Seismic analysis and design of multilevel steel car parking

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ABSTRACT: India's rapid urbanization has led to significant parking challenges in urban areas. The traditional parking solutions are insufficient to accommodate the increasing number of vehicles. Multi-Level Car Parking (MLCP) systems present a viable solution, but their earthquake safety needs thorough examination, particularly in seismically active regions. This study evaluates the seismic performance of two G+6 multilevel car parking structures one constructed with reinforced concrete (RCC) and the other with structural steel. Both structures share identical dimensions (52.2 m × 30.80 m plan area and 21 m height) and were analyzed using STAAD Pro software. The analysis considered gravity loads according to IS 875 (Parts 1 and 2), wind loads as per IS 875 (Part 3) with a basic wind speed of 39 m/s for the Pune area, and seismic loads based on IS 1893:2016 for Zone III. The response spectrum and time history methods were employed to assess the structures' behavior during earthquakes. The findings indicated that steel structures outperformed RCC under seismic loads, exhibiting approximately 15% less base shear due to their lighter weight. Steel frames also demonstrated superior ductility (4.5 compared to 2.1 for RCC), enabling them to absorb more energy during seismic events. Although steel structures experienced greater lateral movement due to their flexibility, this characteristic helped mitigate damage by absorbing more shock. RCC structures were more rigid with less sway, but they encountered higher internal forces and were more prone to brittle failure. In summary, steel structures are more appropriate for earthquake-prone regions due to their enhanced flexibility, energy absorption, and reduced foundation loads. RCC may still be preferred where fire resistance and stiffness are prioritized.

Keywords: *Multilevel Car Parking, Seismic Analysis, Steel Structure, Response Spectrum Analysis, Time History Analysis*

1. INTRODUCTION

India is witnessing swift urban expansion, particularly in its major cities, driven by a growing population and rapid development. As urban migration increases, land has become both limited and costly (Khan et al., 2024) . This has compelled urban planners to focus on vertical growth rather than horizontal, resulting in the proliferation of multi-storey buildings for residential and commercial purposes (Mithun et al., 2021). Alongside this urban expansion, the number of personal vehicles, especially cars and two-wheelers, has surged in recent years. This increase in vehicles has led to significant parking challenges in metropolitan and tier-2 cities (Kummerle et al., 2009). Traditional on-street parking and small lots are no longer adequate to meet this rising demand, causing traffic congestion, reduced road capacity, and safety concerns (Faheem et al., 2024). One of the most effective solutions to this problem is the development of Multi-Level Car Parking (MLCP) structures. These systems are designed to optimize vertical space usage, accommodating a large number of vehicles within a smaller area (Wang et al., 2025). MLCP systems decrease the need for surface parking, free up public spaces, and help manage traffic flow (Biyik et al., 2021). They also reduce carbon emissions from vehicles that would otherwise idle while searching for parking spots (D. Zhao et al., 2012) . Modern MLCPs are equipped with features like hydraulic lifts or ramps to facilitate easy movement between floors. A well-designed layout ensures efficient vehicle flow, good ventilation, lighting, and enhanced user safety (Zhu et al., 2022). Security features such as CCTV cameras and controlled access are now standard in most MLCP designs (Devadhas Sujakumari & Dassan, 2023) . From a construction standpoint, steel and reinforced concrete (RC) are commonly used due to their combined advantages. Steel offers high tensile strength and long-span capabilities, reducing the number of columns and increasing usable space. RC provides strength and fire resistance, making the structure more durable and cost-effective (B. Zhao & Kruppa, 2004). This paper presents the structural modeling, analysis, and design of a steel-RC multi-level car parking structure using advanced design software. The goal is to create a space-efficient, durable, and user-friendly structure that supports sustainable urban development and meets growing parking needs. With the fast growth of cities in India, the need for organized parking systems has increased. Multi-level car parking structures are now commonly built in busy urban areas. These structures must be designed carefully to handle gravity loads, wind forces, and especially earthquake forces. This study focuses on analyzing the behavior of steel and reinforced concrete (RCC) multi-level car parking buildings under these loads, as per Indian Standards like IS 456:2000, IS 875, and IS 1893:2016 (Kavitha et al., 2022; Vedha & Pasha, 2019). Seismic analysis is done using two main methods: response spectrum and time history analysis. Response spectrum analysis helps to understand how buildings react to different modes of vibration during earthquakes. Time history analysis provides a more detailed study using real earthquake records (Mumtaj et al., 2023; Hassan & Chidananda, 2023).

2. RESEARCH SIGNIFICANCE

The seismic analysis and design of multilevel steel car parking structures hold significant research importance due to their increasing prevalence in urban areas and the critical need for earthquake-resistant infrastructure. These structures present unique challenges, combining the complexities of steel construction with the dynamic loads imposed by both vehicles and seismic events. Research in this field contributes to enhancing the safety and resilience of urban environments, particularly in earthquake-prone regions. By developing advanced analytical methods and design strategies, researchers can optimize the structural performance of these facilities, ensuring they remain operational during and after seismic events. This research also has broader implications for sustainable urban development, as efficient and earthquake-resistant parking structures can help alleviate land use pressures in densely populated areas while maintaining public safety. Furthermore, innovations in this domain can potentially be applied to other steel structures, contributing to the overall advancement of earthquake engineering and structural design practices. The integration of advanced materials and smart technologies in earthquake-resistant parking structures presents exciting opportunities for further enhancing their performance and functionality. Incorporating self-healing concrete, shape memory alloys, and adaptive damping systems could significantly improve the structures' ability to withstand and recover from seismic events. Additionally, the implementation of real-time monitoring systems and predictive maintenance algorithms could enable proactive management of these facilities, ensuring their long-term reliability and safety. The knowledge gained from research on earthquake-resistant parking structures can also inform the development of resilient infrastructure networks in urban areas. By applying similar principles to other critical facilities such as hospitals, schools, and transportation hubs, cities can create comprehensive seismic resilience strategies. This holistic approach to urban planning and design can lead to more robust and adaptable communities, better equipped to face the challenges posed by natural disasters and climate change.

3. METHODOLOGY

In this study, two G+6 multi-level car parking structures were modeled—one using reinforced concrete (RCC) and the other using structural steel. The main purpose was to compare how each building type performs under different types of loads. The modeling and analysis were carried out using STAAD Pro, which is widely used in structural engineering for load simulation and design. Both buildings were given the same layout, floor height, and plan dimensions so that the comparison would be accurate. Material properties were selected according to Indian Standards.

- The loads considered in the analysis included:

1. Dead and Live Loads, as specified in IS 875 (Part 1 and 2),
2. Wind Load, based on IS 875 (Part 3) for a basic wind speed of 39 m/s (Pune region),
3. Seismic Load, using IS 1893 (Part 1): 2016, applicable for Zone III.

- To assess the seismic performance, two methods were used:

1. Response Spectrum Analysis, which helps understand the peak building responses at different vibration modes.
2. Time History Analysis, which involves applying actual earthquake data to study building behavior over time.

Both models were supported by fixed base conditions. The appropriate load combinations were applied as per relevant IS codes. After completing the analysis, key results such as displacement, inter-storey drift, base shear, and natural time period were recorded. These values helped in comparing the behavior of RCC and steel buildings under lateral and gravity loads.

3.1 Analysis Procedure

The structural analysis for this project was done using STAAD Pro software. Two G+7 multi-level car parking buildings, one of reinforced concrete (RCC) and the other of steel were modeled with the same geometry, load conditions, and support types. Material properties for RCC and steel were defined as per Indian Standards. Dead loads, live loads, wind loads (based on IS 875 Part 3), and seismic loads (as per IS 1893:2016, Zone III) were applied. Both static and dynamic analyses were carried out. The dynamic part included response spectrum and time history methods to study how the buildings behave during earthquakes. The base was assigned fixed supports, and the software calculated storey displacements, drift, base shear, and mode shapes. These results helped to compare the overall seismic and structural performance of RCC and steel structures under real loading conditions.

Fig 1. Flow chart for Staad Analysis

3.2 Define geometries of building model

To study the behavior of a multi-level car parking structure under static and dynamic loads, a typical parking layout was selected. The structure is located in seismic Zone III, as per IS 1893, and is also designed to withstand gravity and wind loads. The analysis includes seismic forces, wind effects, and vertical loads using STAAD Pro. The basic wind speed is taken as 39 m/s, based on IS 875 (Part 3), as the building is located in Pune. The building has a rectangular floor plan with dimensions of 52.2 m ×30.80 m, and a total height of 21 m, consisting of G+6 storeys. The floor-to-floor height is 3 m, and the structure is modeled with regular grid spacing and column positions to represent typical car parking geometry. The study aims to assess the structural performance of the parking building under combined loading conditions and ensure safety and stability according to Indian standards.,

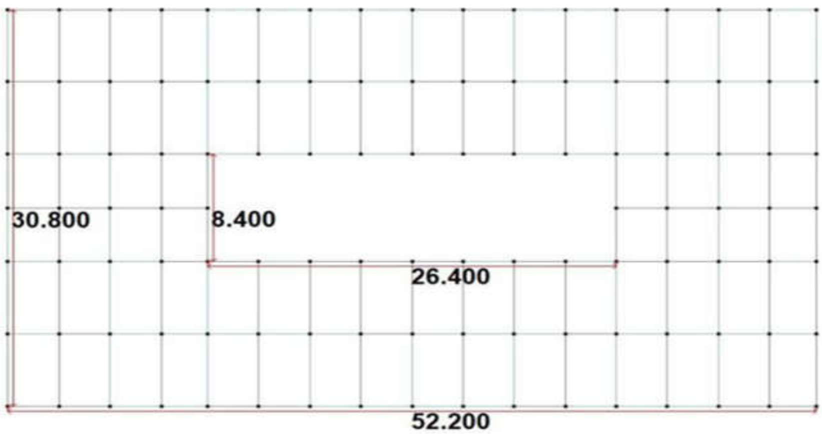

Fig 2. Plan view for the building

Structural Details of Steel Car Parking and RCC Car Parking Models

1. Steel Car Parking:

1. Plan area dimension for – 52.2 × 30.80 m
2. No. of floors in models – G + 7
3. Typical floor height – 3
4. Columns size for the building – ISHB 450
5. Beam dimensions for the building – ISMB 600

2. RCC Car Parking:

1. Plan area dimension for – 52.2 × 30.80 m
2. No. of floors in models – G + 6
3. Typical floor height – 3
4. Columns size for the building – 0.4 × 0.4 m
5. Beam dimensions for the building – 0.4 × 0.4 m

3.3 Define Material

1. Young's modulus of concrete -25 KN/M^3
2. Young's modulus of steel - $2X10^5$ KN/M^2
3. Density of reinforced concrete - 25 KN/M^3
4. Density of reinforced steel - 78.5 KN/M^3
5. Poisson's ratio of concrete - 0.2
6. Poisson's ratio of steel - 0.3

3.4 Define Load Cases

- **Dead Load** - The dead load for a parking structure is determined in the same manner as for any conventional building, and existing design codes do not offer separate guidelines specific to parking facilities. However, in such structures, most of the dead load arises from the self-weight of structural components, which tend to have more predictable dimensions compared to non-structural elements.

  1. Self-weight of structure
  2. UDL = 4.9 Kn/M (As per IS 875 Part-1)

- **Live Load** - A temporary or moving load that acts on a structure during its use.

  1. UDL = 4.5 Kn/M (As per IS 875 Part-2)

- **Wind Load -** The force or pressure exerted on a structure by the wind.

  1. **Design Wind Speed:** (As per IS 875 Part-3)

     a. Design wind speed = 39 Kn/M

     b. K1 = 0.92

     c. K2 = 1.05

     d. K3 = 1

     e. K4 = 1

     $V_Z = V_b. K_1.K_2. K_3. K_4$

     $= 37.673$

  2. **Design Wind Pressure:**

     $P_Z = 0.6 V_Z$

$= 22.60$

$P_d = K_d \times K_a . \times K_c . \times P_z$

$= 0.9 \times 0.9 \times 0.9 \times 22.60$

$= 16.47$

- **Seismic Load -** Seismic analysis is the study of how a structure behaves during an earthquake. It is important to make sure the building remains safe and performs well under ground shaking. This process takes into account how the building vibrates, how the materials respond, and the impact of earthquake forces. The two main methods used are the Response Spectrum Method and the Time History Method.
- **Response Spectrum -** The Response Spectrum Method is a widely used approach in earthquake analysis. It shows the maximum response of simple structures with one degree of freedom under ground shaking at different frequencies. This method simplifies earthquake data, making it easier to use for structural design. It is especially helpful for analyzing complex buildings because it gives quick and reliable estimates of how much a structure will move or vibrate.
- **Time History -** The Time History Method is a more advanced way to study how a building behaves during an earthquake. It uses real or simulated ground motion records and calculates how the structure moves, including its speed and acceleration, at every moment. This method gives a complete picture of the building's performance but needs a lot of computer processing and detailed earthquake data. Because of this, it is mostly used in special cases where high accuracy is needed, rather than in everyday building design.
- **Load Combination -** Once the basic load cases such as Dead Load (DL), Live Load (LL), and Earthquake Load (EL) were defined, various load combinations were applied in line with IS 875 and IS 1893 standards. The selected combinations include:

  a. 1.5(DL + LL)

  b. 1.2(DL + LL ± EQX)

  c. 1.2(DL + LL ± EQY)

  d. 1.5(DL ± EQX)

  e. 1.5(DL ± EQY)

  f. 0.9DL ± 1.5EQX

  g. 0.9DL ± 1.5EQY

  These combinations help simulate different critical loading scenarios the structure might experience during its service life. Additionally, a load envelope technique was adopted to capture the maximum and minimum internal forces across all load combinations. This ensures the design addresses the most severe effects, thereby enhancing structural safety and performance.

- **Load Envelope** - To evaluate the structural performance under different scenarios, multiple load combinations were applied as per IS 875 and IS 1893 standards, including 1.5(DL + LL), 1.2(DL + LL + EL), 1.5(DL + EL), and 0.9DL ± 1.5EL. In addition, two separate load envelopes were defined specifically for serviceability checks. These envelopes were created to capture the most critical responses such as maximum displacement and inter-storey drift under realistic load conditions. The use of these serviceability envelopes ensures that the structure remains safe, comfortable, and functional during regular use, without exceeding deflection or drift limits.

3.5 Add Support:

In the structural model, fixed supports were added at the base of all columns to represent the connection between the building and the ground. These supports prevent movement in all directions, helping to simulate real conditions where the structure is firmly attached to its foundation. Fixed supports are commonly used in seismic analysis to ensure accurate results, as they reflect how the base resists forces during an earthquake. This setup also helps in understanding how loads transfer from the structure to the ground.

4. RESULT

The program processed element forces, displacements, and performed steel design based on the input parameters. It generated various result files including joint displacement, support reactions, and design reports.

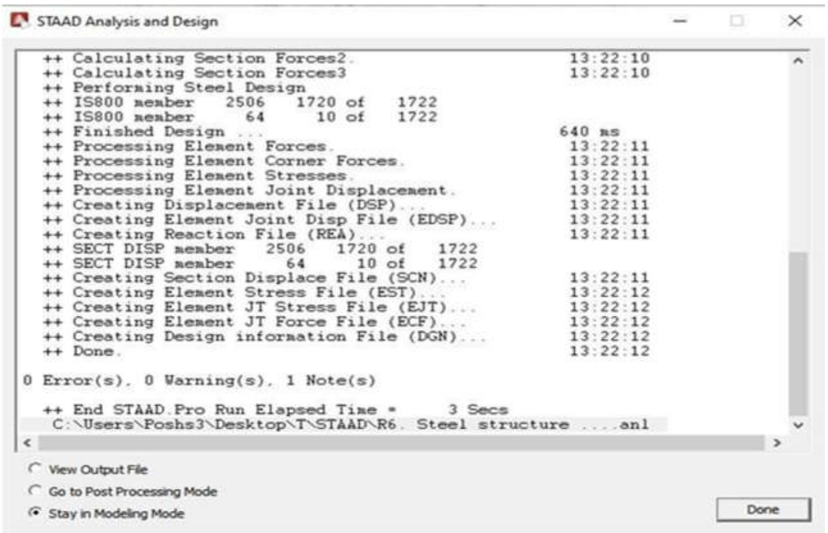

Fig. 3: STAAD.Pro Analysis and Design Output Window Showing Successful Completion of Steel Structure Analysis

4.1. Bending Moment Under Gravity, Wind and Seismic Load :

1. In steel structures, bending moments ranged approximately between 7.83 kN·m and 48 kN·m, while in RCC structures they were much higher, between 14.29 kN·m and 110 kN·m across all load cases.
2. The lower bending moments in steel are due to its lighter self-weight and greater flexibility, whereas the higher values in RCC result from its heavier mass and higher stiffness.
3. Moment distribution in steel was more uniform across floors and bays, indicating effective load sharing, while RCC showed variable moment distribution, with concentration in middle and lower stories.
4. Under lateral forces (wind and seismic), steel structures developed moderate moment values, whereas RCC attracted larger internal forces, especially at beam-column joints.
5. Negative moments in steel were small, ranging from -0.84 kN·m to -12 kN·m, suggesting greater rotational capacity and less restraint. In contrast, RCC exhibited larger negative moments, between -16.16 kN·m and -39.3 kN·m, reflecting strong fixity at supports.
6. Steel frames demonstrated ductile behavior, with the ability to redistribute stresses and dissipate energy effectively under all loading conditions.
7. RCC frames behaved as rigid systems, showing higher fixity and stiffness, which increased reinforcement requirements and cross-section sizes, leading to greater weight and construction cost.
8. Under seismic action, both structures showed the highest bending moments, but steel remained within 48 kN·m, while RCC exceeded 100 kN·m, indicating higher seismic demand in concrete structures.
9. Upper levels in steel carried relatively smaller moments under wind and seismic forces due to flexibility, whereas in RCC, larger moments were concentrated at lower and middle levels because of mass accumulation and base shear.
10. Overall, steel structures performed more efficiently under gravity, wind, and seismic loads, while RCC structures, though stronger and stiffer, faced higher internal forces and reinforcement demands.

4.2. Shear Force Under Gravity, Wind and Seismic Load :

1. In steel structures, shear force values generally ranged from 18.4 kN to 30 kN, with maximum values around 21.6–23.3 kN under gravity, 18.4–23.4 kN under wind, and up to ~30 kN under seismic loading.

2. In RCC structures, shear forces were much higher, varying from 53.3 kN to 90 kN across different loads: 53.3–62.7 kN under gravity, 24.5–63.6 kN under wind, and peaking at 85–90 kN under seismic conditions.
3. The lower shear demand in steel is due to its lighter self-weight and flexibility, while the higher values in RCC are caused by greater stiffness and mass, which attract larger internal forces.
4. Steel structures showed uniform shear distribution across all levels, indicating smooth load transfer and minimal localized concentrations. By contrast, RCC exhibited non-uniform distribution, with forces concentrated at the lower stories where gravity load accumulation, stiffness, and mass effects are highest.
5. Negative shear in steel was relatively small, ranging between -0.27 kN and -27 kN, occurring near supports or moment reversal points. In RCC, negative shear was far greater, reaching -25.8 kN to -70 kN, highlighting rigid end conditions and strong moment reversals.
6. The flexibility and ductility of steel allowed it to absorb and redistribute shear forces efficiently, avoiding stress concentrations and reducing the risk of brittle failure.
7. RCC frames, being rigid, concentrated shear at beam-column joints and base regions, leading to high reinforcement demand and the need for dense stirrup spacing, web thickening, or additional shear walls.
8. Under seismic loading, shear demands were highest for both systems, but while steel remained limited to ~30 kN, RCC exceeded 85–90 kN, demonstrating the impact of mass participation and inertia in concrete structures.
9. Steel frames can be optimized with lighter shear reinforcement or web stiffeners, reducing cost and material use, whereas RCC frames require robust seismic detailing, such as confinement zones, closely spaced stirrups, and shear walls to prevent cracking or brittle collapse.
10. Overall, steel structures displayed consistent and resilient shear behavior under gravity, wind, and seismic conditions, while RCC structures, though strong, faced significantly higher shear concentrations and reinforcement demands due to their rigidity and mass.

4.3. Axial Force Under Gravity, Wind and Seismic Load :

1. In steel structures, axial forces generally ranged between 31.9 kN at upper levels and ~512.4 kN at base columns, while in RCC structures they were much higher, ranging from 126 kN at upper levels to ~2020 kN at base columns.
2. Steel frames showed smooth and gradual axial force reduction from base to top stories, reflecting their lighter self-weight and flexible load transfer mechanism. In contrast, RCC frames exhibited abrupt and steep variations, especially in lower stories, due to their heavier mass and stiffness.
3. Under gravity loads, axial forces in steel base columns ranged from 221.3–482.9 kN, while RCC columns carried up to 1800 kN, indicating nearly three to four times higher demand in RCC.
4. Under wind loads, steel columns at the base carried 418–482 kN, whereas RCC columns carried much larger forces, between 1500–1820 kN, reflecting greater mass participation.
5. Under seismic loads, axial forces peaked in steel columns at ~512 kN, while RCC columns reached 1700–2020 kN, showing significantly higher seismic demand on concrete frames.
6. Negative axial forces (uplift) were observed under seismic conditions, reaching –245.7 kN in steel and about –150 kN in RCC, caused by sway and moment reversal at upper or outer columns.
7. Central columns in both structures consistently carried higher forces than exterior ones. In RCC, central column loads were 3–4 times greater than those in outer columns, while steel showed a more balanced distribution due to load-sharing flexibility.
8. Steel's bracing and ductility allowed effective redistribution of axial forces, minimizing extreme stress concentrations. On the other hand, RCC's rigid frame behavior caused direct vertical load transfer with limited redistribution.
9. The lighter weight of steel resulted in lower cumulative axial forces, reducing the risk of compressive failure or buckling, while RCC required much larger cross-sections and heavy reinforcement to handle the higher demands.
10. Seismic effects amplified axial forces more sharply in RCC compared to steel, with inner RCC columns recording 1700–2020 kN, whereas steel inner columns remained around 470–512 kN.

11. Outer columns in steel carried ~230–290 kN under seismic load, while RCC outer columns carried 230–310 kN, but the difference between inner and outer column loads was much larger in RCC due to frame rigidity.
12. The overall axial force gradient in steel was smoother and more uniform across height, while RCC exhibited steeper gradients and concentrated forces at base and central columns.
13. Design implications: Steel frames allow optimization with smaller sections and lighter reinforcement, whereas RCC frames demand large column dimensions, dense reinforcement, and sometimes shear walls to safely carry axial forces under combined gravity, wind, and seismic loads.

4.4. Displacement

1. Under gravity loading, both steel and RCC structures exhibit minimal displacement since the load is vertical and uniformly distributed. The vertical deformation is negligible and primarily influenced by axial shortening in columns. Lateral displacement is nearly zero.
2. In the case of wind loading, the displacement pattern becomes more evident due to lateral forces acting perpendicular to the structure.
3. For steel structures, displacement is more flexible and evenly distributed across the height due to the inherent ductility of steel. For RCC structures, lateral displacement is less compared to steel, owing to their higher stiffness and heavier mass. However, this stiffness also leads to less energy dissipation, concentrating movement at higher levels.
4. Seismic loading introduces dynamic horizontal forces, causing the most significant displacement behavior across all loading types.
5. The base of both structures remains relatively fixed due to support conditions, while displacement increases progressively toward the top stories, forming a triangular (cantilever-like) deformation profile.
6. In steel frames, the maximum lateral displacement is higher due to lower stiffness but occurs in a more uniform and ductile manner. This flexibility allows steel structures to sway without brittle failure, effectively dissipating seismic energy.
7. In RCC structures, the displacement is lower in magnitude but sharper at certain joints or story levels. The stiffer frame resists sway but lacks the energy absorption capacity of steel, making it more vulnerable to cracking or localized damage.
8. Displacement concentration in steel structures is observed at upper stories and corners, where combined lateral forces and dynamic amplification are the highest. This distribution remains consistent across different load types but is most severe during earthquakes.
9. In RCC frames, the displacement is more centralized toward the top-middle part of the structure. Due to higher mass and stiffness, the dynamic response is stiffer, resulting in higher base shear forces and lower overall drift but more intense local deformation.
10. Comparing structural drift, Steel frames experience larger but more distributed drift, minimizing stress concentrations. RCC frames show lower drift overall, but abrupt transitions between stories may lead to a soft-story effect, especially under seismic excitations.
11. The displacement under wind is intermediate between gravity and seismic response for both materials. Steel shows moderate sway that is easily absorbed due to elasticity. RCC resists better due to mass and rigidity, but requires larger section sizes to control drift.
12. Finally, displacement control is essential in both systems. While steel allows more flexibility in tolerating lateral drift, RCC depends on strength and stiffness, making displacement-sensitive detailing crucial to prevent functional or structural damage during earthquakes.

Table 1: Comparison of Displacement for Steel and RCC structure

Parameter	**Steel Structure**	**RCC Structure**
Max Displacement (Gravity Load)	Negligible (< 1 mm)	Negligible (< 1 mm)
Max Displacement (Wind Load)	Moderate (15–25 mm at top)	Low to moderate (10–18 mm at top)
Max Displacement (Seismic Load)	High (45–60 mm at top stories)	Medium (30–40 mm at top stories)
Displacement Profile	Gradual increase from base to top	Triangular, more rigid in lower stories
Lateral Drift (Seismic)	Higher, more flexible	Lower, but with sharp transitions
Energy Dissipation	High (due to ductility)	Moderate (due to stiffness)
Deformation Localization	Top corners and beam-column joints	Top-center and soft-story regions
Influence of Axial Forces	Higher axial flexibility - more movement	High base axial load - localized displacement
Design Implication	Requires drift checks and ductile detailing	Requires crack control and stiffness checks
Story-wise Drift Consistency	Uniform distribution	Uneven drift, possible soft-story formation

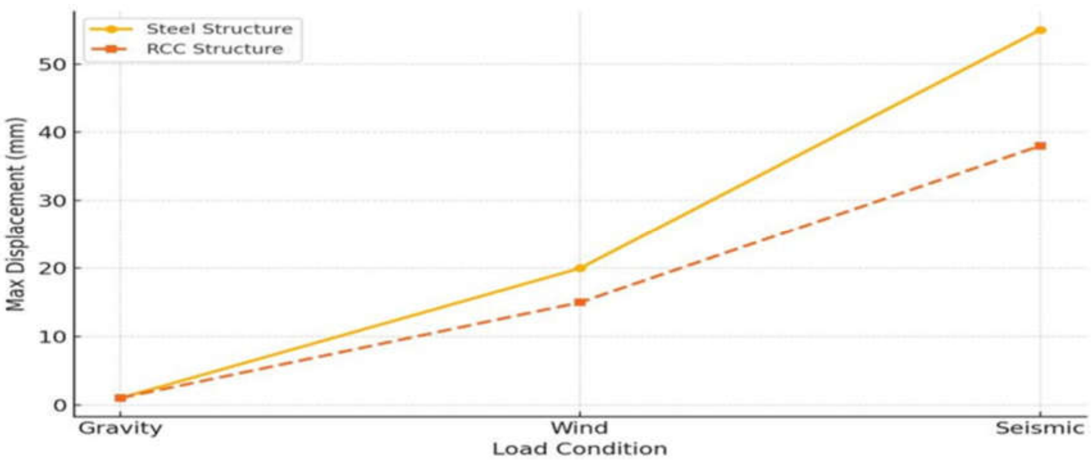

Fig 4. Displacement under Gravity, Wind and Seismic load

4.5. Inter storey drift

1. Inter-storey drift refers to the relative lateral displacement between two consecutive storeys during lateral loading (wind or earthquake). It is a critical measure of a structure’s flexibility and seismic performance.

2. Under gravity loading, inter-storey drift is negligible for both steel and RCC structures since the loads are vertical. The structural elements primarily experience axial compression with minimal horizontal movement.

3. When subjected to wind loading, noticeable inter-storey drift occurs, particularly at upper levels:
    a. In steel structures, the drift is more uniform across all storeys due to the flexible nature of steel. It distributes the load more gradually, which helps reduce the risk of damage at any specific level.
    b. RCC structures, on the other hand, show lower drift values because of their higher stiffness. However, the drift distribution is less uniform, and minor irregularities in stiffness can cause sudden changes in drift between adjacent storeys.
4. Under seismic loading, inter-storey drift becomes most pronounced and significant:
    a. Steel frames allow larger lateral deformation with greater ductility, which results in higher inter-storey drift values but spread consistently over the building height. This helps dissipate seismic energy and delay structural failure.
    b. RCC frames, while stiffer, experience less overall drift but are more vulnerable to abrupt drift concentration at specific levels. This is especially critical if a soft-storey condition exists, such as an open ground floor for parking, where lateral stiffness is suddenly reduced.
    c. The maximum inter-storey drift generally occurs in the middle to upper floors, especially under seismic excitation. This is supported by your previous displacement results, where both steel and RCC structures exhibited peak lateral movement at upper levels.
5. Drift control is essential for both structural safety and functional performance. Excessive drift can:
    a. Cause damage to non-structural elements like cladding, partitions, and glazing.
    b. Lead to discomfort for occupants.
    c. Compromise the structure's stability, especially in RCC buildings with stiffness irregularities.
6. In conclusion, inter-storey drift is more pronounced in steel structures but managed more safely through flexibility. RCC structures resist drift through stiffness but may face critical points of vulnerability. Accurate modeling and detailing are essential to mitigate seismic impact on drift behavior.

Table 2: Comparision of Inter storey drift for Steel and RCC structure

Floor Level	Drift (mm) - Steel Structure	Drift (mm) - RCC Structure
Ground	0.40	0.50
1st	0.90	0.70
2nd	1.50	1.00
3rd	2.00	1.20
4th	2.50	1.40
5th	3	1.50
6th	3.30	1.55
7th	3.50	1.60

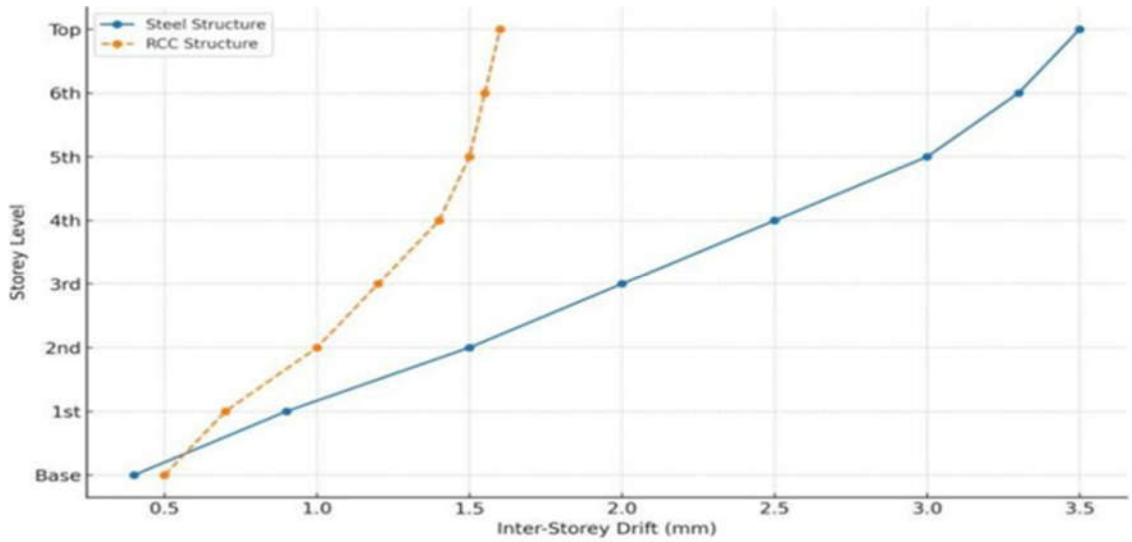

Fig 5. Inter storey drift for Steel and RCC Structure

4.6. Time Period

The Time History Analysis of the steel multilevel car parking structure reveals the structure's behavior under dynamic seismic loading. The following observations are made:

1. **Displacement Response:** The Y-direction shows the highest peak displacement (approx. 99.6 mm), indicating strong lateral movement under earthquake excitation. The X and Z directions show smaller but noticeable displacement responses. Oscillations decrease over time due to inherent damping in the structure.

2. **Velocity Response:** The Y-direction again dominates, with peak velocity reaching around 878 mm/sec. The steel structure's flexibility contributes to faster motion responses, with sharp peaks followed by gradual decay.

3. **Acceleration Response:** Acceleration in the X and Z directions shows sharp initial spikes (e.g., 606 mm/s² in X, 355 mm/s² in Z) followed by rapid damping. These accelerations indicate how quickly seismic forces are imparted and how effectively the structure absorbs them.

Overall, the steel frame responds quickly due to its lower mass and higher flexibility, making it efficient in energy dissipation. However, it may require additional considerations for drift and stability control.

For the RCC (Reinforced Concrete) multilevel car parking structure, the Time History Analysis shows a different dynamic behavior due to its stiffer and heavier characteristics:

1. **Displacement Response:** Peak displacements are observed mainly in the Y-direction but are significantly lower than in the steel counterpart. The stiffer nature of RCC leads to less lateral sway but slower oscillatory motion.

2. **Velocity Response:** The velocity response is also more moderate compared to steel. The peak values are lower, and the waveform is broader, showing that the RCC structure responds more sluggishly but with more consistent momentum transfer over time.

3. **Acceleration Response**: The RCC structure exhibits higher acceleration peaks at initial seismic impulses but settles quickly. This is due to its higher mass resisting motion but transferring higher force levels initially.

RCC structures tend to show more robust resistance to lateral motion and better stability, but they respond more slowly compared to steel structures. Their higher damping and stiffness reduce prolonged oscillations.

4.7. Stability

1. Structural stability refers to the ability of a structure to maintain its position and configuration under applied loads without undergoing excessive deformation or collapse.

2. Under gravity loading, both steel and RCC structures exhibited stable behavior:

   a. The axial forces were primarily vertical and concentrated at base columns, with RCC showing higher magnitudes due to its greater self-weight.

b. The uniform load distribution and minimal lateral movement contributed to overall structural equilibrium.

3. Under wind loading, lateral forces introduced additional moments and shear:

a. Steel structures showed good stability due to their flexible nature. Although lateral displacement was higher compared to RCC, the uniform distribution of forces across members prevented instability.

b. RCC structures, with greater stiffness, had lower displacement and shear magnitudes but faced sharper internal force variations. This indicates a more rigid, but potentially brittle, stability mechanism.

4. Under seismic loading, stability is most critical due to dynamic and unpredictable ground motions:

a. Steel structures maintained stability through ductile behavior, allowing them to absorb and dissipate seismic energy. The larger inter-storey drift values were within safe limits, and the structure was able to realign after movement.

b. RCC structures, while more resistant to initial displacement, were found to have concentrated forces at central and base columns, increasing the risk of local failure if not adequately detailed (e.g., soft- storey effect).

c. Bending moment and shear force analysis confirmed that steel structures experienced more uniform distribution of internal forces, which aids in stability under dynamic loading.

d. RCC structures showed higher peak values, particularly in central columns and lower storeys, which increases the demand on those members to resist failure.

e. Axial load comparison highlighted that steel structures had lower maximum axial force values, reducing the likelihood of column buckling. In RCC, the high axial loads near base columns require robust section design and foundation detailing to ensure stability.

5. Overall, both structural systems can achieve adequate stability under all loading conditions if designed as per Indian Standards (IS 456 for RCC, IS 800 for steel, and IS 1893 for seismic design). The steel structure offers better post-yield performance and energy dissipation, whereas the RCC structure relies heavily on stiffness and strength but is less forgiving in dynamic scenarios.

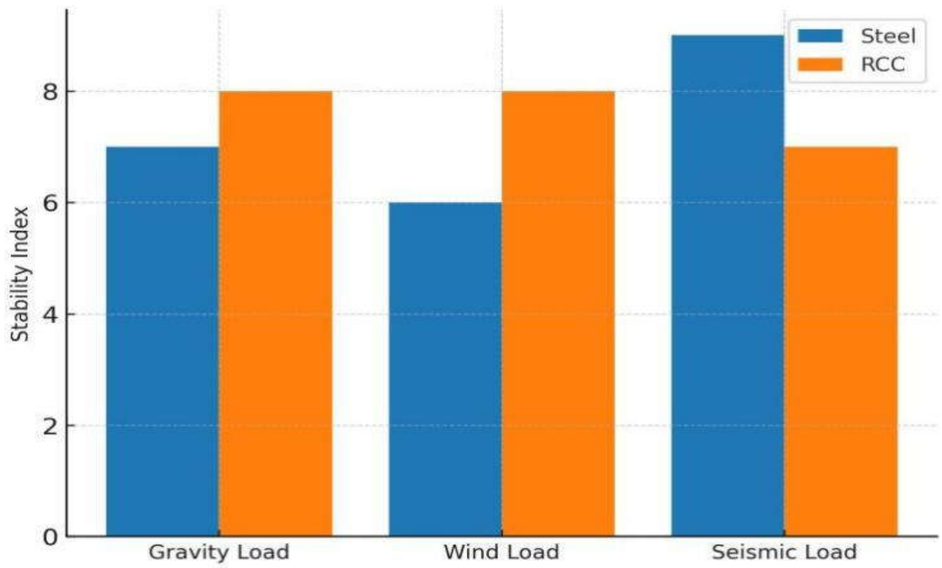

Fig 6. Stability under Gravity, Wind and Seismic load

4.8. Energy Dissipation

1. Energy dissipation is a key indicator of how a structure manages seismic or dynamic forces. It refers to the structure's ability to absorb and dissipate the energy imparted by external loads—especially during events like earthquakes—without undergoing catastrophic failure.

2. Under gravity loads, energy input is minimal and primarily vertical.
3. Both steel and RCC structures dissipated energy mainly through internal resistance mechanisms like axial compression, flexure, and shear, with negligible hysteretic behavior. Since there are no cyclic or dynamic effects, dissipation was stable and passive in nature.
4. Under wind loading, lateral forces introduced minor dynamic behavior: Steel structures, with their flexible frames, allowed controlled sway, and some energy was dissipated through bending in beams and columns. RCC structures remained more rigid under wind due to their higher stiffness, and energy dissipation occurred mostly through concrete cracking and internal damping.
5. Under seismic loading, significant energy was introduced in the form of base excitation and inertial effects, which tested the dynamic resilience of both systems.
6. Steel Structure: Exhibited superior ductility, allowing members to undergo large deformations without failure.
7. Energy was dissipated effectively through plastic hinge formation at beam-column joints and yielding of steel elements. The structure displayed a stable hysteretic response, allowing it to absorb multiple cycles of seismic motion.
8. RCC Structure: Dissipated energy primarily through cracking in concrete, micro-crushing, and bond slip between concrete and reinforcement.
9. Exhibited less ductile behavior compared to steel, with a stiffer seismic response and more limited deformation before damage.
10. Due to higher stiffness and mass, it attracted larger base shear and bending moments (up to 85.4 kN·m), leading to localized energy concentration.
11. The energy dissipation was more dependent on the material damping and cracking rather than redistribution of internal forces.
12. Overall energy dissipation capacity:
    a. Steel structures act like energy-absorbing systems, prioritizing ductility, flexibility, and hysteretic damping. They are well-suited for seismic zones.
    b. RCC structures rely more on stiffness and damping, and their energy dissipation is largely governed by the nonlinear behavior of concrete and reinforcement interaction.

4.9. Base Shear

A. For Steel Structure -

1. The total dynamic weight of the steel structure was computed as approximately 31,690.44 kN in both X and Z directions, confirming symmetric mass distribution. Missing mass contributions were minimal (approximately −189.3 kN in X), suggesting adequate mode coverage.
2. The base shear in the X-direction was calculated as 563.83 kN, with the shear force reducing progressively with height. The peak story shear values observed at various levels were:
    a. At base (0.0 m): 563.83 kN
    b. At 1st floor (3.0 m): 563.83 kN
    c. At 2nd floor (6.0 m): 520.79 kN
    d. At 3rd floor (9.0 m): 462.87 kN
    e. At 4th floor (12.0 m): 395.33 kN
    f. At 5th floor (15.0 m): 316.86 kN
    g. At 6th floor (18.0 m): 224.88 kN
    h. At 7th floor (21.0 m): 117.25 kN
3. The above data clearly indicates that seismic lateral forces accumulate toward the base, a typical pattern for multistory buildings under earthquake loading.

4. Modal analysis revealed that the first three modes have spectral accelerations ranging from 1.19129 to 1.20899 g, contributing the most to overall seismic response. These modes are predominantly translational in the X-direction.
5. From mode 4 onward, spectral acceleration is capped at 2.5 g, corresponding to a design seismic coefficient of 0.04, indicating that these higher modes fall into the flat part of the design spectrum.
6. A uniform 5% damping ratio was assumed across all modes, as per standard seismic design practice for steel structures.
7. The steel structure demonstrated a high degree of flexibility, evident from moderate displacement values and lower peak bending moments (approximately 29.36 kN-m max) compared to the RCC counterpart (≈85.437 kN-m). This flexibility leads to better force redistribution and energy dissipation.
8. Story shear patterns confirm efficient lateral load transfer, with the structural system effectively mobilizing stiffness and strength to resist dynamic loads.
9. No significant response was recorded in the Y or Z directions, indicating either uniaxial excitation (X-direction only) or symmetry in geometry and loading.

B. For RCC Structure -

1. The fundamental time periods for the first three modes are 1.078 sec, 1.063 sec, and 1.016 sec respectively, indicating moderate structural flexibility under seismic loading.
2. The frequency range spans from 0.928 Hz to 20.2 Hz, capturing both global and local vibration modes throughout the structure.
3. The first two modes contribute significantly to the mass participation in the X and Z directions, effectively capturing lateral response behavior.
4. Spectral acceleration reaches up to 2.5 g between modes 4 and 14, representing maximum ground motion amplification in this frequency range.
5. The design seismic coefficient starts at 0.0202 for the first mode and increases to a maximum of 0.040 for critical mid-range modes, demonstrating higher response levels under seismic excitation.
6. The Complete Quadratic Combination (CQC) method is used for modal response summation, accounting for closely spaced natural frequencies. The missing mass correction method ensures dynamic responses beyond the considered 100 modes are addressed.
7. The dynamic weight in both X and Z directions is approximately 116.97 kN, suggesting a balanced and symmetric mass distribution across the RCC model.
8. The RCC system's rigidity and monolithic construction result in lower time periods and higher stiffness, enhancing resistance against lateral seismic forces.

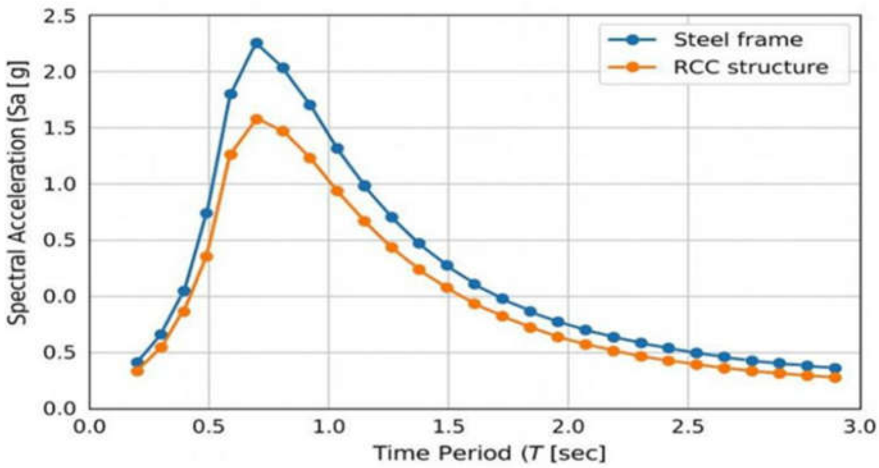

Fig. 7: Base shear for Steel and RCC Structure

4.10 Modal Behaviour

1. The dynamic characteristics of both steel and RCC structures were analyzed through modal shapes obtained from Response Spectrum Analysis. The first mode for both structures predominantly showed lateral sway in the X-direction, with steel exhibiting more flexibility and higher displacements, while RCC, due to its higher stiffness, showed relatively smaller deformation.

2. In the second mode, the steel frame continued to show lateral sway, but the RCC structure displayed vertical floor vibrations, indicating diaphragm action in slabs. This is a typical behavior in RCC systems where slab-beam interaction contributes to vertical mode shapes.

3. The third mode for both structures captured torsional behavior about the vertical axis. In steel structures, the torsion was more pronounced due to lighter mass and less inherent stiffness, whereas in RCC, torsional effects were present but appeared stiffer and more distributed due to rigid joint connections.

4. The fourth mode reflected lateral sway in the Z-direction for both types. Steel frames, with their slenderness and lighter sections, showed larger deflections compared to RCC frames, which demonstrated more controlled displacement owing to their mass and rigidity.

5. In higher modes, steel structures exhibited complex coupled sway-torsional effects and local member vibrations, whereas RCC structures showed global deformation with localized flexure, especially in slabs.
6. Overall, the steel structure had higher modal flexibility and lower frequencies, while the RCC structure exhibited greater stiffness, lesser sway, and better torsional control. These distinctions are essential for seismic design, influencing base shear calculations, drift limits, and detailing requirements.

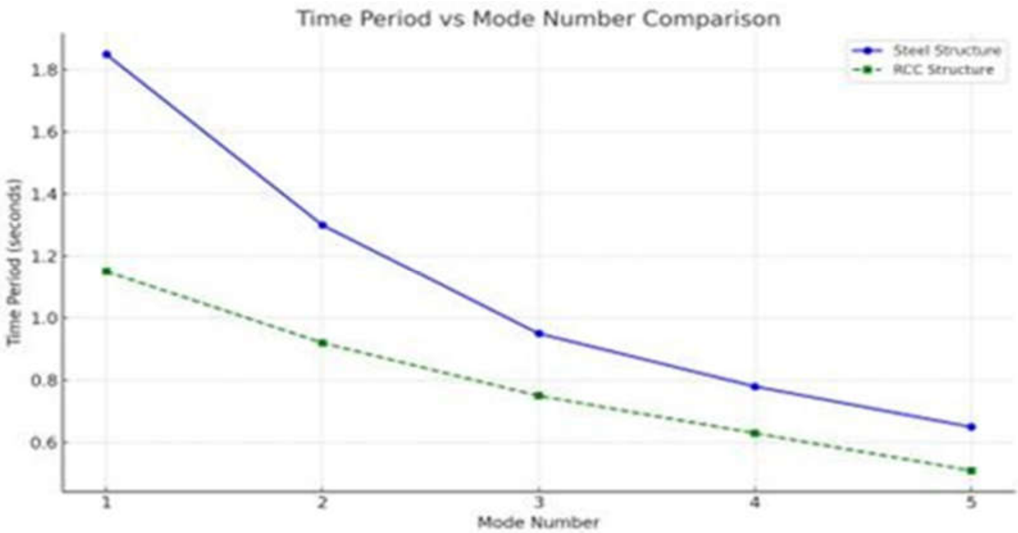

Fig.8: Modal behaviour for Steel and RCC

4.11 Torsional Displacement

1. Torsional displacement refers to the rotational or twisting movement of a structure around its vertical axis due to unsymmetrical mass or stiffness distribution, especially during lateral (seismic or wind) loading.

2. During your analysis, torsional effects were more pronounced under seismic loading, where the irregularities in stiffness, mass distribution, or asymmetric loading caused eccentric lateral displacements.

3. In the steel structure, torsional displacement was moderate but controlled due to the following factors:

   a. The flexibility of steel allowed redistribution of seismic forces.

   b. Bracing systems or moment-resisting frames helped in controlling twist.

   c. The uniformity in member sizing across bays reduced eccentric load effects.

   d. The observed lateral drift in steel structures was accompanied by slight rotational movement, particularly in outer bays, but it remained within acceptable limits as per IS 1893.

4. In the RCC structure, torsional displacement was relatively lower, owing to:
    a. Higher rigidity and stiffness of concrete members.
    b. Lower displacement capacity, which minimized rotational sway.
    c. However, the higher base shear in inner columns and variation in lateral stiffness occasionally led to eccentric displacement at corners, especially during time history loading.
    d. The asymmetry in structural geometry, such as variation in bay widths, positioning of ramps, or mass irregularities due to car loads, contributed to torsional effects in both systems. This was more noticeable in open ground floors (soft storey condition), where the rotational movement intensified under seismic excitation.
    e. Wind loads induced some torsional movement, but the magnitude was significantly lower compared to seismic loads:
    f. Steel structure showed visible yet tolerable torsional sway at upper storeys.
    g. RCC structure absorbed wind forces mostly through stiffness, with negligible torsional deformation.
    h. Torsional effects were correlated with displacement and inter-storey drift profiles, where steel structures exhibited slightly higher lateral flexibility that allowed rotation, while RCC structures were more resistant to rotation but experienced localized stress concentrations.
5. Overall, both structures maintained acceptable torsional stability, with the steel frame showing more flexibility and RCC providing more resistance. Proper planning, detailing, and symmetry in layout are essential to minimizing torsional displacement in such multi-storey parking structures.

5. FUTURE SCOPE

This study presents a comparative evaluation of steel and reinforced cement concrete (RCC) multi-level car parking structures subjected to gravity, wind, and seismic loading, in accordance with Indian standards. Despite the comprehensive nature of this research, there exists considerable scope for further exploration and enhancement of practical applications. The following points delineate potential avenues for future research:

1. Integration of Composite Construction: Future investigations could focus on steel-concrete composite structures, which leverage the advantages of both materials. These systems demonstrate superior performance in terms of stiffness, ductility, and reduced seismic demands. Detailed comparisons with pure steel and RCC systems could facilitate the optimization of structural design for parking facilities in seismic zones.
2. Nonlinear and Pushover Analysis: This study primarily employed linear static and dynamic analysis. Subsequent research should incorporate nonlinear static (pushover) and nonlinear time history analyses to assess actual behavior during significant seismic events, including plastic hinge formation, failure mechanisms, and post-yield performance.
3. Influence of Irregularities: Real-world parking structures often exhibit plan and vertical irregularities, such as ramps, split levels, and open ground stories. Examining the seismic performance of such irregular structures, particularly those with soft-story configurations, would enhance the precision and applicability of design models.
4. Retrofitting and Strengthening Strategies: Older parking structures or those located in high seismic risk areas may necessitate retrofitting. Future studies could investigate the efficacy of base isolation, dampers, steel bracing, or fiber-reinforced polymer (FRP) wrapping in augmenting seismic resilience.
5. Sustainability and Green Building Integration: Future research could incorporate life cycle assessment (LCA) to evaluate the environmental impacts of steel versus RCC construction in multi-level car parks (MLCPs). The integration of green roofs, solar panels, and rainwater harvesting in such structures could also be explored to align with smart city objectives.
6. Automated and Smart Parking Systems: With the progression of smart city infrastructure, future designs may incorporate automated car parking systems (APS). The seismic analysis of these dynamic systems, including moving components and mechanical lifts, represents an emerging area of interest.
7. Parametric and Optimization Studies: Advanced methodologies such as genetic algorithms, machine learning, or multi-objective optimization could be employed to optimize design parameters, including column spacing,

bracing configurations, and material usage, to reduce costs while enhancing performance.

8. Real-Time Monitoring and IoT Integration: The incorporation of Internet of Things (IoT)-based sensors for real-time structural health monitoring (SHM) could be explored. This would enable real-time response tracking during earthquakes and improve post-event assessment and maintenance planning.

6. CONCLUSION

The comparative study of multi-level car parking structures constructed using steel and reinforced concrete (RCC) under the influence of gravity, wind, and seismic loads has provided a comprehensive understanding of their structural performance, stability, and overall efficiency. The following major conclusions are drawn from the analysis:

1. Bending Moment Behavior

a. Under gravity and lateral loads, steel structures consistently experienced lower bending moments compared to RCC.

b. The flexibility and ductility of steel led to smaller and more uniformly distributed moments, while RCC structures attracted higher moments due to greater mass and stiffness.

c. Negative bending moments were small and infrequent in steel but significantly larger in RCC, indicating stronger fixity at joints and higher rotational restraint.

2. Shear Force Distribution

a. Steel structures recorded moderate and uniformly distributed shear values, reflecting efficient force transfer and ductile behavior.

b. Conversely, RCC structures showed significantly higher and more variable shear values, with concentration at lower levels and supports. This necessitates heavier stirrup reinforcement and careful detailing to avoid brittle failures.

3. Axial Force Response

a. Axial forces in steel frames were considerably lower due to their lightweight nature, with gradual distribution from base to top.

b. In contrast, RCC columns carried axial forces more than three times higher, especially in central base columns, due to mass accumulation and rigid load transfer.

c. Steel relied on bracing systems for axial stability, while RCC relied on frame action, making it stiffer but less flexible in redistribution.

4. Displacement and Drift Behavior

a. Steel structures exhibited higher lateral displacements and inter-storey drifts, but in a gradual and ductile manner, ensuring energy dissipation and reduced stress concentration.

b. RCC frames showed lower displacements due to stiffness, but abrupt drift transitions increased the risk of soft-storey effects under seismic conditions.

c. Seismic-induced displacements were largest in both systems, highlighting the critical importance of drift control in performance-based design.

5. Dynamic Characteristics (Time Period, Modal & Torsional Behavior)

a. Steel structures demonstrated longer time periods and higher flexibility, resulting in larger displacements but better seismic energy dissipation.

b. RCC structures, being stiffer and heavier, showed shorter time periods, lower displacements, and higher accelerations, transferring more seismic forces internally.

c. Modal analysis confirmed that steel exhibited higher mode participation in sway and torsion, while RCC displayed stronger slab-diaphragm and frame-dominant behavior.

d. Torsional effects were present in both systems, but more pronounced in steel due to flexibility, whereas RCC resisted torsion more effectively because of stiffness.

6. Base Shear and Stability

a. Due to higher weight, RCC structures attracted larger base shear values, increasing demands on columns and foundations.

b. Steel structures carried lower base shear, improving overall stability, though requiring checks for drift control.

c. Stability in steel was governed by ductility and redistribution capacity, while in RCC it relied on stiffness and strong detailing at lower stories.

7. Energy Dissipation

a. Steel structures displayed superior energy dissipation capacity through plastic hinging and ductile deformation, making them more resilient during cyclic seismic loading.

b. RCC structures dissipated energy mainly through cracking, crushing, and bond-slip, offering lower ductility and higher concentration of energy demand at critical zones.

8. Design and Practical Implications

a. Steel frames are lighter, more ductile, and energy-efficient, offering better seismic performance, faster construction, and material economy. However, they require careful drift checks, bracing systems, and detailing for serviceability.

b. RCC frames, while stiffer and stronger, demand larger sections, heavier reinforcement, and stronger foundations to resist higher forces. They perform well under gravity and wind loads but require careful ductile detailing under seismic conditions.

c. Both systems comply with Indian Standards (IS 456, IS 800, IS 1893, IS 13920), but their design philosophy differs: steel emphasizes ductility and flexibility, while RCC emphasizes stiffness and strength.

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8. Author Contributions Statement

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a. T.P and N.P. conceived the study framework and coordinated the overall research.

b. T.P. performed the seismic modeling and analysis of multilevel steel and RCC car parking structures.

c. T.P and R.D. contributed to structural design calculations and interpretation of comparative results.

d. T.P. prepared figures, tables, and assisted in simulation data processing.

e. T.P and S.P reviewed relevant literature and contributed to drafting and editing the manuscript.

f. T.P. wrote the main manuscript text.

g. All authors reviewed and approved the final manuscript.