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Analysis and Design of Modern Parking Structure by Considering Optimized Bracing Systems Under Dynamic Load

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Abstract

The design and implementation of effective bracing systems are crucial for ensuring the structural stability and safety of G+10 parking buildings, particularly in regions prone to seismic and wind loads. This study evaluates and optimizes various bracing systems, including X-type, V-type, inverted V-type, and eccentric bracing, to determine their suitability for use in G+10 parking structures in the Chhatrapati Sambhajinagar City area. The research focuses on assessing each bracing system's structural performance, material efficiency, construction feasibility, architectural flexibility, maintenance requirements, and seismic resilience. Through comprehensive computational simulations and physical testing, this study analyses the lateral load resistance, energy dissipation capabilities, and overall structural stability each bracing configuration provides. A cost-benefit analysis is conducted to evaluate material utilization and long-term economic impacts. Additionally, collaboration with architects ensures that the selected bracing systems integrate seamlessly with the building's design, maximizing space utilization and aesthetic appeal. The study also explores advanced materials and construction techniques to enhance the efficiency and sustainability of bracing systems. Optimization algorithms are developed to identify the best configurations that balance performance, cost, and design flexibility. Furthermore, this research contributes to the development of updated design guidelines and standards, promoting safer and more resilient construction practices. By achieving these objectives, this study provides valuable insights into the optimal selection and implementation of bracing systems for G+10 parking buildings, ultimately contributing to the advancement of structural engineering practices and the development of safer, more efficient, and sustainable multistory parking structures.

Keywords: Bracing systems, structural stability, seismic resilience, ETABS, G+10 parking buildings, X-type bracing, V-type bracing, inverted V-type bracing, eccentric bracing, Chhatrapati Sambhajinagar

INTRODUCTION

In Chhatrapati Sambhajinagar, the number of vehicles is increasing at the same rate as the population of the city. The number of vehicles in Chhatrapati Sambhajinagar district has crossed 14 lakh. The number of four-wheelers is increasing every day. According to the regional transport office (RTO), the number of four-wheelers has gone up to 88,076 by 31 November 2021.

The goal of this project is to reduce the amount of open parking space in the city and create an effective parking system. In our metropolises, parking has grown to be a big worry. One suggested smart city is Chhatrapati Sambhajinagar, which has all the amenities needed for institutions, tourism, and business buildings. Every day, the traffic situation is evolving. The construction of "multi-level parking"

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at Paithan Gate in Aurangpura, a major shopping center, is suggested as a solution to this issue. The ability to park cars on multiple floors, thanks to this multi-level parking, minimizes space waste.

This study examines how steel, composite, and reinforced concrete structures respond to seismic loads as well. Utilizing the special qualities of both steel and reinforced concrete, structures made of these materials are typically more economical and safer than those made of just one of them alone [1–6].

METHODOLOGY

This structure consists of G+10 floors, having the headroom top as open parking with a roof. Each floor of the multilevel parking carries 16 cars to park conveniently. A total of 15 motorized two-wheeler can also park. A total of 112 cars and 105 two-wheelers can be parked at a time. The corner of the floor lift is also provided for a vertical moment of the vehicle for a backup point of view. Ramps are provided for the movement of the vehicle from floor to floor. We can use this as per the flexibility of parking requirement.

If only four-wheeler parked – 15 (per floor)

If only two-wheeler parked – 60 (per floor)

We analyze the differences between steel concrete composite structure elements, such as composite columns and steel beam deck slabs, and multilevel reinforced concrete cement (RCC) parking structures. The parking complex has been modelled using ETABS software. The seismic analysis is conducted with attention to IS 1893:2016. The seismic properties of zone II. When examining the parking structure, take into consideration the load for G+10 and carefully compare the two categories of structural parameters: maximum displacement, maximum story drift and fundamental time period (Figures 1 and 2 and Table 1) [7–12].

DIFFERENT TYPES OF BRACING USED

For this project, we have used different types of bracings as follows.

1. *X-Type Bracings:* X-type bracings are structural elements used to enhance the lateral stability of buildings by forming an "X" shape across a bay between two columns. These bracings intersect at mid-span, creating a diagonal cross that effectively distributes lateral loads, such as wind or seismic forces, throughout the structure. This configuration provides high rigidity and strength, minimizing lateral displacement and improving the building's overall resistance to horizontal forces. X-type bracings are commonly used in both steel and concrete structures to ensure safety and durability (Figure 3).
2. *V-Type Bracings:* V-type bracings are structural elements used in buildings to enhance their lateral stability by forming a "V" shape between two columns. These bracings connect at the top to a beam and at the bottom to two adjacent columns, creating a triangular configuration. This design effectively distributes lateral loads, such as those from wind or seismic activity, across the structure, thereby reducing lateral displacement and increasing overall rigidity. The V-type bracing helps maintain structural integrity by providing additional support against horizontal forces (Figure 4).
3. *Inverted V-Type Bracings:* Inverted V-type bracings, also known as chevron bracings, are structural elements used to enhance the lateral stability of buildings. These bracings form an inverted "V" shape by connecting to the beam at the midspan and the columns at their bases. This configuration efficiently distributes lateral loads, such as those from wind or earthquakes, reducing overall deflection and improving the structure's resistance to horizontal forces. The design also helps in maintaining the architectural integrity of the building by minimizing interference with the internal space (Figure 5).
4. *Eccentric Back-Type Bracings:* Eccentric back-type bracings are structural elements used in buildings to resist lateral forces such as those caused by wind or earthquakes. Unlike concentric

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bracings, where bracing members meet at a single point, eccentric bracings are deliberately offset to create a controlled deformation zone. This design enhances the ductility and energy dissipation capacity of the structure, improving its ability to absorb and dissipate seismic energy, thereby reducing the risk of structural failure (Figure 6).

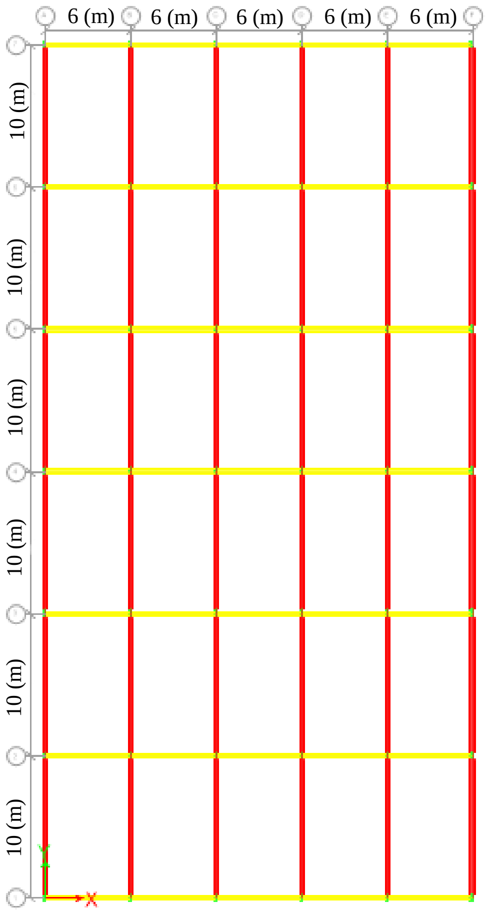

Figure 1. Plan view of building model in ETABS.

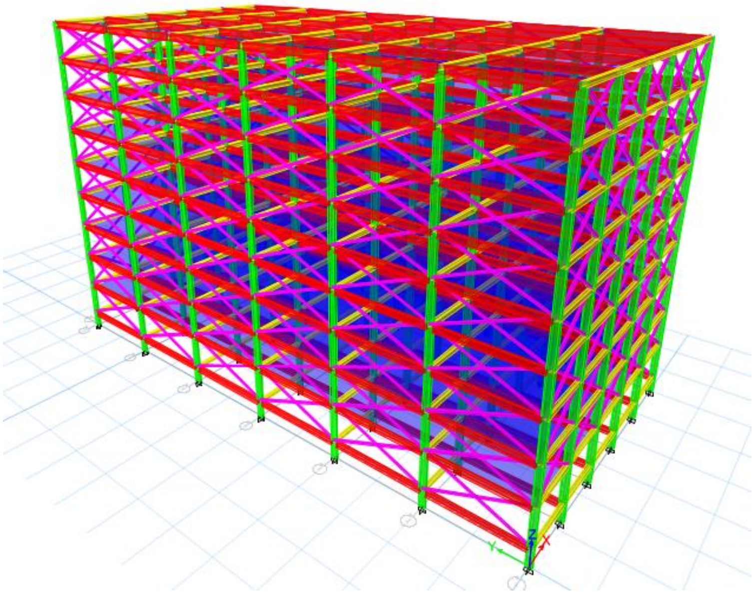

Figure 2. Three-dimensional (3D) view of building model in ETABS.

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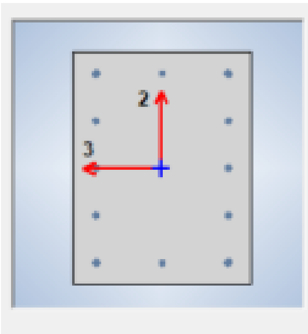
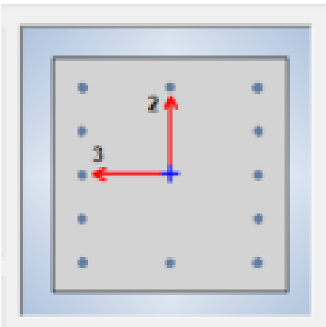
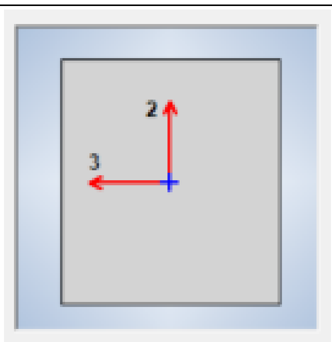
Table 1. Parameters considered for reinforced concrete cement (RCC) modeling.

S.N.	Particulars	Dimension/Value
1	Area dimension	1010.40 m^2
2	Total height of the structure	18.2 m
3	Height of each story Height of headroom	2.7 m 2 m
4	Thickness of RCC slab	150 mm
5	Grade of longitudinal bar Grade of lateral ties Grade of concrete column Grade of concrete beam Grade of concrete slab Density of concrete	Fe500 Fe415 M25 M20 M20 25 kN/m
6	Size of Column C1 C2	 450 × 600mm  450 × 450mm
7	Size of Beam B1	 400 × 450mm
8	Semitic zone Importance factor Zone factor Damping ratio	II 10 0.5 5%
9	Floor finish Live load Vehicle load	1 kN/m 4 kN/m 5 kN/m

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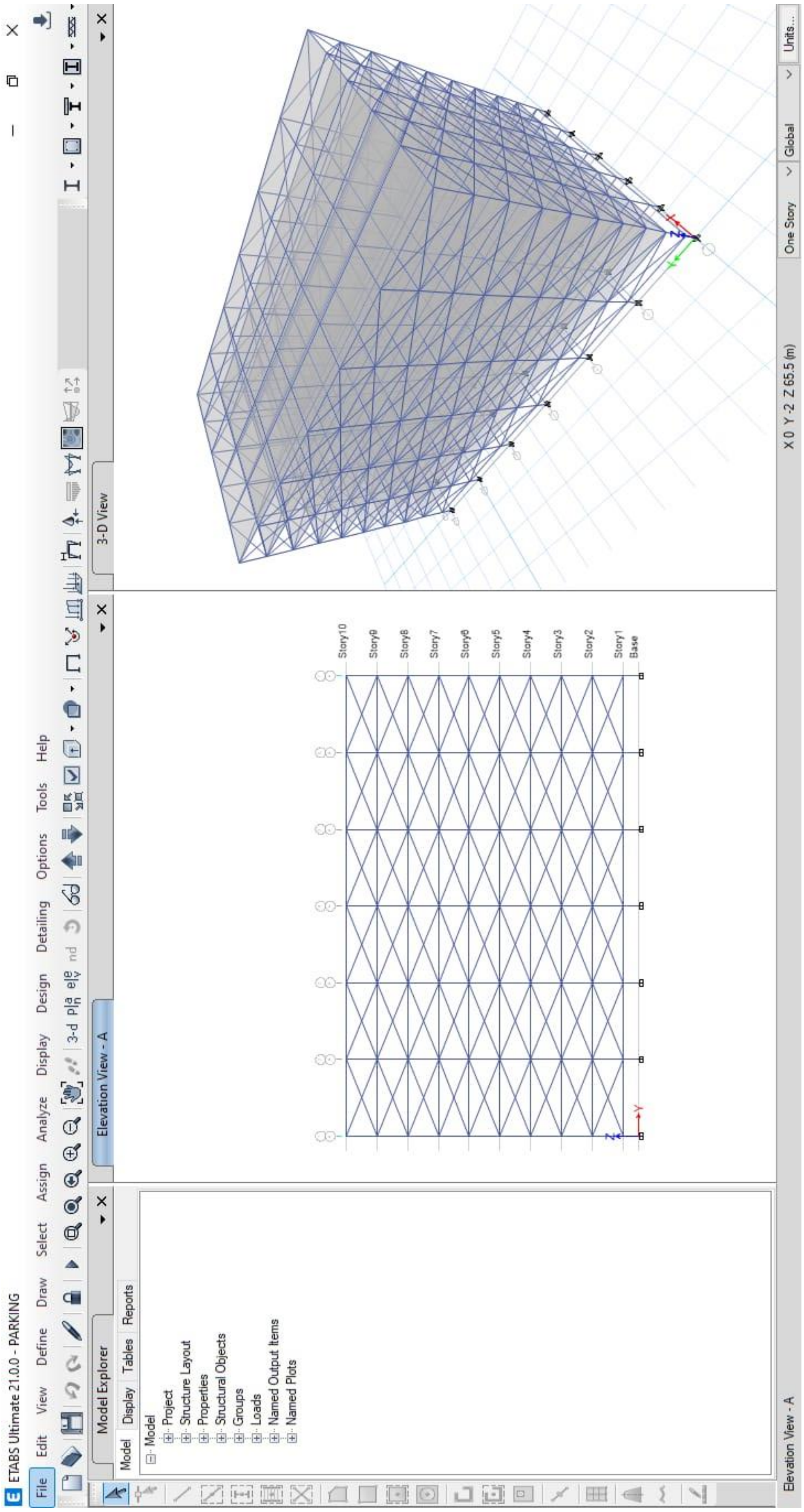

Figure 3. X-type bracing.

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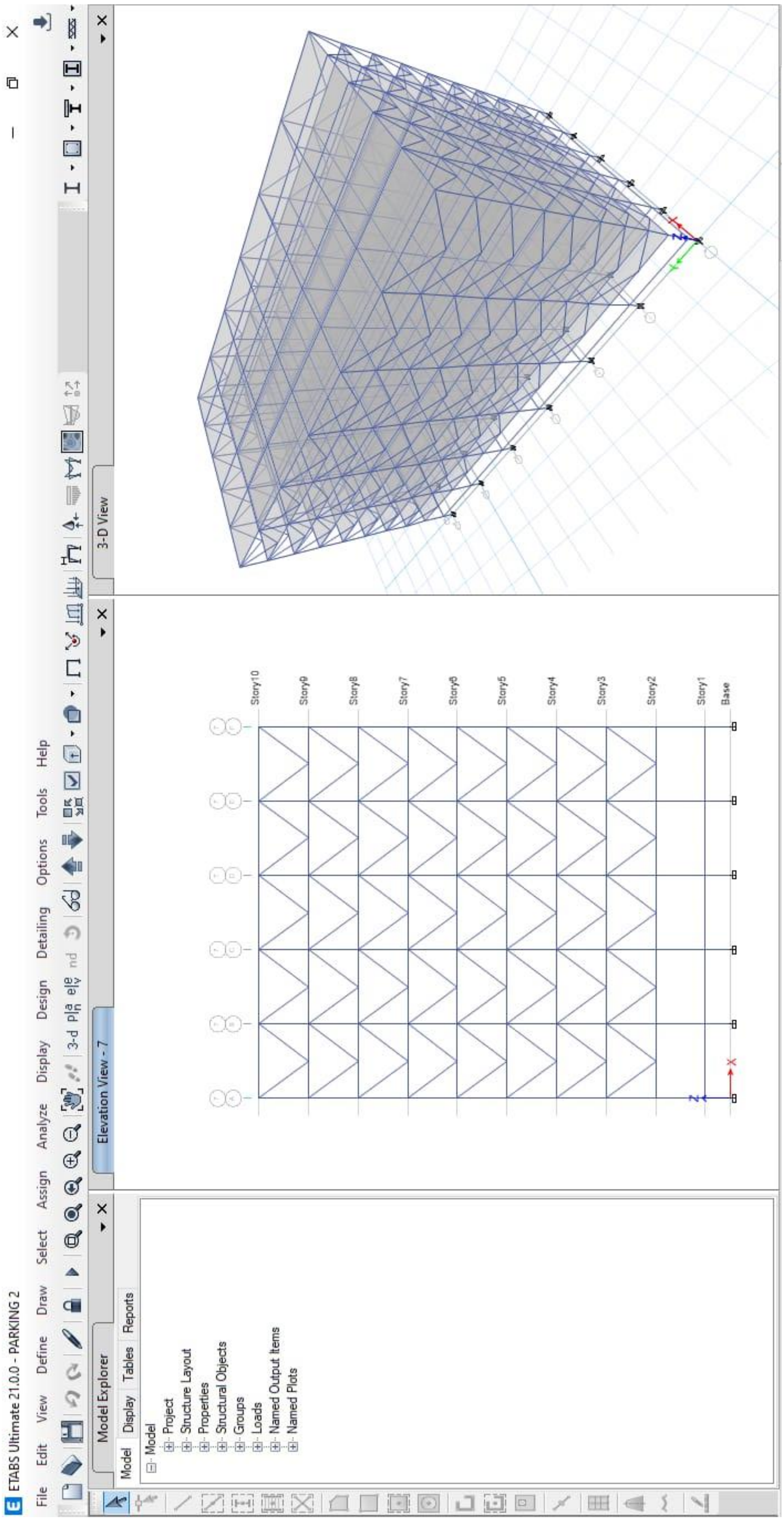

Figure 4. V-type bracing.

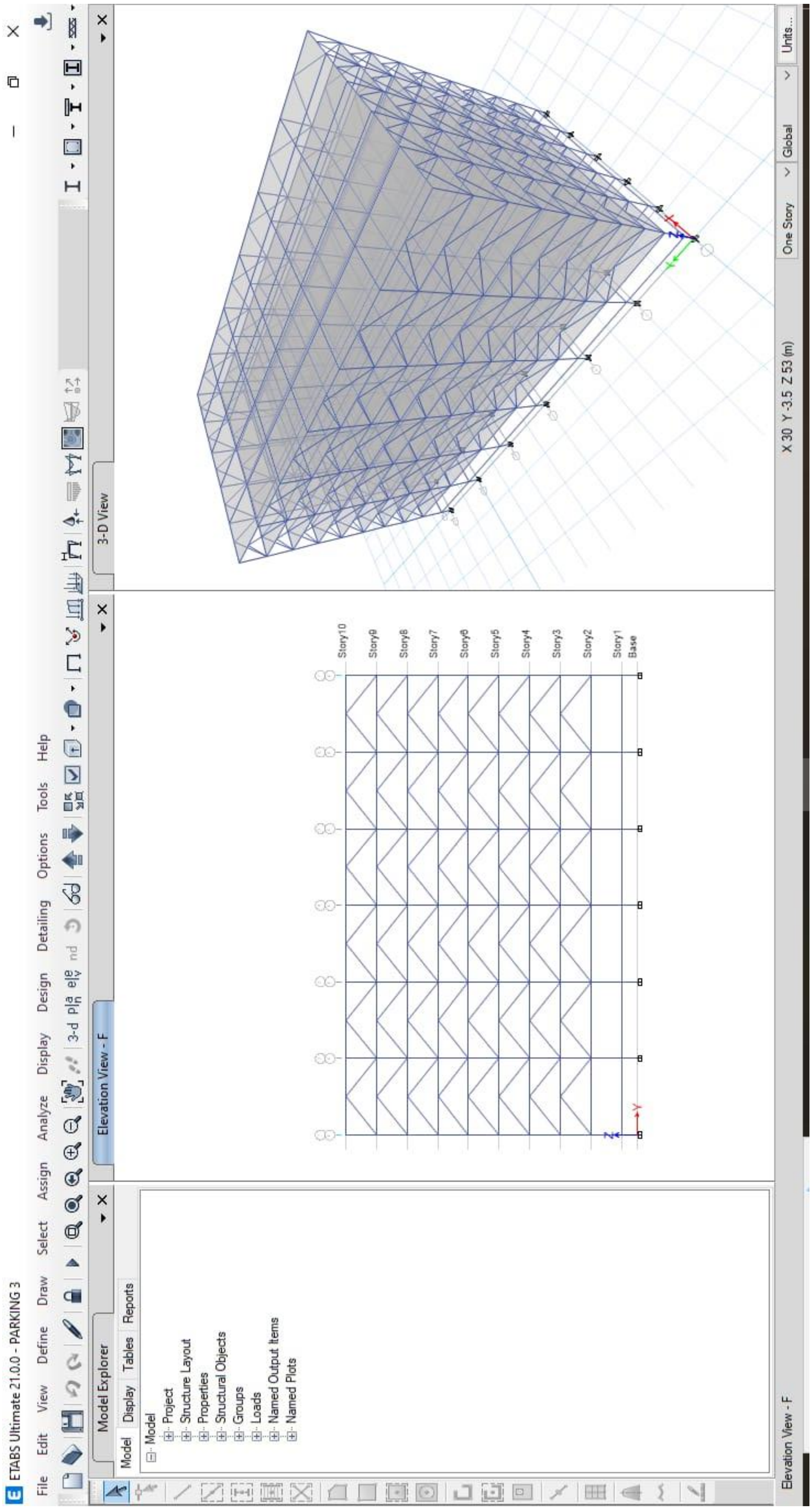

Figure 5. Inverted V-type bracing.

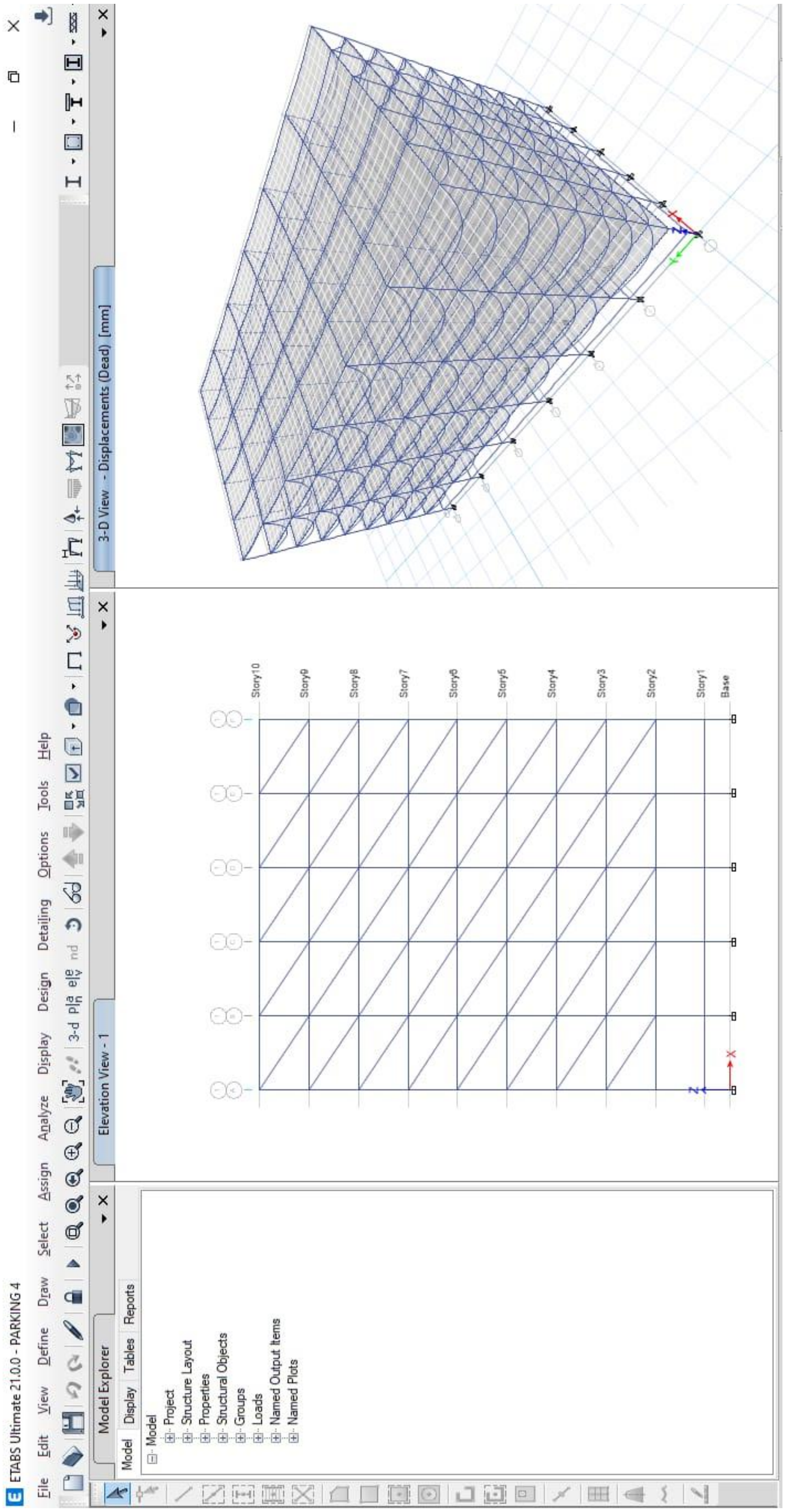

Figure 6. Eccentric back-type bracing.

PERFORMANCE ANALYSIS

Ten-story parking building has been analyzed and designed using ETABS by following provisions and specifications as per IS Code (BIS), The dimension of the longitudinal direction is 60 m and the transverse direction is 30 m. The height of the building is 32.5 m. There are six spans in the long direction and five spans in the short direction having 150 mm slab. For the determination of the performance of the parking structures with different bracing systems, story stiffness and drift parameters are used. A detailed elaboration of the results is given below by using some charts and tables.

Displacement Analysis

Displacement analysis measures the movement or deformation of a structure under applied loads, determining how much and in which direction parts of the structure shift. This analysis is essential for assessing the performance and safety of structures under various conditions, such as seismic activity, wind, or operational loads. Accurate displacement analysis helps in designing structures that can withstand expected forces without excessive deformation or failure (Figures 7–14 and Table 2).

Table 2. Story displacement in X and Y directions.

Table: Story response										
			X type		***Y type***		***Inverted V type***		***Eccentric back***	
Story	*Elevation*	*Location*	*X-Dir*	*Y-Dir*	*X-Dir*	*Y-Dir*	*X-Dir*	*Y-Dir*	*X-Dir*	*Y-Dir*
	m		mm	mm	mm	mm	mm	mm	mm	mm
Story10	38	Top	24.415	17.073	28.061	17.565	27.592	17.475	32.492	22.096
Story9	34	Top	24.595	16.373	27.117	17.006	26.706	16.927	31.381	21.348
Story8	30	Top	23.474	15.23	25.783	16.108	25.424	16.039	29.737	20.073
Story7	26	Top	22.118	13.729	24.138	14.94	23.833	14.883	27.656	18.362
Story6	22	Top	20.591	11.962	22.249	13.568	22.016	13.522	25.244	16.323
Story5	18	Top	18.959	10.012	20.249	12.055	20.054	12.019	22.609	14.052
Story4	14	Top	17.279	7.944	18.162	10.452	18.02	10.428	19.841	11.628
Story3	10	Top	15.613	8.52	16.065	8.816	15.992	8.812	17.039	9.12
Story2	6	Top	13.839	3.653	13.814	6.863	13.802	6.861	13.953	6.2
Story1	2	Top	2.421	1.684	2.407	1.245	2.407	1.247	2.408	1.079
Base	0	Top	0	0	0	0	0	0	0	0

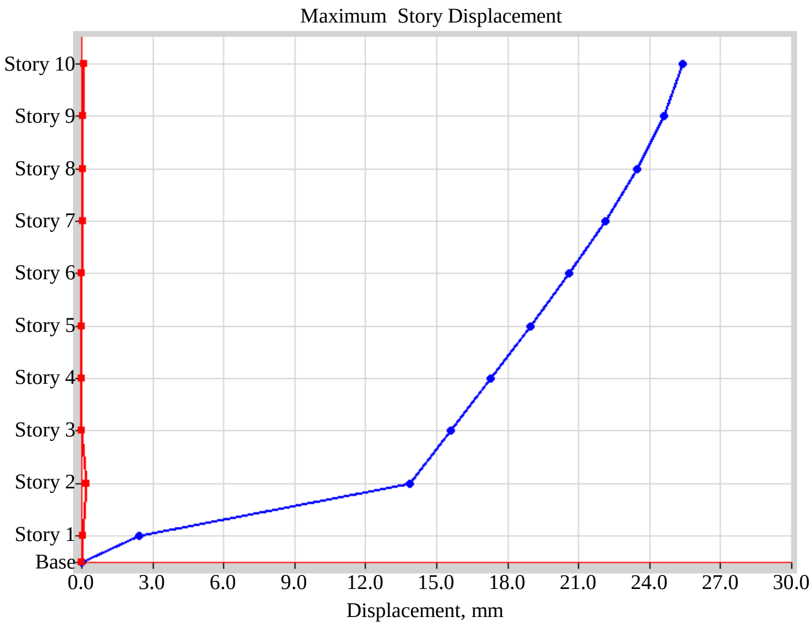

Figure 7. Displacement in X direction: X-type bracing.

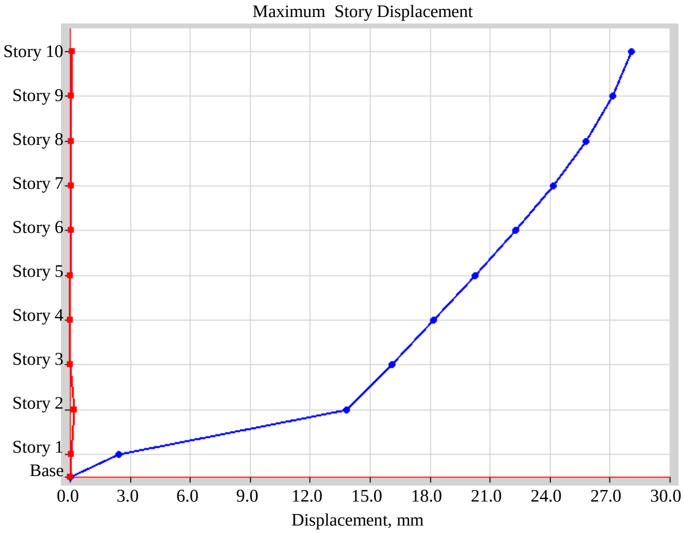

Figure 8. Displacement in X direction: V-type bracing.

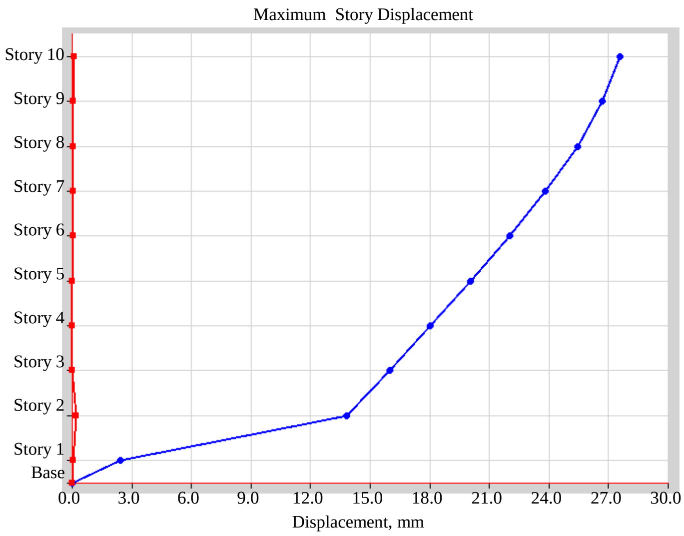

Figure 9. Displacement in X direction: inverted V-type bracing.

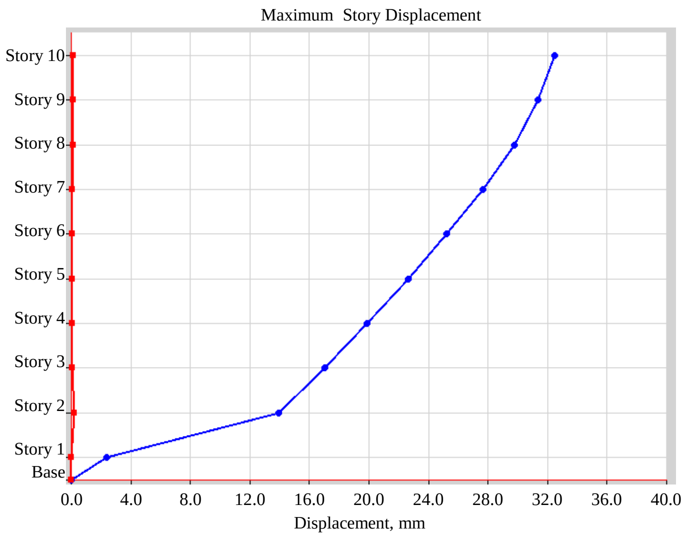

Figure 10. Displacement in X direction: eccentric back-type bracing.

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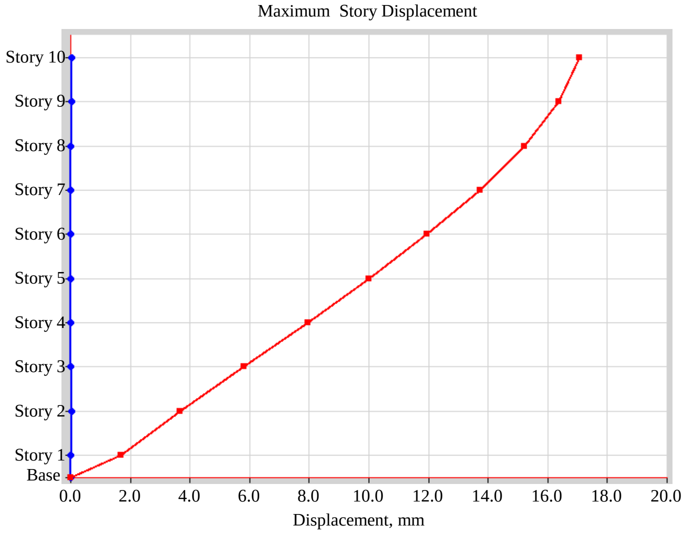

Figure 11. Displacement in Y direction: X-type bracing.

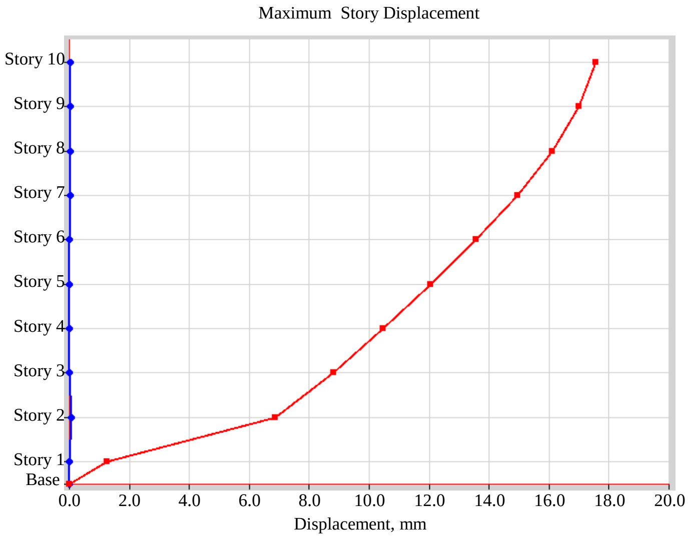

Figure 12. Displacement in Y direction: V-type bracing.

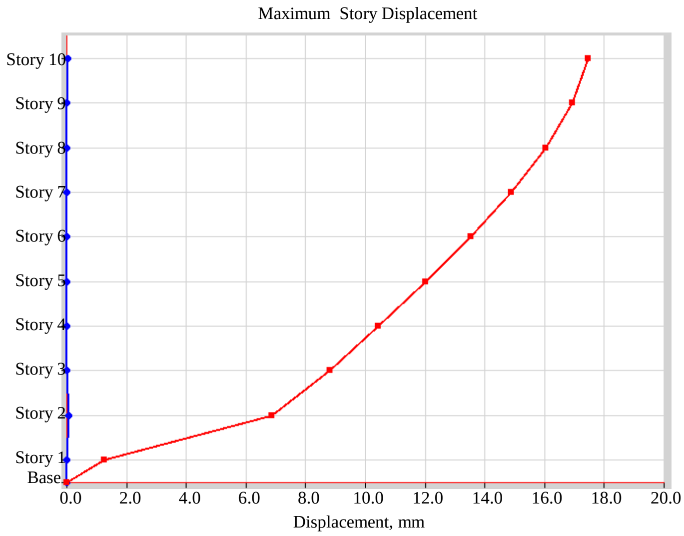

Figure 13. Displacement in Y direction: inverted V-type bracing.

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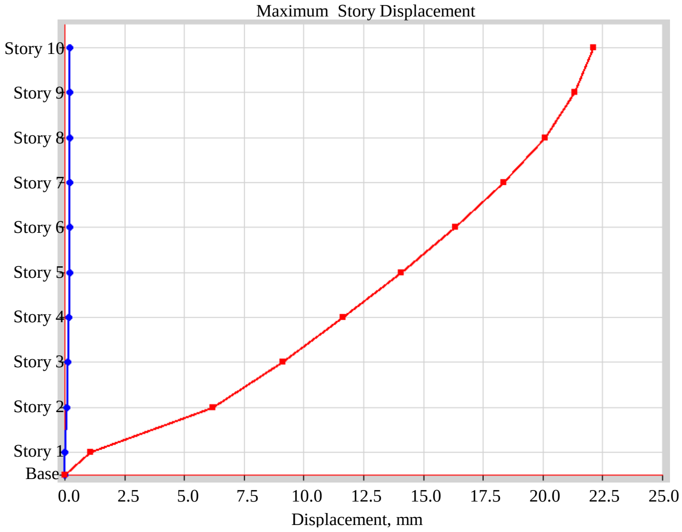

Figure 14. Displacement in Y direction: eccentric back-type bracing.

Table 3. Story stiffness in X direction.

Story	X Type	V Type	Inverted V Type	Eccentric Back Type
	Story Stiffness in X Direction			
10	589908	507709	542592.4	427808.69
9	777863	648241.4	675391.2	514531.073
8	865678	708405.1	732328.9	548902.987
7	918806	743360.9	765844.8	569149.941
6	958988	768809.7	791070.2	583957.035
5	995446	790973.5	813967.5	596644.552
4	1043071	817784.9	843125.6	613429.279
3	888892	714792.8	732965.8	551450.894
2	158283	157506	157412.3	155390.23
1	742979	742119.2	741894.7	739650.017

Table 4. Story stiffness in Y direction.

Story	X Type	V Type	Inverted V Type	Eccentric Back Type
	Story Stiffness in Y Direction			
10	1119869	1194686	1237308	734716
9	1249889	1359452	1381696	801244.2
8	1287596	1409547	1427180	814671.2
7	1308802	1436961	1452817	822379.2
6	1323556	1455973	1471262	827810.1
5	1336494	1471382	1486562	832223.1
4	1350824	1504762	1519217	837657.8
3	1340700	1253345	1261793	747895.5
2	1189272	453694.9	453462.6	424942.9
1	2559885	2045479	2044422	2012068

Story Stiffness Analysis: Story stiffness analysis assesses the rigidity of individual floors in a multistory building to ensure structural stability and performance under loads such as wind or seismic forces. This analysis helps in identifying potential weaknesses and ensuring that each story can adequately support the applied forces. Properly evaluating and optimizing story stiffness is crucial for the overall safety and resilience of the structure (Tables 3 and 4; Figures 15 and 16).

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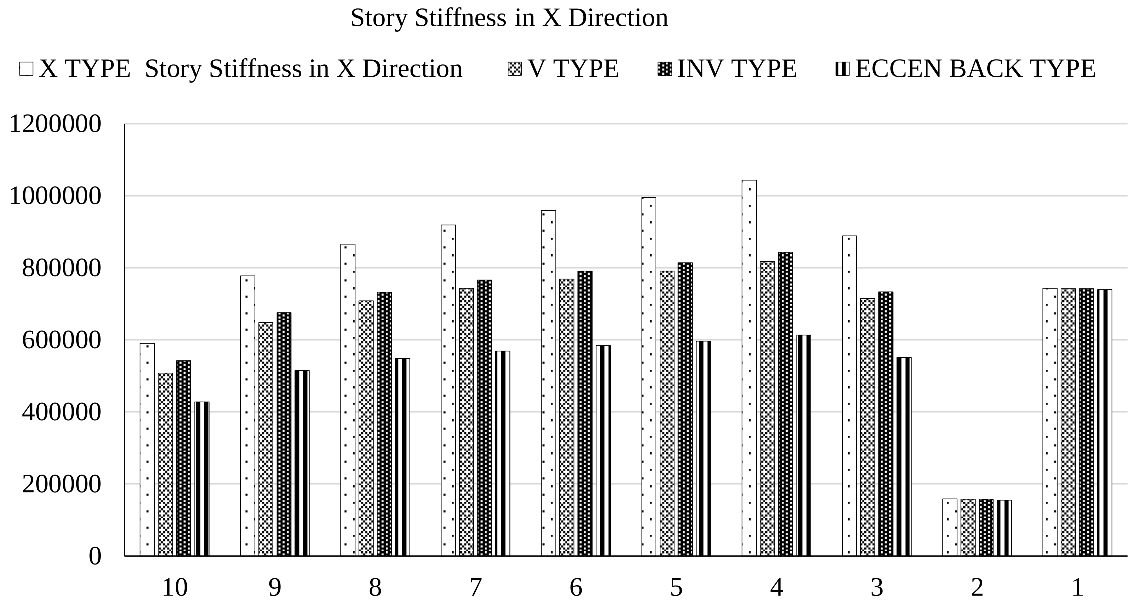

Figure 15. Story stiffness in X direction.

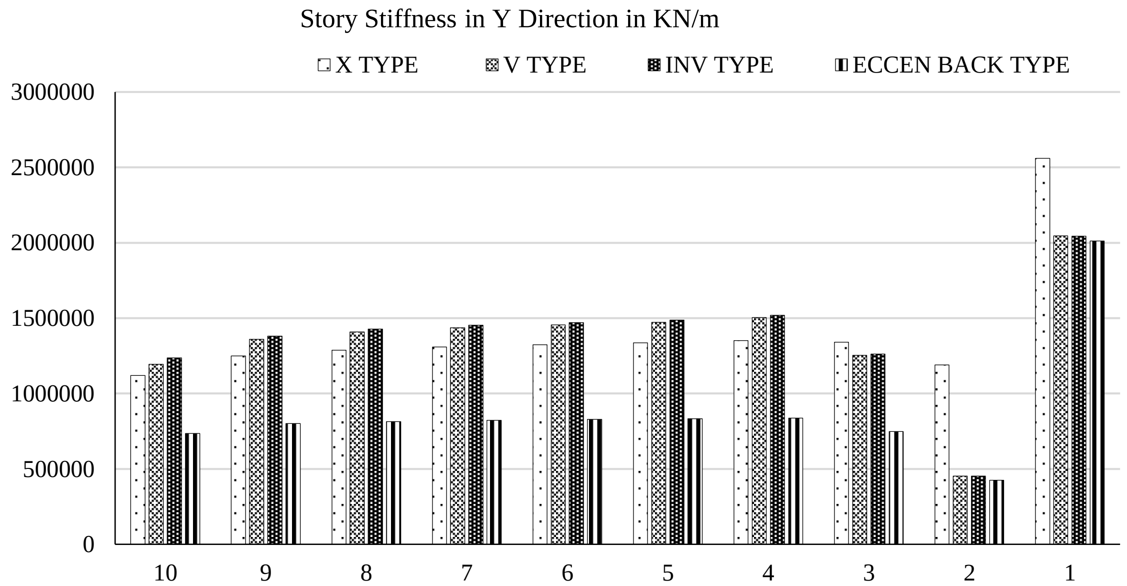

Figure 16. Story stiffness in Y direction.

Time Period Analysis

Time period analysis involves evaluating data collected over different time intervals to identify trends, patterns, and changes. This method helps in understanding temporal variations and can be applied to various fields such as finance, climatology, and marketing. By examining data points over specific periods, analysts can make more informed decisions and forecasts (Tables 5 and 6; Figure 17).

KEY CONSIDERATIONS

Structural Stability and Safety

- *X-type bracing* provides the highest lateral stiffness and is highly effective in ensuring the structural stability of tall buildings, making it a strong candidate for a G+10 structure.
- *Eccentric bracing* offers excellent energy dissipation and ductility, which is crucial for seismic resistance, but its complexity and higher cost may be a consideration.

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Table 5. Time period.

Mode	X Type	V Type	Inverted V Type	Eccentric Back Type
	Time Period			
	SEC			
1	2.141	2.214	2.203	2.335
2	1.231	1.52	1.519	1.672
3	1.136	1.428	1.424	1.619
4	0.59	0.639	0.633	0.709
5	0.408	0.438	0.436	0.54
6	0.328	0.364	0.363	0.445
7	0.303	0.335	0.335	0.384
8	0.241	0.241	0.241	0.309
9	0.215	0.237	0.236	0.271
10	0.176	0.192	0.192	0.239
11	0.174	0.189	0.189	0.214
12	0.172	0.167	0.167	0.214

Table 6. Comparison between X-type, V-type, inverted V-type, and eccentric bracings.

Feature	X-Type Bracing	V-Type Bracing	Inverted V-Type Bracing	Eccentric Bracing
Structural stability	High, provides significant lateral stiffness	Moderate, good lateral resistance	Moderate, good lateral resistance	High, excellent energy dissipation
Architectural flexibility	Low, can obstruct windows and doors	Moderate, less intrusive than X-bracing	Moderate, more flexible than X-bracing	High, offers more design flexibility
Material efficiency	High, efficient use of materials	High, efficient use of materials	High, efficient use of materials	Moderate, link segments require careful design
Ease of construction	Moderate, requires careful alignment	Moderate, easier than X-bracing	Moderate, requires precise connections	Complex requires specialized techniques
Cost	Moderate, material and labor costs	Moderate, potentially lower than X-bracing	Moderate, similar to V-bracing	High, due to complex design and construction
Maintenance	Moderate, regular inspection needed	Moderate, regular inspection needed	Moderate, regular inspection needed	High, especially after seismic events
Energy dissipation	Low, primarily resists forces without dissipation	Low, primarily resists forces without dissipation	Low, primarily resists forces without dissipation	High-link segments dissipate energy
Potential for buckling	Moderate, can buckle under compressive loads	Moderate, can buckle under compressive loads	Moderate, beam can buckle if not designed well	Low, designed to yield in a controlled manner
Load distribution	Even distribution across the structure	Even distribution across the structure	Even distribution, but stress at the meeting point	Concentrates on link segments, protecting the main structure
Interference with space	High, occupies significant interior space	Moderate, less intrusive than X-bracing	Moderate, can interfere with space utilization	Low, more flexible integration into the design
Suitability for tall buildings	High, very effective for tall structures	Moderate, effective for low to mid-rise buildings	Moderate, effective for low to mid-rise buildings	High, particularly beneficial for seismic areas

Architectural Flexibility and Space Utilization

- *V-type and inverted V-type bracings* offer more architectural flexibility and less interference with interior spaces compared to X-type bracing, which can be beneficial for parking layouts.
- *Eccentric bracing* also provides high flexibility in architectural design, allowing for more innovative and functional use of space.

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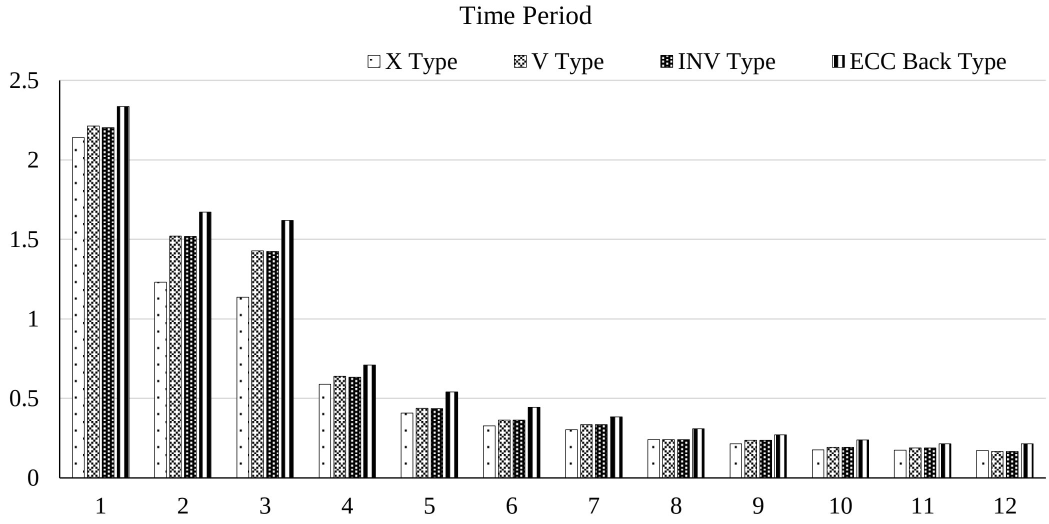

Figure 17. Time period graph.

Cost and Construction

- *V-type and inverted V-type bracings* are generally less expensive to construct than X-type and eccentric bracing due to their simpler design and fewer connection requirements.
- *X-type and eccentric bracings* may incur higher costs due to the need for precise construction techniques and materials.

Maintenance

- All types require regular maintenance, but eccentric bracing may have higher maintenance needs, especially after seismic events, due to the potential for damage to the link segments.

CONCLUSION

From the above total structural analysis of the parking structure by considering the various bracing systems, the following conclusions are drawn:

1. Maximum story displacement is found in structures with eccentric back-type bracing. It is near about 22.5% more than structures with X type of bracing.
2. In terms of story displacement, structures with X type of bracing will perform better than another type of bracing.
3. Story stiffness is found more in X type of bracing, that is, on the fourth floor. As the stiffness is more, it will perform well in all types of analysis conditions.
4. In the eccentric back type of bracing, near about 41.19% lesser value of story stiffness was found with respect to X type of bracing.
5. In V type bracing, near about 21.60% and in inverted V type bracing, 19.17% lesser story stiffness value was found with respect to X type of bracing. Time period was found to be the least in the structures with X type of bracing followed by inverted V type of bracing, V type of bracing, and eccentric back type of bracing.
6. Near about 8.30% variation in the time period was observed between the structures with X type of bracing and eccentric back type of bracing.

RECOMMENDATIONS

Primary Choice: X-Type Bracing

- For a G+10 parking building, X-type bracing is recommended as the primary choice due to its superior structural stability and effectiveness in resisting lateral forces. It ensures the safety and integrity of the building, especially under wind and seismic loads. However, architectural planning must account for the spatial constraints posed by the braces.

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Secondary Choice: V-Type or Inverted V-Type Bracing

- If architectural flexibility and interior space utilization are critical, V-type or inverted V-type bracing can be considered. These systems provide adequate lateral resistance while allowing for a more open and functional parking layout. They are also generally more cost-effective and easier to construct.

Seismic Considerations: Eccentric Bracing

- In regions with high seismic activity, eccentric bracing should be considered due to its excellent energy dissipation and ductility. Despite its higher cost and complexity, the enhanced safety and performance during earthquakes can justify the investment.

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