort, and structural durability. The results underscore the significance of combined lateral resistance systems, such as shear walls and outriggers, and their optimal placement in managing story drift effectively. Further investigation into the interaction between these systems and the building's overall dynamic response could lead to more refined strategies for controlling story drift in high-rise structures.



a) Story Drift ratio in X-Direction



b) Story Drift ratio in Y-Direction

Figure 5: Story Drift ratio for all Models

According to the ASCE 7-10 code, the permissible drift in both directions is equal to $0.02\ h_{sx\ or\ sy}$. Where $h_{sx\ or\ sy}$ is the height of each floor in the x and y directions. When referring to the results of the structural analysis, it was found that the drift doesn't exceed this limit in the x and y directions for all structural systems.

Table 3- Seismic Weight and Base Shear

Models	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Seismic weight (Ton)	37192	38568.6	37509.5	38568.6	38721.5	37596	38722	37596	38660	38660
Base Shear (Ton)	497.8	515.8	502	515.8	517.8	503	517.8	503	517	517

Table 4- Ratio of Base Shear and Seismic Weight

Models	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Seismic weight (Ton) %	100	103.7	100.9	103.7	103.6	101.1	104.0	101.1	104.0	104.0
Base Shear (Ton) %	100	103.6	100.8	103.6	104.0	101.0	104.0	101.0	103.9	103.9

Table 5- Time period calculated by ETABS software

Models	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Time Period (sec.)	4.093	2.05	2.923	2.226	2.43	2.99	2.62	3.011	1.823	1.613

Table 6- Ratio of time period

Models	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Time Period%	100	50	71	54.4	59.4	73	64	73.6	44.5	39.4

Table 7-Maximum-Story Stiffness Ratio in X & Y Directions

Model	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
X- Dir.%	100	640	170	510	493	209	423	210	578	848
Y- Dir.%	100	720	160	644	507	200	445	200	764	814

Table 8-Maximum-Story Displacement Ratio in X & Y Directions

Model	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
X- Dir.%	100	33	58	37	44	63	50	62	24	20
Y- Dir.%	100	23	48	25	40	56	45	57	16	14

Table 9-Maximum-Story Drift Ratio in X & Y Directions

Model	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
X- Dir.%	100	31	56	36	43	59	47.5	58	23	19
Y- Dir.%	100	22	49	24	40	55	45.5	56	16	13

5. Conclusions

Based on thorough analysis and observed data, the key conclusions are as follows:

1. The base shear forces in all models are similar, with differences within 4.0%, indicating consistent seismic response across configurations.
2. Incorporating concrete shear walls improves structural performance compared to bracing systems, with additional gains when an outrigger system is added to the core shear wall, whether positioned at the top or mid-height of the building.
3. For concrete shear wall systems, the optimal placement is at the middle perimeter around the core. If mid-positions are not feasible, distributing shear walls as in Model S4 (moment-resisting frame with shear walls at mid-perimeter) increases stiffness by 410% in X-direction and 544% in Y-direction.
4. Placing concrete bracing systems at building corners (as in Model S6) proves most effective, leading to a 109% increase in stiffness in the X direction and a 100% increase in direction Y compared to the frame system. Lateral displacements are reduced by approximately 37% in X and 44% in Y directions.
5. An outrigger system positioned at mid-height reduces the building's fundamental period by about 60.6% compared to a moment-resisting frame, signifying improved dynamic performance and increased stiffness.
6. Mid-height placement of the outrigger yields better stiffness than at the top, with an 18% increase in stiffness observed when located at mid-level.
7. Among all models, Model S10 combines a

moment-resisting frame, a core shear wall, and a mid-height outrigger, and exhibits the lowest lateral story displacement in both directions. Conversely, Model S1 (moment-resisting frame alone) shows the highest displacement, demonstrating the e ffectiveness of comprehensive lateral resistance systems.

8. Implementing a core shear wall reduces story drift by approximately 69% compared to a pure moment-resisting frame, and when combined with a mid-height outrigger, this reduction further increases to about 81%, highlighting the benefits of combined lateral stability strategies.

6. References

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