Assessment of Seismic Parameters in Reinforced Concrete Tall Structures Utilizing Shear Cores, Shear Walls, and Shear Cores with Outriggers

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DECLARATION

I hereby declare that the work presented in this dissertation titled "Assessment of Seismic Parameters in Reinforced Concrete Tall Structures Utilizing Shear Cores, Shear Walls, and Shear Cores with Outriggers" is my original research work carried out under the supervision of **Dr. Prem Pal Bansal**, Professor, Department of Civil Engineering, Thapar Institute of Engineering and Technology, Patiala, and my industry guide, **Mr. Ankit Rawat**.
The research work presented in this dissertation has not been submitted for the award of any other degree or diploma from any other institution or university. All the references, ideas, and contributions of other researchers have been duly acknowledged and cited in the dissertation.

I take full responsibility for the content of this dissertation and the accuracy of the information presented herein.

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With a mindset of learning and growth, I, **Gaurav Kinariwale**, am pleased to submit this dissertation report on "**Assessment of Seismic Parameters in Reinforced Concrete Tall Structures Utilizing Shear Cores, Shear Walls, and Shear Cores with Outriggers**." I would like to express my heartfelt gratitude to all individuals and institutions who directly or indirectly contributed to the successful completion of this work through their support, encouragement, and guidance.

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ABSTRACT

The increasing demand for vertical development in urban areas has led to a growing need for tall buildings that are both efficient and safe under lateral loads such as wind and earthquakes. As buildings rise in height, their vulnerability to lateral forces becomes a significant concern in structural design. Engineers adopt different structural systems to strengthen buildings and limit lateral movement during seismic or wind events. This study focuses on evaluating and comparing the seismic performance of a G+30 reinforced concrete (RC) building using different structural configurations, including a moment-resisting frame, corner shear walls, a central shear core, and outrigger systems.

The building models were developed in ETABS 2021 and analysed under seismic Zone IV conditions following IS 1893 (Part 1): 2016. Two methods-Equivalent Static Analysis method and Response Spectrum Analysis method were used to examine key performance parameters such as storey displacement, base shear, inter-storey drift, and storey shear. Five structural cases were studied to observe how different arrangements affect the distribution of seismic forces and the overall behavior of the structure.

Among all configurations, the model with a central shear core combined with double outriggers exhibited the most favorable results, showing significant reductions in lateral displacement and storey shear. The results clearly indicate that the inclusion of outriggers enhances lateral stiffness and improves seismic performance, making them a reliable choice for high-rise structures situated in earthquake-prone areas. This comparative study aims to assist structural designers in selecting suitable lateral systems during the planning and analysis of tall RC buildings

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ABBREVIATIONS AND SYMBOLS

RC	=	Reinforced Concrete
SMRF	=	Special Moment Resisting Frame
ETABS	=	Extended Three-dimensional Analysis of Building Systems
EQ	=	Earthquake
WL	=	Wind Load
IS	=	Indian Standard
DL	=	Dead Load
LL	=	Live Load
SSI	=	Soil-Structure Interaction
P-Δ	=	P-Delta (secondary moment effect due to axial load and displacement)
G+30	=	Ground Floor plus 30 upper storeys
OMRF	=	Ordinary Moment Resisting Frame
UBC	=	Uniform Building Code
FEMA	=	Federal Emergency Management Agency
PBD	=	Performance-Based Design
DO	=	Double Outrigger
SO	=	Single Outrigger
B/H	=	Breadth-to-Height Ratio

CHAPTER 1
INTRODUCTION

1.1 BACKGROUND TO THE STUDY

As the infrastructure in many parts of the world, particularly in developing countries like India, is still being built, there is a significant migration of people towards major urban centres. This influx is leading to overcrowding in these metro cities.

The growing population has a significant impact on land availability for agricultural and other purposes, driving up land prices and increasing the demand for high-rise buildings. In areas prone of seismic activity, this trend is especially important. Conventional reinforced concrete (RC) buildings have prolonged oscillation durations and too much swaying under horizontal loads, thereby performing poorly in such areas.

To address these challenges, it is essential to incorporate lateral load-resisting elements. Various systems are available, including braced frame structures, rigid frame systems, shear wall structures, couple wall systems, and core and outrigger systems. However, moment-resisting frames and braced frame systems can sometimes be inadequate for resisting all lateral forces and may lack the necessary stiffness against wind and seismic loads.

To prevent deflections caused by lateral forces-ensuring structural integrity and non-structural safety-stiffness must be maintained in the design and analysis of tall RCC buildings.

In India, particularly in seismic zone 4, high-rise structures face considerable horizontal forces from both earthquakes and winds, necessitating the use of coupled shear walls to manage these forces effectively. As building heights increase, sustaining structural stiffness becomes even more important, and innovative external solutions are vital in mitigating the effects of wind and seismic forces.

One effective structural solution is the Outrigger System. This system relies on the tension and compression created between the core and the exterior columns, acting as a rigid connection that redistributes horizontal forces through the core and about the perimeter of columns.

In this study, we focus on how wind and seismic loads are resisted by employing shear/stiff cores, shear walls, and an outrigger-braced system.

A stiff shear core, placed at the centre of the structure and supported by stiff truss arms, facilitates the effective transfer of lateral loads to the beam and column connections.

Noteworthy instances of the outrigger system can be seen in the Taipei Tower in Taiwan and the Plaza Rakyat Tower in Kuala Lumpur, Malaysia.

Figure 1. 1 Taipei 101 Tower, Taiwan

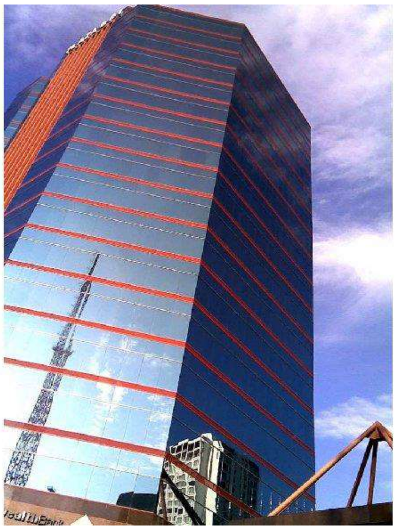


Figure 1. 2 Plaza Rakyat Tower, Kuala.

1.2 DEFINING THE CONCEPT OF TALL BUILDINGS

As per IS-16700:2017, a reinforced concrete (RC) structure with a height exceeding 50 meters but not surpassing 250 meters is classified as a tall building. If the height goes beyond 250 meters, the structure is referred to as a super tall building. Based on structural engineering consideration, a building is considered tall when its framework must be specifically planned to economically and effectively handle lateral loads.

The defining feature of such buildings lies in their ability to effectively withstand lateral actions-this ability fundamentally justifies their classification as tall structures. When talking to taller structure, the influence of lateral loads-such as the loaded which generated by the wind and earthquakes—intensifies. This is due to greater overturning effects, more pronounced horizontal displacements, and increased relative motion between floors. Such behaviors can undermine the building's structural soundness and functional performance, potentially affecting occupant comfort and posing safety concerns.

1.3 CLASSIFICATION OF STRUCTURAL SYSTEMS IN TALL BUILDINGS

Structural systems can be categorized according to their ability to resist lateral loads. This classification includes the following types:

1. Braced frame structural system
2. Rigid frame structural system
3. Shear wall system
4. Coupled wall system
5. Wall-frame system (dual system)
6. Core and outrigger structural system
7. Tube structural system

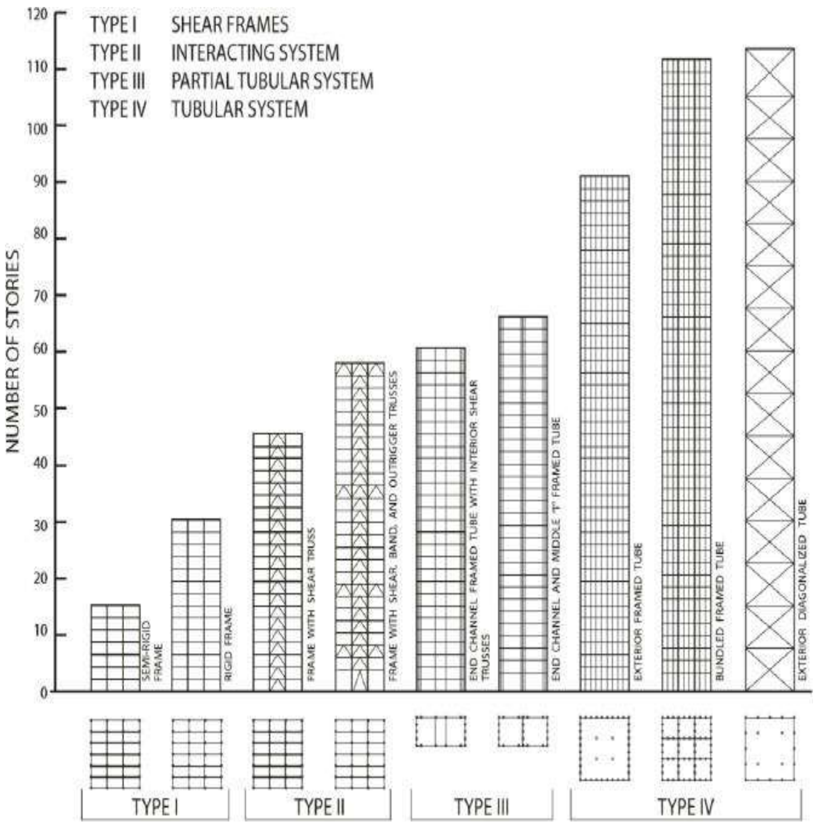


Figure 1. 3 Structural system of tall system(Ali et al., 2007)

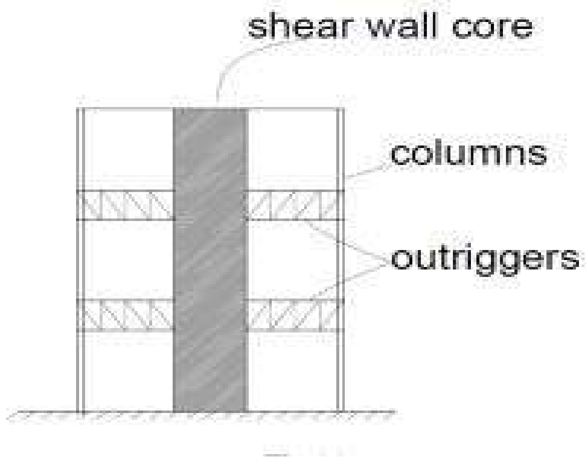


Figure 1. 4 Building Model with Shear Core and Outrigger Bracing

1.3.1 Structural Systems with Shear Wall

The shear wall system, which can be designed as a vertically orientated wide beam in a reinforced concrete frame construction, is used to withstand all of the lateral loads acting on the building. These shear walls give residential or high-rise buildings the proper amount of rigidity. Depending on the needs, shear walls can range in thickness from 150 to 500 mm. They are also simpler to build than traditional methods. In addition to the building's beams, columns, and slabs, there is a shear wall. Because the dimensions and design of the beams and columns in tall buildings are too heavy, clogging at the junction occurs. To remove this, shear walls are utilised, which gives the building rigidity. For the past 20 years, shear walls have been used extensively in high-rise buildings. Because shear walls are especially susceptible to lateral loads and seismic stresses, they are very important in structures, especially tall ones.

Geometry and location of shear wall

The configuration and placement of shear walls greatly affect their efficacy under lateral stresses. The lateral loads are conveyed through the structure, acting as a horizontal diaphragm that directs the force towards the shear walls, which must be oriented in the direction of the load. When a core is positioned eccentrically in relation to the building's shape, it is required to handle not only bending and direct shear but also torsion. Shear walls effectively counteract horizontal forces due to their substantial rigidity, acting similarly to deep beams that resist shear and flexural forces to prevent overturning. Torsion can also arise in buildings with symmetrically arranged shear walls when wind impacts the facades with varying textures or does not align with the building's mass center. Shear walls are commonly designed with an elongated vertical profile, where the height or length in one direction are considerably larger comparing to the thickness in perpendicular directions. Generally, rectangular shapes are common, Although U and L shaped cross-sections are also utilized. Additionally, slender, hollow reinforced concrete shafts encircling the elevator core can function as shear walls which should leveraged to withstand seismic force. The types of shear wall shapes utilized in this project include:

i. U - Section
ii. W - Section
iii. H - Section
iv. T - Section

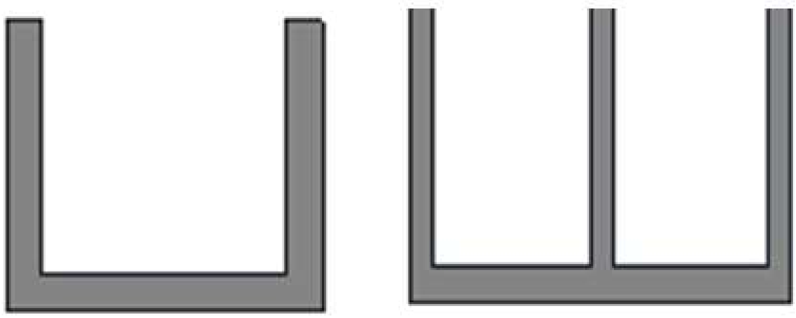


Figure 1. 5 U & W Shaped Shear Walls

Figure 1. 6 H & T Shaped Shear Wall

1.3.2 Structural Systems with Outrigger

These systems are basically lateral load-resisting mechanisms which significantly enhance the stiffness and stability of tall structures by effectively limiting horizontal deflections. These systems integrate both the building's central core and its peripheral columns to work in unison against lateral forces.

Outrigger trusses, which act-as rigid stiff arms, that are connected the Core with exterior columns. When lateral loads - such as sesmic or wind forces—act to the structure, the core tends to rotate. The rotation causes the windward columns to undergo tensile forces, while the leeward columns experience compressive forces.

Consequently, the restoring moment develops within the outrigger level, increasing the structure's effective depth and improving its resistance to bending.

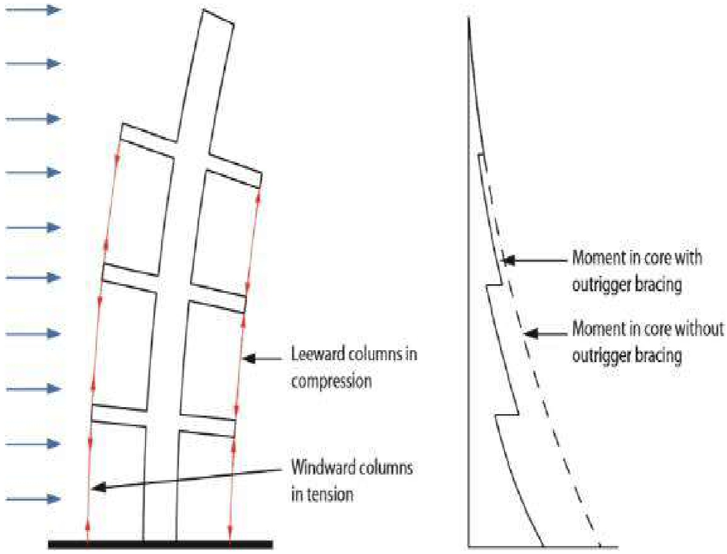


Figure 1. 7 Outrigger and Core interaction

To further control rotation and lateral displacement, a "belt wall"—typically a one- or two-story deep structural element—can be employed around the perimeter at the level of the outriggers. This element acts in conjunction with floor diaphragms above and below, which attempt to move laterally due to core rotation and overturning effects. The belt wall, in resisting this motion, generates opposing forces through the façade columns, effectively restricting rotation and enhancing structural performance.

A centrally located braced frame, integrated with symmetrical outrigger trusses, offers an efficient configuration, resembling the behavior of a concrete shear wall with attached outriggers. These trusses span the full story height and contribute to increased stiffness by forcing double curvature deformation patterns. In this arrangement, the building's exterior columns resist further rotation of the outriggers, producing significant tension and compression forces that counteract the applied lateral loads.

In simplified analytical models, the behavior of such systems has often been approximated using a single bending stiffness parameter for the concrete wall, excluding shear-induced deformations. However, in more refined models—especially for steel trussed systems—this simplification proves inadequate. The interaction of wall, outrigger, and column stiffness can instead be represented by a set of dimensionless parameters, allowing for the development of graphical tools to optimize outrigger placement for minimum deflection at the top of the structure.

Research by Hoenderkamp and Snijder (2002) emphasized the importance of incorporating both racking shear deformations and double curvature effects in the analysis of outrigger systems. Trussed outriggers, unlike planar concrete walls, are subject to deformations in their diagonal members, leading to complex behavior not captured by axial stiffness alone. In braced frames, where outriggers must deform in sync with the core undergoing both bending and racking, the assumption of planarity used for concrete walls becomes invalid. The evolving analytical methods—including those later refined in 2005—support the accurate representation of these effects without significant alterations to existing design tools.

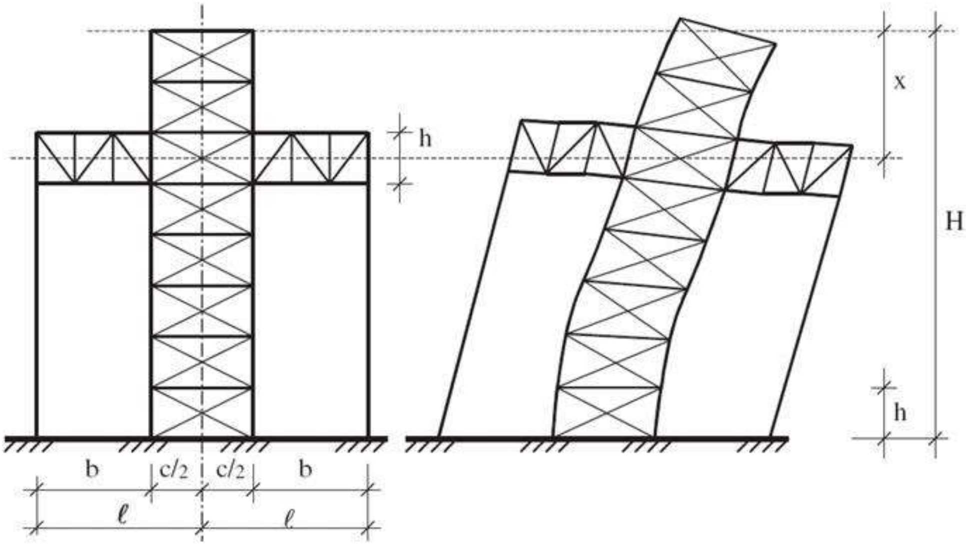


Figure 1. 8 Schematic View of Framed Outrigger System

Figure 1. 9 Building with Outrigger System (Source: First Wisconsin Bank, designed by Fazlur Rahman Khan, Tokyo)

1.3.3 Various Outrigger System Types

Outrigger systems are typically divided into two categories based on how they link to the building's central core. The first is known as the direct outrigger system, where the outriggers, which typically extend to exterior columns, are physically connected the core structure-often a braced core or shear wall.

In contrast, the indirect (or virtual) outrigger system avoids a direct structural connection within core and the perimeter columns. Instead, load distribution was achieved through secondary structural elements, such as belt trusses, which facilitate lateral stiffness without tying directly into the core. This distinction is illustrated in the following figure.

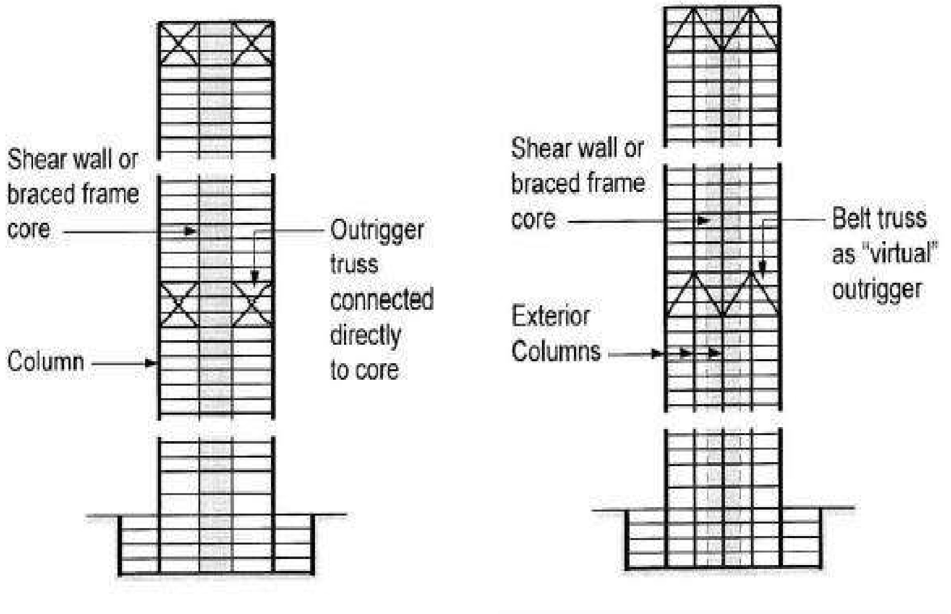


Figure 1. 10 Side-by-Side View of Conventional and Virtual Outrigger Designs

Basically, the choice between direct and indirect outrigger systems largely depends on the building's design and structural requirements. Direct outriggers generally offer greater stiffness and efficiency because of the shorter and more direct load paths between core and vertical element as with perimeter columns. To achieve a same level of performance to that of indirect (or virtual) outriggers, it is often necessary to implement them across multiple floors.

In some cases, both types of outriggers may be used within the same structure. Virtual outriggers can be advantageous when direct connections between the core and outer columns are impractical or would lead to complex detailing. In some situations, certain floors may not be ideal for placing direct outriggers because of limitations in the architectural design or the need to accommodate building services. Furthermore, vertical member shortening can lead to more pronounced issues in direct outrigger systems than in virtual ones, particularly on specific levels where these effects are more critical.

1.4 PRIMARY OBJECTIVES OF THE STUDY

1. To assess the earthquake performance of high-rise structures situated in Seismic Zone IV.

2. To assess the impact of different types of loads on the high-rise buildings across multiple structural configurations, including:
    - Conventional SMRF (Special Moment Resisting Frame) buildings
    - Buildings incorporating shear walls at all four corners.
    - Buildings with a central shear core
    - Structures featuring a shear core combined with an outrigger-braced framework
3. To examine the seismic performance of different structural models subjected to Zone IV seismic activity.
4. To investigate how seismic events affect high-rise buildings with varying structural systems.
5. Determine and compare key seismic performance metrics some like story drift, story base shear and lateral displacement across the different structural systems.
6. To determine the most effective structural configuration for resisting lateral forces- comparing shear wall systems, shear core systems, and shear core systems integrated with outriggers placed at optimal elevations.

1.5 DESIGN METHODOLOGY: SOFTWARE AND STANDARDS

Software Tools Used

- **AutoCAD** – For drafting architectural and structural drawings.
- **ETABS** – For structural modeling and seismic analysis of buildings.

List of Indian Standard Codes Referenced

- IS 456-2000 (reinforced concrete design)
- IS 1893 (PART-I) 2016, (criteria for earthquake resistant design of structure)
- IS 16700: 2023 (tall building design)
- IS 875: 2015 (wind load).

1.6 NEED AND SCOPE OF WORK

Need of the Study

The growing demand for space in the urban areas had led to a significant rise in construction of the high-rise buildings. As buildings increase in height, they become more vulnerable to lateral forces generated by wind and earthquakes. Conventional moment-resisting frames alone are often not adequate to maintain serviceability and stability in such tall structures. To address this, systems like shear walls, central cores, and outrigger mechanisms are commonly employed to enhance stiffness and control lateral movements.

In seismic Zone IV regions of India—such as areas in the northern and northeastern parts—structures are at higher risk during earthquakes. It is, therefore, essential to evaluate the performance of different lateral load-resisting systems under seismic forces. Although many researchers have studied these systems individually, there is still a lack of comprehensive comparison using a unified building model, standardized load conditions, and advanced structural analysis tools. This study aims to bridge that gap by comparing various structural systems through ETABS software, offering practical insight for safe high-rise design in earthquake-prone zones.

Scope of Work:

- To model a **G+30 RC framed building** (99.7 m tall) using ETABS software, conforming to IS 456:2000 and IS 1893 (Part 1):2016 standards.
- To design and analyze five different structural configurations:
    a) Case I: Regular RC Building (SMRF)
    b) Case II: RC Building with Corner Shear Walls
    c) Case III: RC Structural Model with a Core Wall at the Center
    d) Case IV: Reinforced Concrete Structure with Central Shear Core and Single Outrigger Brace
    e) Case V: Reinforced Concrete Structure with Central Shear Core and Double Outrigger Brace
- To evaluate each structural model through Equivalent Static and Dynamic (Response Spectrum) analysis.
- To compare and evaluate structural parameters such as:
    - Maximum storey displacement
    - Storey drift
    - Base shear
- To identify the most efficient lateral load-resisting system suitable for tall buildings located in seismic regions.
- To contribute valuable insights for structural engineers and designers for selecting appropriate systems in high-rise construction projects.

1.7 INTRODUCTION TO THE STRUCTURAL CONFIGURATIONS

This study conducts a comparative examination of five different reinforced concrete structural systems utilising ETABS software. Each configuration is simulated and assessed to determine its performance under lateral and gravitational loads. The main aim is to comprehend how differences in lateral load-resisting systems affect stiffness, drift control, and overall stability in tall structures.

Chapter 4 provides a comprehensive account of the sizes and dimensions of structural members for all scenarios, as well as the employed design philosophy and material specifications. By upholding uniform loading conditions and essential design parameters across all models, the comparison methodology guarantees that variations in performance may be exclusively ascribed to the selection of structural system.

Case I – Regular RC Building (SMRF)

A Special Moment Resisting Frame (SMRF) system in reinforced concrete relies on rigid beam–column connections to resist both vertical and lateral loads. The absence of shear walls allows for more architectural flexibility, while its high ductility and energy dissipation capabilities make it ideal for earthquake-prone regions. However, for tall buildings, the inherent flexibility can result in greater lateral drift, demanding careful design of member sizes and reinforcement to meet serviceability and safety requirements.

Case II – RC Building with Corner Shear Walls

A building's lateral stiffness and torsional resistance are greatly increased when shear walls are positioned at its corners. These walls function as vertical cantilevers, giving seismic and wind forces a direct load route. Because of their peripheral location, displacement and torsional effects may be effectively controlled. Although the structural performance is enhanced by this arrangement, the practical arrangement of corner spaces may be restricted.

Case III – RC Structural Model with Central Core Wall

A core wall system that is located in the middle of a building is commonly combined with vertical circulation areas and service shafts. The core is a rigid centre part that helps with torsional stability by being placed symmetrically and taking on a lot of the lateral loads. This setup lets the perimeter framing be rather flexible, which means that it may be used for more architectural purposes without losing its strength.

Case IV – RC Structure with Central Shear Core and Single Outrigger Brace

In this design, a single outrigger system is positioned in the midpoint of the structure. It links the central core to specific exterior columns using a robust horizontal truss or deep beam. This configuration enables the exterior columns to help counteract overturning moments, thereby enhancing lateral stiffness and minimizing deflection. Placing the outrigger at mid-height maximizes structural efficiency for buildings of moderate to high elevation while ensuring effective construction practices.

Case V – RC Structure with Central Shear Core and Double Outrigger Brace

The double-outrigger system enhances the idea by integrating two outrigger levels—one located at the mid-height of the structure and another at the uppermost floor. This dual configuration activates perimeter columns at various elevations, leading to a more consistent distribution of overturning moments and a significant enhancement in lateral stiffness relative to the single-outrigger system. It is especially appropriate for very tall structures where strict drift limitations must be adhered to, however it requires meticulous structural details and integration with the architectural design.

CHAPTER 2
LITERATURE REVIEW

2.1 SUMMARY OF EXISTING STUDIES

Moudarre, F. R. (1985): Analysis of the effect of stiffening outrigger basis on the behaviour of a pair of coupled RC shear walls reveals that the stiffening outriggers is more effective in reducing the drift of the coupled wall because it mobilises axial stiffnesses of outer columns. For base moments of walls of the building, the outriggers has a small influence compared within the effect of drift to the shear walls.

Bayati, Z.,& Rahaei, A. (2008): Examined the efficacy of multi-outrigger systems in improving the lateral stiffness and seismic resilience of tall structures. The research examined a typical 80-storey steel-framed structure utilizing both traditional and virtual outrigger systems. The findings indicated that the utilization of numerous outriggers markedly diminished core base moments and upper deflections in response to lateral loads. Optimal placement of outriggers at fractional building heights, namely at 1/3 and 2/3, demonstrated greater structural efficiency compared to conventional top-level placements. The analysis indicated that the gradual addition of outriggers enhanced drift control, yielding diminishing returns after the third outrigger. Virtual outriggers with belt trusses provide design arrangement flexibility while effectively including all perimeter columns in lateral resistance. While less rigid than traditional outriggers, they alleviated geographical and structural limitations. The research determined that an effectively designed multi-outrigger system improves structural efficiency and performance against wind and seismic forces.

M. Samadzadand, S. Epackachi, and O. Esmaili Mirghaderi, S.R. (2014): The objective of this article is to analyse the structural behaviour of one of the tallest reinforced concrete buildings globally. It is located in high seismic zone V and comprises 56 stories above ground. This skyscraper employs shear wall systems including irregular openings subjected to lateral and gravitational pressures, potentially resulting in specific challenges regarding the behaviour of structural elements such as coupling beams and shear walls. The essential demands are observed to manifest at the mid-height structure (i.e., between 25th floor and 35th floors) in assessments of tall buildings that consider both time-dependent behaviour of the concrete and the loading sequence during construction. He also discovered that elevating the axial stress level diminishes the R factor. As a result, both the moment of inertia of the section and the design base shear will augment. The cross-sectional area expands as the axial load diminishes.

Srinivas B. N and Abdul Karim Mulla (2015): A study was conducted on the use of outrigger systems in both regular and vertically irregular reinforced concrete (RC) buildings subjected to seismic and wind loads. Their analysis involved comparing the performance of structures equipped with outriggers at two distinct levels to those without outriggers, with steel bracing as the outrigger mechanism. The results indicated that positioning outriggers at mid-height floors led to greater reduction in top-floor displacements. Additionally, concrete outriggers were found to be more effective than steel X-bracing outriggers in minimizing lateral storey displacements.

Denge, S. V., & Raut, S. P. (2016): Conducted an extensive review on the application of belt truss systems as lateral load-resisting components in high-rise structures. The research underscores the belt truss as a feasible substitute for traditional outriggers, providing equivalent lateral stiffness and drift management without the intricate core-to-outrigger linkages. The text examines how belt trusses function as virtual outriggers, transferring loads through reinforced floor diaphragms, so facilitating structural integration. A study of several previous research demonstrates the efficacy of belt trusses positioned at mid-height or in combination at 1/4, 1/2, and 3/4 of building heights for optimal reduction of drift and moment. The research highlights the advantages of belt trusses in minimizing lateral displacement, particularly when the rigidity of the diaphragm and truss is increased. Belt trusses enhance resistance to progressive collapse and preserve stability following partial failure. The analysis determines that while outriggers exhibit marginally superior rigidity, belt trusses present practical, adaptable, and economical options in contemporary high-rise architecture. Additional study is recommended to enhance their stiffness distribution and performance under dynamic loads.

Santhosh and Mathew (2017): The seismic performance of multi-storey RC buildings incorporating shear walls of various shapes-U, H, T, and W was analyzed using ETABS and the Response Spectrum Analysis method. G+14 and G+29 building models were evaluated under seismic Zones III and V to assess storey drift and base shear. The study found that W and U-shaped shear walls provided superior performance in reducing storey drift in X-direction for both zones. In Y-direction, H-shaped walls performed better in drift control, while T-shaped walls were more effective in resisting base shear. Results remained consistent across different seismic zones. The W and H shapes were especially beneficial for the taller G+29 structure, offering both stability and efficient lateral load resistance. The research concluded that shear walls geometry has a significant impact on structural response, emphasizing importance of optimized shapes in tall building design.

Dangi and Jamle (2018): The Objective of this paper is to investigate the seismic behavior of reinforced concrete multistorey buildings incorporating various outrigger systems, focusing on a G+10 storey structure modelled in STAAD Pro. The study compared seven structural configurations, ranging from a regular building model to those using shear cores, wall belts, and truss belts. Seismic response parameters such as base shear, column axial forces, member shear forces, bending moments, and torsion were analyzed using the method response spectrum with code provision IS 1893 (Part 1): 2002. Among all the configurations, the shear core outrigger with wall belt system emerged as the most effective in controlling lateral loads and structural responses, particularly in minimizing shear forces and bending moments. The shear core-only system showed superior performance in reducing base shear and axial column forces, making it ideal for specific seismic conditions. The study concludes that wall belt systems are generally more effective than truss belt systems in seismic performance. This work provides valuable comparative insight into the seismic efficiency of different outrigger configurations in medium-rise structures and supports the selection of optimal systems based on specific structural performance criteria.

Dahake and Azghar (2019): Performed a parametric analysis to identify the optimal positioning of outrigger systems utilizing reinforced concrete shear walls and braces in high-rise structures subjected to seismic forces. A G+24-storey commercial edifice situated in Zone IV was simulated in ETABS with five configurations: devoid of outriggers and incorporating shear walls or X-braces at different elevations. A response spectrum study was conducted to assess seismic characteristics including top-storey displacement, base shear and time period. The research indicated that X-bracing at the 8th, 16th, and 24th floors (Model V) resulted in the most significant reduction in lateral displacement (9.5%) and time period, alongside a modest 8% drop in base shear. Peripheral shear walls at equivalent levels (Model IV) demonstrated significant enhancements. The results highlight the efficacy of strategically positioned outrigger system in enhancing stiffness as well as seismic resistance, with multi-level X-bracing identified as the most effective approach.

Dangi and Jamle (2019): Investigated the seismic behavior of a G+10 residential structure incorporating shear core, outrigger braces and belt steel truss systems arranged in various structural configurations.. Seven structural examples were examined utilizing STAAD Pro and the response spectrum method, concentrating on characteristics including nodal displacement, storey drift, member stresses, and time period. The shear core with wall belt supported system (Case S4) consistently demonstrated superior performance across the majority of criteria among the configurations. This configuration considerably diminished nodal displacements and storey drift in both the X and Z axes, while also reducing tensile and compressive stresses. The temporal context and mass participation variables were particularly advantageous for this setup. The research illustrates that the strategic positioning of belt-supported outriggers improves structural stiffness and seismic resilience. The results indicate that Case S4 is the most stable and efficient option for mid-rise structures in seismic regions.

Kurzekar et al. (2020): Analyzed a 20-storey RC building to study the effect of core and outrigger systems on structural performance under wind and seismic loads. Using ETABS 2016, they compared models with and without outriggers placed at various heights. The study showed that outrigger systems significantly reduce storey displacement (by up to 47%) and decrease the time period (by 64%). Optimal placement—at the top and two-thirds height—improved stiffness by 34–38%. The core-outrigger system effectively minimized inter-storey drift and enhanced lateral resistance. Compared to conventional frames, this configuration provided superior performance in seismic zone III. The results highlight the importance of strategic outrigger positioning for tall building stability.

Ahamad and Pratap (2020): This research investigated how the positioning of shear walls influences the seismic response of a G+20 reinforced concrete building. The study, carried out in ETABS 2015 using the response spectrum method in line with IS 1893:2016, examined building models without shear walls, with asymmetrically placed shear walls, and with symmetrical arrangements at multiple ends. The performance of each configuration was evaluated for all seismic zones in India. Findings revealed that a symmetrical layout at multiple ends was the most effective in minimising storey displacement, base shear, and torsional irregularity, particularly in the most severe seismic zones. Models lacking shear walls experienced the greatest displacements, while asymmetrical layouts resulted in uneven stiffness and higher concentration of lateral loads. The authors highlighted that balanced stiffness distribution plays a key role in improving seismic efficiency, stiffness, and overall stability.

John and Kamath (2023): The study Conducted an in-depth investigation into the performance and optimal positioning of hybrid outrigger systems in high-rise buildings under wind and earthquake loads. The hybrid system comprises both conventional and virtual outriggers, strategically located at different levels to balance structural efficiency and architectural practicality. Their study analyzed 40-, 60-, and 80-storey concrete structures, using a comprehensive parametric approach involving variations in core and outrigger stiffness, arm length, and building geometry. Utilizing both static analysis (based on IS codes) and nonlinear time history analysis for dynamic loads, the study assessed performance based on inter-storey drift, roof displacement, acceleration, and base bending moments. A key contribution of the research is the introduction of a Performance Index (PI), which integrates multiple response parameters to determine the optimal outrigger positions. The results consistently showed that hybrid systems outperform single-type outriggers, especially when the outrigger arm length is maximized. Additionally, the study provided a design flowchart for preliminary selection of outrigger positions based on building characteristics and load conditions. This work not only validates the efficiency of hybrid systems in minimizing lateral responses but also offers practical design recommendations for engineers and designers of tall structures.

2.2 RESEARCH GAP

Many previous studies have examined individual structural systems such as shear walls, outrigger systems, and shear cores to improve the lateral stability of the high-rise buildings. However, most of these studies focus on one system at a time or compare limited configurations.

Despite their proven benefits, the following research gaps remain:

- **Limited Comparative Studies in a Single Model Framework**: There is a lack of studies where all three systems—shear core, outrigger, and shear wall—are modelled and compared within the same building layout using a consistent method (e.g., in ETABS). This makes it hard to decide which system performs best under similar conditions.
- **Gap in Performance-Based Evaluation**: While studies mention improvements in displacement and drift, very few clearly compare key parameters like the base shear, time period, and storey drift for different systems side by side.
- **Need for Practical Modelling in Mid-Rise Buildings**: Most research is based on tall (40+ storey) buildings. There is limited research focused on mid-rise buildings (like

G+10 to G+20), which are more common in cities and more relevant for real-world application.

- **Insufficient Focus on Zone-Specific Behaviour**: Many studies don't evaluate how these systems perform in specific seismic zones (e.g., Zone III or IV), which is important for earthquake-prone regions in India.
- **Lack of Visual and Simplified Interpretation for Students/Practitioners**: A need exists for clear, comparative graphical results and conclusions that can help future students, designers, or engineers choose the right lateral load resisting system.

CHAPTER 3

STRUCTURAL ANALYSIS APPROACHES FOR SESMIC EVALUATION

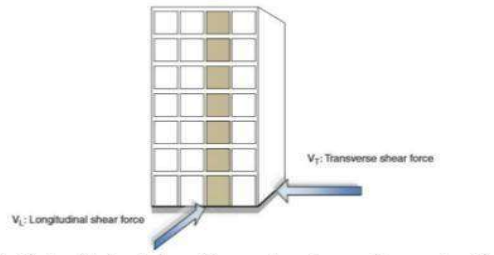
To understanding how buildings react to lateral forces will help one to guarantee their stability and safety during an earthquake. The structural behavior is analyzed using various methods, depending on the complexity of the building and the scope of the study. Among other things, these techniques help one ascertain important variables such displacement, drift, and time period. Factors include the height of the building, the structural system in use, and the seismic zone the building is located in affect the suitable approach to be chosen. The major analytical methods used in seismic analysis are discussed in this chapter together with their application to evaluate the performance of high-rise buildings.

3.1 DIFFERENT METHODS OF ANALYSIS

- Principles of Linear static analysis
- Principles of Nonlinear static analysis
- Principles of Linear Dynamic Analysis
- Principles of Non-linear dynamic analysis

3.1.1 Principles of Linear Static Analysis

- It is also referred to as equivalent static analysis
- This method uses a basic, static methodology to estimate earthquake forces.
- Site-specific elements like soil type and foundation behaviour are not adequately considered.
- Usually applied to low-rise structures with uniform mass distribution and conventional shape.
- According to the research, the structure predominantly vibrates in each direction in its initial mode.
- Because the approach ignores higher vibration modes, it is less appropriate for tall or irregular buildings.
- Despite its drawbacks, it offers a fair approximation of seismic forces for basic constructions.



Equivalent lateral shear force along two orthogonal axis

(Source: Nouredine Bourahla, *"Equivalent Static Analysis of Structures Subjected to Seismic Actions"*, Encyclopedia of Earthquake Engineering, Springer-Verlag Berlin Heidelberg, 2013)

Figure 3. 1 Distribution of Seismic Shear Force Along X and Y Axes

Design and Analysis Steps:

- Determine the design seismic base shear (VB) for the building.
- Distribute the calculated base shear vertically along the building height.
- Disperse lateral forces horizontally across the plan dimensions of the structure.
- Evaluate structural responses such as inter-storey drift, overturning moments, and the P-Delta effect.

Computation of Base Shear (Vb)

The seismic base shear is calculated using the formula:

$$\mathbf{V_B = A_h W} \qquad (3.1)$$

In the Formula:

V_B = Seismic base shear

W – seismic weight of structure

A_h – horizontal seismic constant

This formulation is given in IS 1893 (Part 1):2016 (Bureau of Indian Standards, 2016).

Seismic Acceleration Coefficient (Ah)

$$Ah = \left(\frac{Z}{2}\right) * \left(\frac{Sa}{g}\right) * \left(\frac{I}{R}\right) \qquad (3.2)$$

The terms are defined as follows:

Z - Zone factor (based on seismic zone)

I - Importance (structure significance)

R- Response Reduction factor (depends on structural system)

$\frac{Sa}{g}$ - Mean Value of Response Acceleration

T - Natural time period of a structure

This formulation is given in IS 1893 (Part 1):2016 (Bureau of Indian Standards, 2016).

3.1.2 Principles of Non-Linear Static Analysis

- This method is commonly referred to **Pushover Analysis**.
- The assessment of existing buildings for structural strength and drift capacity, along with the analysis of seismic performance in structures previously affected by earthquakes, is carried out using this method.
- Also applied to verify the adequacy of new structural designs under seismic loads.
- This analysis involves creating the mathematical model that captures the non-linear load deformation behavior of the structural components subjected to progressively increasing lateral forces, simulating earthquake inertia, until the structure reaches a predefined "target displacement."

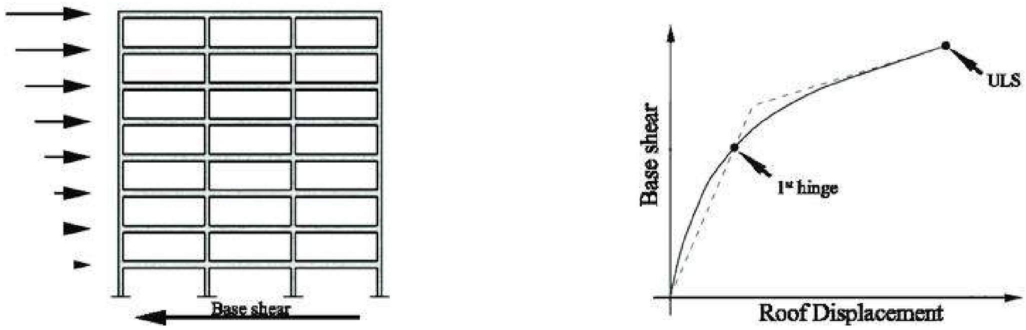


Figure 3. 2 Non-linear Static (Pushover) Analysis

3.1.3 Principles of Linear Dynamic Analysis

- This method is commonly referred to as the **Response Spectrum Analysis method**.
- The method evaluates the diverse ways a building can behave under seismic forces by determining its different vibration modes using advanced computational techniques.
- The structural response in each vibration mode is determined using the design spectrum, considering the modal frequency and the associated mass.
- The modal responses are integrated through particular ways to assess the building's overall behavior.

Parameters Impacting the Response Spectrum:

1. Earthquake magnitude (Richter scale)
2. Natural period of the structure
3. Earthquake focal length
4. Soil and ground conditions

5. Structural damping

3.1.4 Principal of Non-Linear Dynamic Analysis

- The time history method is applicable for analyzing both elastic and non-elastic performance of structures.
- A representative earthquake acceleration record pertinent to the location of the structure is needed in order to do this study.
- To simulate the seismic forces operating at the base, the structural model is exposed to ground accelerations captured during real earthquakes.
- By gradually integrating the equations of motion during the course of the earthquake, the reaction is calculated.
- Elastic analysis makes the assumption that the building's stiffness won't change during the seismic event.
- In order to account for structural yielding and degradation, the stiffness may change over time in an inelastic analysis.

3.2 THEORETICAL PURPOSE OF EACH METHOD

Structural analysis methods are specifically developed to predict how buildings will respond under various loading conditions. When it comes to earthquake-resistant design, these methods help in understanding the sideways movements, stress distribution, and deformation patterns that occur due to seismic forces. The choice of analysis approach depends largely on how detailed the assessment needs to be and the complexity of the building's design.

Table 3. 1 Purpose and Use of Seismic Analysis Methods

Analysis Method	Purpose	Recommended Usage
Linear Static	Basic estimate of lateral forces; assumes elastic behavior	Low-rise, regular buildings in low seismic zones
Nonlinear Static (Pushover)	Evaluates inelastic behavior; used in performance-based or retrofit design	Existing structures, retrofit cases, performance design
Linear Dynamic (Response Spectrum)	Captures multiple vibration modes under elastic behavior	Mid- to high-rise buildings, regular structures

Nonlinear Dynamic (Time History)	Simulates full response to actual ground motion data	Irregular/tall/critical structures in seismic zones

3.3 LIMITATIONS OF ANALYSIS METHODS

While each method serves a specific purpose in structural engineering, none is universally applicable. Every approach involves assumptions and simplifications that can affect the accuracy of results.

- **Linear Static Analysis** does not consider the effects of higher vibration modes or material inelasticity. It may underestimate demand in irregular or tall buildings.
- **Nonlinear Static (Pushover)** assumes a fixed lateral load pattern, which may not accurately reflect dynamic behavior during actual earthquakes. Its accuracy diminishes in structures influenced by higher modes.
- **Response Spectrum Analysis** assumes that the structure behaves elastically. It does not capture nonlinear deformation or the actual sequence of load application.
- **Time History Analysis** requires detailed ground motion records, which are not always available. It also requires considerable computing power and expertise for precise interpretation.

3.4 REAL-LIFE APPLICATIONS

Across various structural engineering projects and studies, the choice of analysis method is guided by the building's height, importance, seismic zone, and complexity. In practical design offices and academic research, these methods are applied based on need, performance objectives, and regulatory requirements.

In one notable study, Esmaili et al. (2008) evaluated a 56-storey reinforced concrete tower using initial static analysis to determine base shear and lateral demand, serving as the foundation for further dynamic modeling. This early-stage approach is commonly applied in low- to mid-rise buildings, where the behavior is dominated by fundamental mode response and structural regularity.

For structures where nonlinear behavior is expected—such as retrofitted buildings or those in performance-based design frameworks—pushover analysis has proven effective. Moudarre (1985) utilized this method to examine the inelastic behavior of coupled shear wall systems with outrigger bracing. More recently, Kurzekar et al. (2020) applied pushover analysis to compare drift reduction in a 20-storey building using core and outrigger systems.

Dynamic methods are essential in design of the high-rise buildings, especially in moderate to severe seismic zones. Dangi and Jamle (2019) performed response spectrum analysis on various lateral systems in a G+10 RC building, allowing them to compare inter-storey drift, base shear, and displacement for different structural layouts. Their work reflects standard practice in design firms where modal analysis is required by code.

Where even greater precision is needed—particularly in tall, irregular, or critical structures-nonlinear time history analysis is used. Bayati et al. (2008) employed this technique in a study on outrigger optimization in steel high-rises, simulating building response to actual earthquake records. Globally recognized projects like the Burj Khalifa and Taipei 101 have also used this method to validate seismic safety through detailed ground motion modeling.

3.5 GUIDELINES FOR METHOD SELECTION

The selection of a effective structural analysis method is a critical decision throughout the design stage, particularly for buildings located in seismic-prone regions. This choice is influenced by several factors, which further including the height and regularity of the structure, the seismic zone classification, material behavior (elastic or inelastic), and the intended performance objectives.

In practical design, engineers must strike a balance between accuracy, time, computational effort, and the level of detailing required. For example, simpler linear methods may suffice in early-stage design or for low-rise buildings, while more advanced nonlinear techniques are necessary for irregular, tall, or essential structures where precision is vital.

The table below summarizes a set of general recommendations for selecting an appropriate analysis method based on structural complexity and design context:

Table 3. 2 Selection Guidelines for Seismic Analysis Methods

Criteria	Suggested Analysis Method
Low-rise buildings (up to G+5), regular layout	Linear Static Analysis
Mid-rise buildings (G+6 to G+20), regular layout	Response Spectrum Analysis

Buildings with irregular mass/stiffness	Response Spectrum or Nonlinear Static (Pushover)
Structures requiring performance-based design	Nonlinear Static (Pushover)
Tall buildings (G+30 and above) in seismic zones	Response Spectrum or Time History Analysis

CHAPTER 4
MODELLING AND ANALYSIS OF G+30 RECTANGULAR BUILDING

4.1 METHODOLOGY

This study focuses on examining and comparing the structural behavior of a 30-story reinforced concrete (RC) building under lateral forces, specifically from seismic and wind impacts, across five distinct structural designs. The building reaches a height of 99.7 meters, categorizing it as a tall structure (over 50 meters), located in seismic Zone IV, known for significant earthquake forces. To facilitate this analysis, ETABS 2021 software is utilized due to its sophisticated capabilities in modeling high-rise buildings and addressing dynamic load conditions.

By keeping all other design parameters constant while varying the lateral resisting systems, the impact of each setup on structural response can be effectively assessed. Key performance metrics – such as story drift, lateral displacement, base shear, and time period – are derived from the ETABS analysis. The comparative assessment of these metrics aids in identifying the most effective system for reducing lateral deflection and improving overall seismic resilience in tall RC structures.

4.2 STRUCTURAL MODELLING

In this study, a 30-story (G+30) tall building with a height of 99.7 meters (classified as a tall building between 50 m and 250 m) is analyzed under five different scenarios.

4.2.1 Structural Model: CASE-I

Regular reinforced concrete building incorporating a special moment-resisting frame (SMRF).

4.2.2 Structural Model: CASE-II

A regular reinforced concrete building featuring shear walls located at the corners to improve resistance against lateral forces like earthquakes and wind.

The shear walls provide strength and lateral rigidity, helping to limit sway, deflection, and potential structural damage occurring along the building’s primary orientation.

4.2.3 Structural Model: CASE-III

A conventional RC structure featuring a centrally positioned shear core.

The stiff core, connected to beams and columns, transfers all lateral loads through these structural elements, enhancing the building’s resistance to lateral forces.

4.2.4 <u>Structural Model: CASE-IV</u>

A Standard RC Structure with Shear Core and One Outrigger-Braced System

A typical reinforced concrete building with a central shear core and a single outrigger system supported by steel bracings makes up this structural model. By enhancing the axial stiffness of outer columns of the structure, outriggers reduce lateral deflections and avoid overturning moments. This arrangement withstands lateral loads like wind pressure and earthquake forces. With the outriggers and steel bracings, the shear core is the main component that resists lateral loads. Increasing axial compression in the perimeter columns lowers shear forces in columns and bending moments in beams. The structural framework of the building is made with a centrally shear core that is joined with the external columns by steel-braced horizontal girders or cantilever-type trusses or outriggers. To provide balanced load transfer, the shear core is centred within the building plan with the assistance of extending outriggers on both sides. The advantage of outriggers is it prevents the rotation of the shear core and lateral displacement by causing axial forces in the perimeter columns that counterbalance overturning moments when lateral loads are applied. By improving the building's total lateral stiffness and stability, this technology successfully mitigates the effects of wind and seismic loads.

4.2.5 <u>Structural Model: CASE-V</u>

A typical RC building with a double outrigger-braced system and shear core. The building's outrigger-braced system is installed at two points: the fifteenth floor and the twenty-ninth floor. Although concept behind using a double outrigger system as to offer improved stiffness and resistance to lateral loads compared to a single outrigger configuration.

Additionally, the shear core prevents shear in the structure, while the outrigger system offers superior flexural stiffness.

4.3 GEOMETRIC PROPERTIES

Table 4. 1 Building Specification

Typical stories height	3.3 m
Bottom story height	4 m

Plan Dimension	42m X 35m
Spacing in X-direction	5 m
Spacing in Y-direction	6 m
Beam Sizes	(650X750) mm, (450X750) mm, (450X600) mm, (350X750) mm
Column sizes	(900X900) mm, (750X750) mm
Slab Thickness	175mm, 225mm(staircase)
Thickness of shear wall	350 mm
Number of bays along X-axis	7 bays
Number of bays along Y-axis	7 bays
Number of storeys	G+30 (including Terrace)

4.4 ARCHITECTURAL DESIGN APPROACHES FOR SPECIFIC USE CASES

This study examines a high-rise mixed-use building with a ground level and 30 additional stories (G+30). The structure is planned with a conventional floor layout, while certain floors exhibit diverse floor layouts to meet functional and spatial needs. The building's footprint measures 42 meters in length and 35 meters in breadth, necessitating meticulous structural evaluation due to its significant plan area. Lateral load-resisting features, such as shear walls and a central shear core, are systematically arranged in diverse configurations across many design schemes to assess their influence on structural response towards the seismic and wind loads. The arrangement and layout for these components are dictated by architectural constraints and the requirement for optimal distribution of rigidity and strength. The study aims to assess the effectiveness of these configurations concerning overall performance, inter-storey drift, base shear, and displacement characteristics, in accordance with relevant design standards and seismic guidelines. The architectural blueprints depicting the many combinations examined in this study are presented below.

4.4.1 Architectural Layout for Case I - Special Moment Resisting Frame (SMRF)

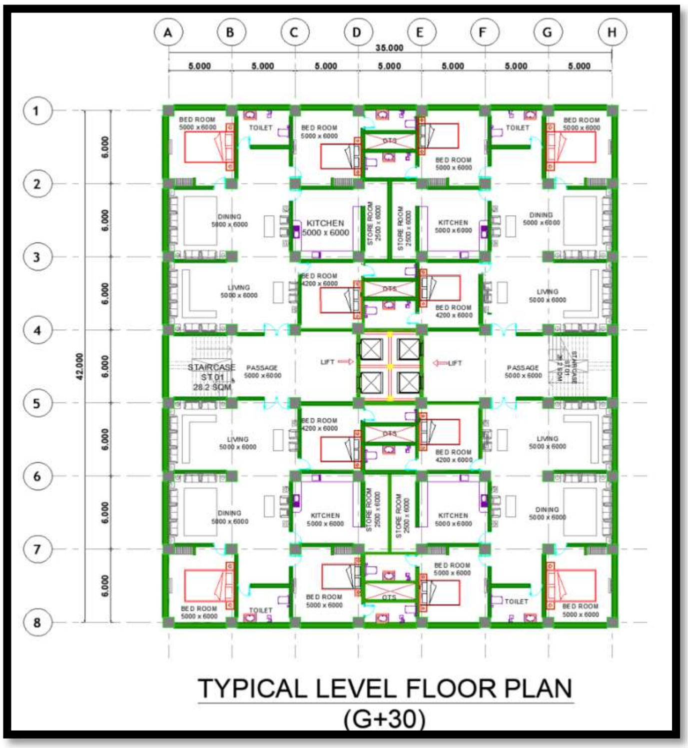


Figure 4. 1 Typical Floor plan for G+30 for Case-I

4.4.2 Architectural Layout for Case II - RC building with corner Shear wall

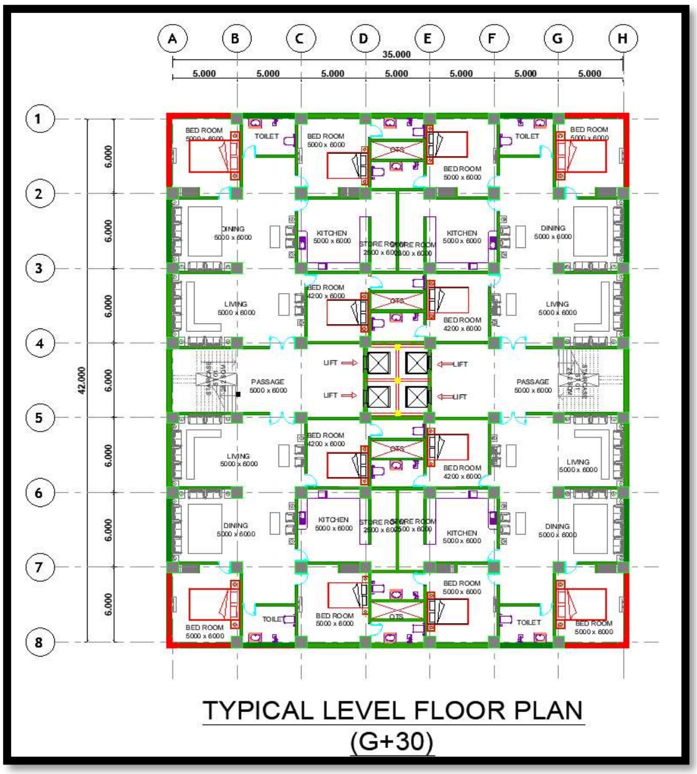


Figure 4. 2 Typical Floor plan for G+30 for Case-II

4.4.3 Architectural Layout for Case III, Case IV & Case V - RC building with Shear Core at centre

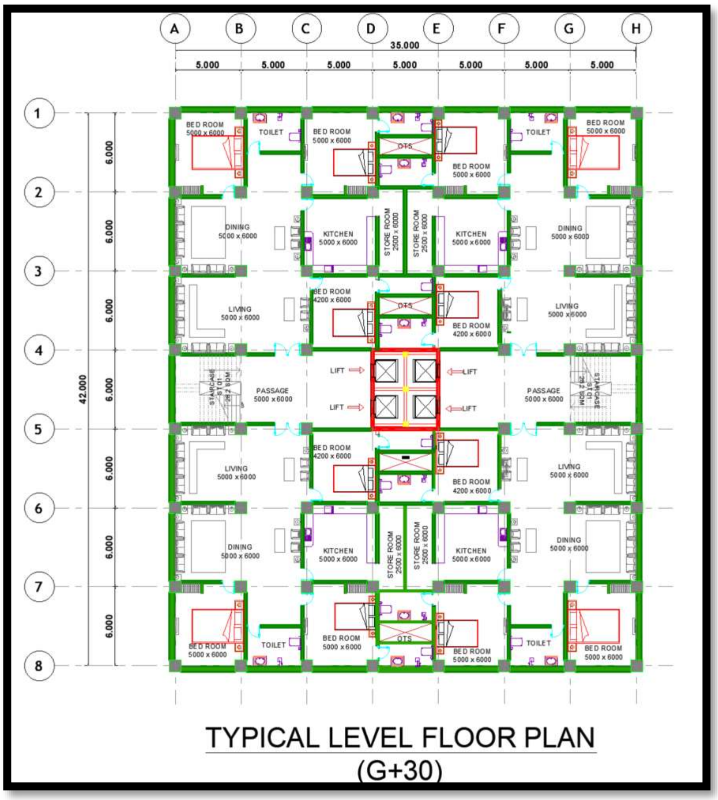


Figure 4. 3 Typical Floor plan for G+30 for Case-III, Case-IV & Case-V

4.5 MATERIAL PROPERTIES

Table 4. 2 Material properties specification

Parameter	Value
Grade of Concrete	M40 used for columns and beams
	M40 adopted for shear walls and core
	M30 for slab
Concrete Compressive Strength	40,000 kN/m² for beams and columns
	45,000 kN/m² for shear core and walls
Steel Grade	Fe500 for Reinforcement Bars (Rebar)
	E350 for Outrigger Truss (Structural Steel)
Design Strength of Reinforcement Steel (fy)	500,000 kN/m² (characteristic yield strength)
Unit Weight of Concrete	2548.531 kg/m³ (material density)

4.6 LOADING DETAILS

4.6.1 Gravity Load:

Forces acting vertically as a result of gravity are referred to as gravity loads. Usually, these kinds of loads fall into one of the following types:

Dead load:

Structural Self-Weight: The software determines the self-weight using the given section parameters and material constants. The Structural Self-Weight components within its structure are referred to as the structure's own weight. These are the constant loads that are always applied to the structure.

Superimposed load: The partition walls, floor finish, and other components are subject to a superimposed load in the model.

- Outer Wall Load (Super Dead Load) of 200mm thick brick masonry wall:
  =0.2x2.7x20= 10.8 KN/m
- Partition Wall Load (Super Dead Load) of 100mm thick brick masonry wall:
  = 0.1x 2.7x 20=5.4 KN/m
- Parapet wall load= 0.2x1.2x20=5 KN/m
- Floor Load / Super Dead Load on Slab (including floor finishing): 2.75 kN/m^2

Live Load (Variable Loads):

According to Indian standards, residential buildings are typically designed for live loads ranging from 3 to 4 kN/m^2.

Considered,

- LL on Slab = 3 KN/m^2
- LL on Slab (Staircase) = 4 KN/m^2

4.6.2 Loads acting Laterally

a) Earthquake Load (Seismic load)

b) Wind Pressure (Wind load)

4.6.2.1 Earthquake Load

In ETABS, the seismic analysis is conducted following the guidelines of IS 1893 (Part-I): 2016. This study examines the structure through the response spectrum methodology.

The following section defines all parameters used in the response spectrum method.

Response Spectrum Method (SRS):

The response spectrum analysis for seismic evaluation is conducted using the hard soil spectra defined in IS 1893 (Part-1): 2016.

Seismic Zones as Per Code: In this study investigates the structural behavior under various seismic zones specified in IS 1893 (Part-1): 2016. Seismic zonal factors and intensity values extracted within the respective tables provided in the standard.

In this study, we have considered sesmic zone as Zone IV for our research analysis.

Sesmic Zone Factor : 0.24

Soil Type: Understanding the specific soil type or soil characteristics is essential for calculating lateral horizontal load. The average spectral acceleration coefficient (Sa/g) depends on both the soil classification and the structure's natural period (T).

Therefore, the type of soil adopted in this study is Hard Soil = I

Energy Dissipation Factor (Damping ratio): The energy dissipation factor is a dimensionless parameter that quantifies the rate at which a vibrating or oscillating structure reduces its motion and eventually returns to a stable state.

This study adopts a damping ratio of 5%.

Importance factor of structure: The significance factor for the selected structure, designated for residential or commercial use with an occupancy exceeding 200 individuals, is I=1.2, as specified in Table-8 of Cl.7.2.3 in code IS 1893 (Part I): 2016, for tall reinforced concrete buildings.

Type of building: This study employs a novel moment-resisting frame structure.

Consequently, we have taken into consideration the value of response reduction factor R=5.

The values below refer to the spectral acceleration coefficient (Sa/g) applicable to rocky and hard soil types, Sa/g = 1 + 15T, ($T < 0.10s$)

Sa/g = 2.5, ($0.10s < T < 0.40s$)

Sa/g = 1/T, ($0.40s < T < 4.00s$)

Sa/g = 0.25 ($T > 4.00s$).

Where, T= time period in seconds

The structural analysis was performed for varying acceleration values across different time periods using the ETABS software.

The value of the scale factor is derived from this equation:

$$S = \frac{(I*g)}{(2R)}$$

Table 4. 3 Factors Adopted in Seismic Analysis

Parameters	**Adopted Values**	**IS:1893-2016 Code Ref/ Remarks**
Seismic Zone	IV	Annex E
Soil Type	Type-I	Hard Soil
Zone factor (Z)	0.24	Annex E or Table 3
Importance Factor (I)	1.2	Table 8, Clause 7.2.3
Structure	Residential buildings	Table 8, Clause 7.2.3
Response Reduction Factor (R)	5.0	Ductile RC structural wall with RC SMRFs
Structure height considered for time period calculation	Base to Terrace	Clause 7.6.2 (Page 21)
Time period considered (T)	$T=0.075 * h^{0.75}$ $T=0.085 * h^{0.75}$ $T=0.09*h/ d^{0.5}$	Bare MRF Buildings (without Infill panels) (For steel MRF Frame building) (For All other Building)
Seismic Weight (W)	Dead Load – 100% Live Load <=3KN/m2) –25% Live Load >3KN/m2) –50%	IS 1893:2016 (Page 20, 21)

	$$A_h = \frac{ZIS_a}{2Rg}$$ $$v_b = A_h \times W$$ Sa/g = Average spectral acceleration coefficient (dimensionless)	
Damping factor	5% damping	Clause 7.2.4 (Page 19)
Type of analysis	Response Spectrum analysis	Clause 7.7 of IS 1893-2016

4.6.2.2 <u>Wind Assessment</u>

Wind analysis in ETABS is conducted using the recommendations of IS-875 (2015). The following values for wind analysis have been extracted into the specified Indian standard code below: -

This research involves the structural planning and analysis of a building assumed to be located in the Delhi area.

Table 4. 4 Wind Specification

Parameter	**Value**	**Reference/Remarks**
Basic Wind Speed	47 m/s	As per IS 875 (Part III): 2015 (Delhi region)
Terrain category	3	Represents suburban or open terrain
Importance factor	1.2	Based on structure classification
Risk coefficient (k1)	1	Standard value for general buildings
Topography (k3)	1	Assumed due to flat or mildly sloped terrain

The structure must demonstrate exposure from the boundaries of the diaphragms.

The wind coefficients utilized are detailed in the table below,

Table 4. 5 Wind coefficient

Windward coefficient, Cp	0.8
Leeward coefficient, Cp	0.5

4.7 SERVICE AND DESIGN LOAD COMBINATIONS

Serviceability load combinations and Ultimate load combinations utilize for analysis and design as per the code IS 456 and IS 1893 is as follows:

Table 4. 6 Serviceability Limit State Load Combinations

Load Combination	**Dead Load (DL)**	**Live Load (LL)**	**Seismic Load (EQ)**	**Wind Load (WL)**	**Temp Load (TR/TF)**
DL + Live/Temp	1.0	1.0	-	-	1.0
DL + EQ	1.0	-	1.0	-	1.0
DL + Wind	1.0	-	-	1.0	1.0
DL + live + EQ/Wind	1.0	0.8	0.8	0.8	1.0

Table 4. 7 Ultimate State Load Combinations

Load Combination	**Dead Load (DL)**	**Live Load (LL)**	**Seismic Load (EQ)**	**Wind Load (WL)**	**Temp Load (TR/TF)**
DL + Live/Temp	1.5	1.5	-	-	1.5
DL + EQ	1.5 or 0.9	-	1.5	-	1.5/0.9
DL + Wind	1.5 or 0.9	-	-	1.5	1.5/0.9
DL + live + EQ/Wind	1.2	1.2	1.2	1.2	1.2

4.8 ADDITIONAL CONSIDERATIONS FOR TALL BUILDING ANALYSIS

4.8.1 Element-Based Stiffness Reduction Parameters: -

For slabs where mainly bending occurs primarily in the out-of-plane direction, it is necessary to modify the stiffness parameters m_{11}, m_{22}, and m_{12} to model the cracking behavior accurately.

When the slab is modeled as a shell, the parameters m_{11}, m_{22}, m_{12}, along with f_{11}, f_{22}, and f_{12} = 0.25

Stiffness adjustments for beams and columns modelled as frames are implemented as follows:

- For beams, I_{22} and I_{33} = 0.35.
- For columns, I_{22} and I_{33} = 0.7
- For uncracked walls, the values are:
  - f_{11} and f_{22} = 0.7
  - m_{11}, m_{22} and m_{12} = 0.7 (when bending is considered as out-of-plane)

4.8.2 P-Δ Effect

Assessing P-Delta effects is among the most effective evaluations for high-rise structures. The P-Delta effect occurs in tall structures or components when they experience substantial lateral displacement, leading to abrupt alterations distribution of ground base shear, overturning moment, and axial force at the base.

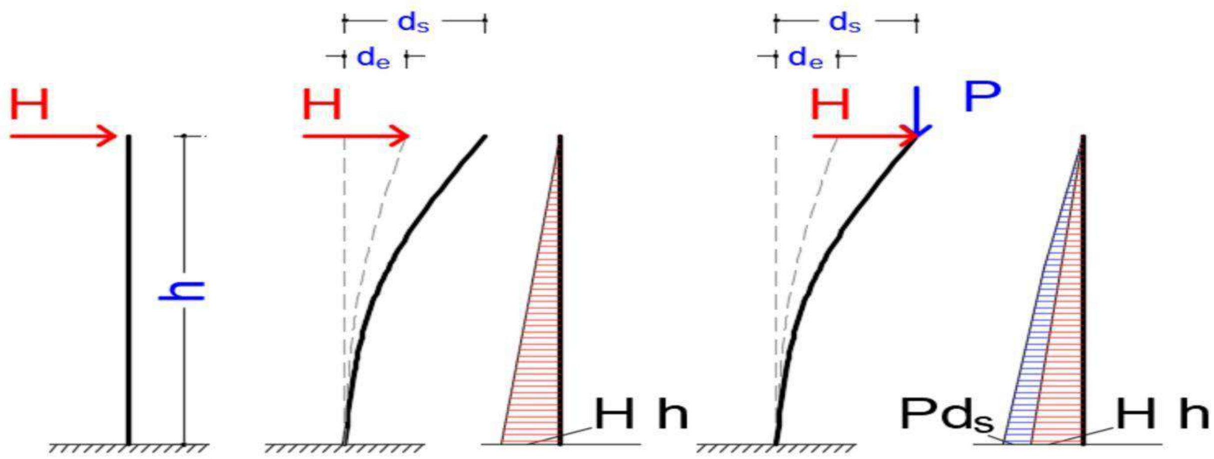


Figure 4. 4 High-Rise Model Showing P-Delta Induced Displacement

For Computation, the following formulas are used:

$$\theta = \frac{Px * \Delta}{Vx * hsx * Cd} \qquad (3.3)$$

Where,

$$\theta \max = \frac{0.5}{\beta * Cd} \qquad (3.4)$$

In this Equation, $\theta \leq 0.25$.

If the computed value of θ exceeds 0.25, the P-Delta effect must be considered in analysis of the high-rise structures.

4.9 MODELING APPROACH FOR ANALYSIS

4.9.1 Case I: Regular RC Building (SMRF)

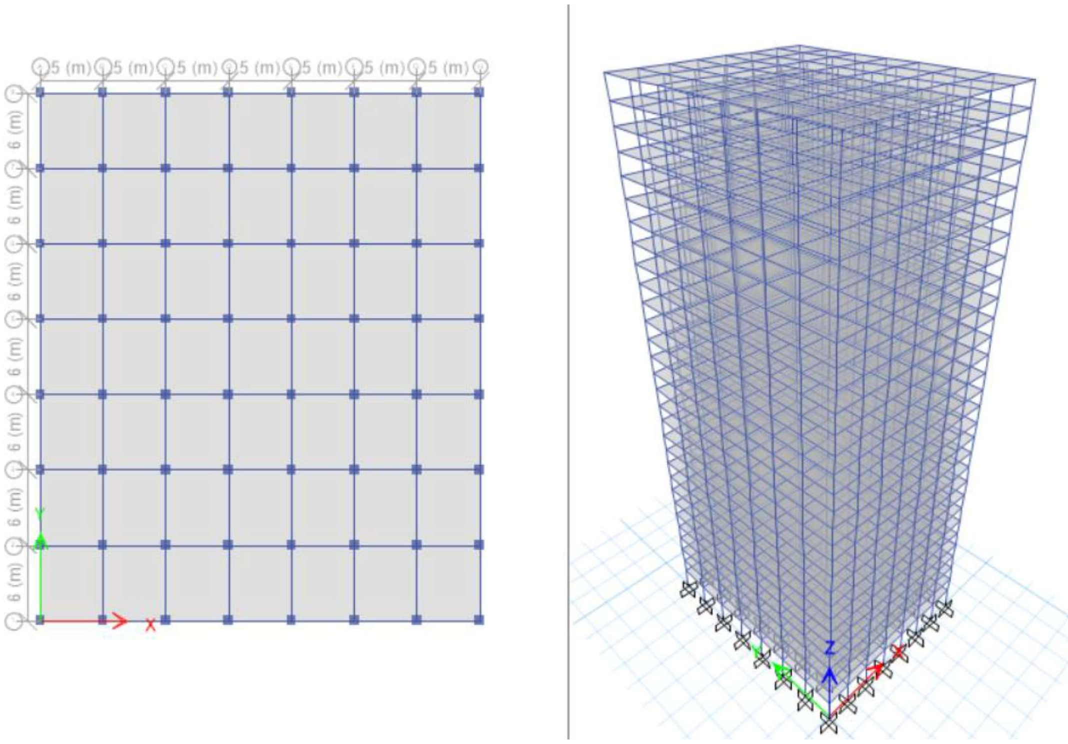


Figure 4. 5 Structural Plan and Elevation Views of Case I Model

4.9.2 Case II: RC Building with Corner Shear Walls

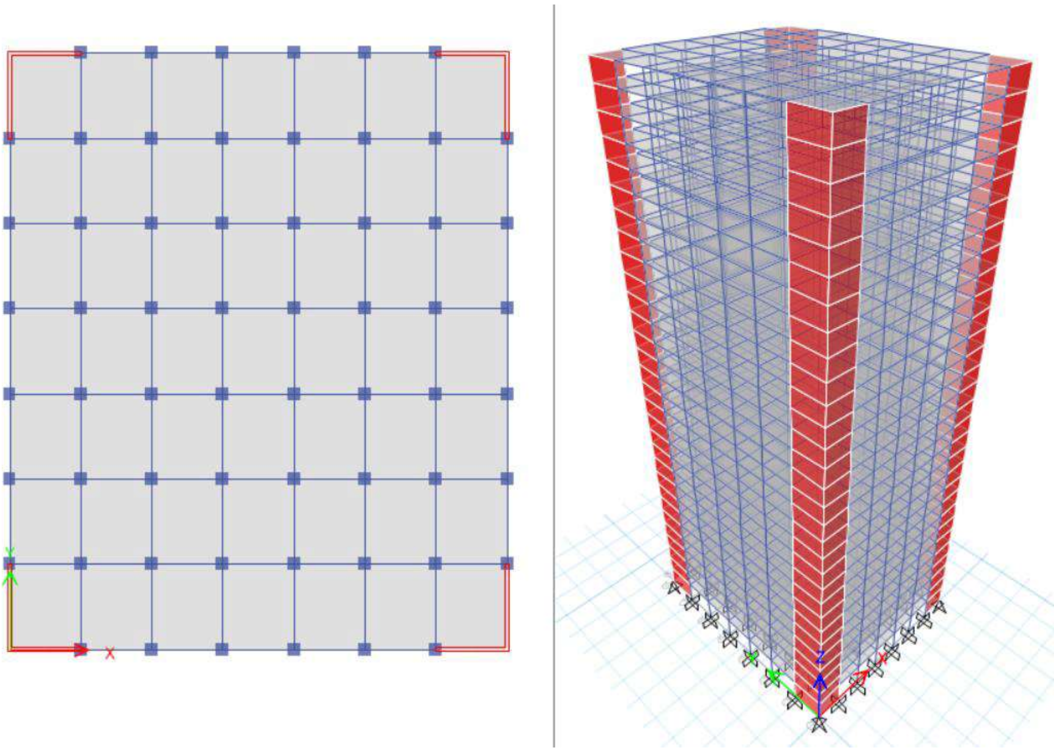


Figure 4. 6 Structural Plan and Elevation Views of Case II Model

4.9.3 Case III: RC Building with Central Shear Core

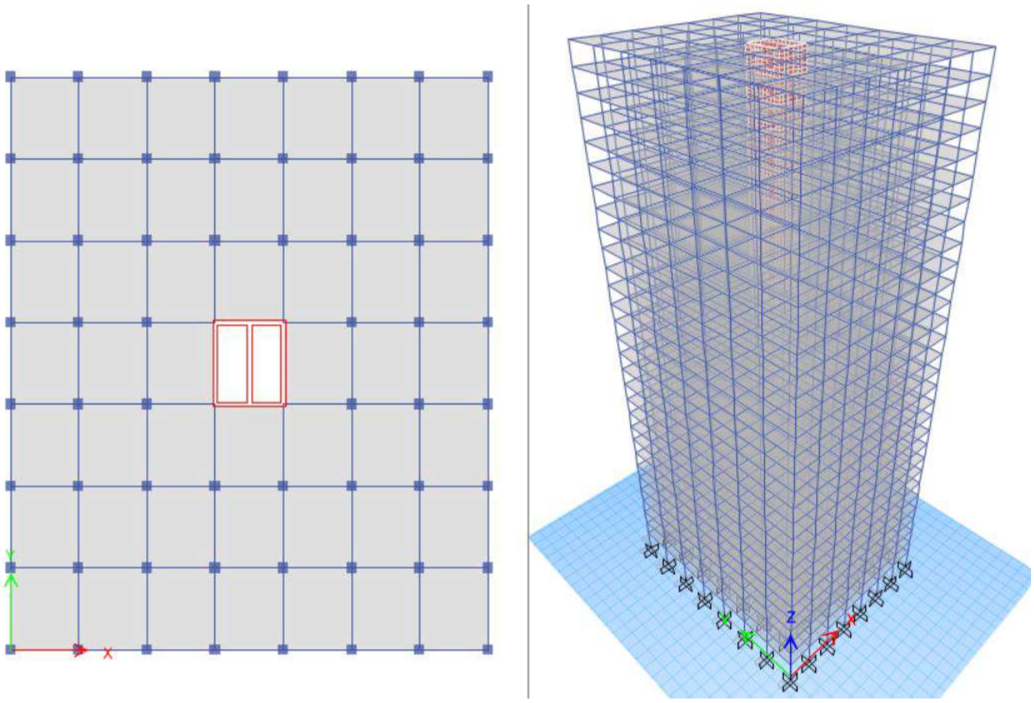


Figure 4. 7 Structural Plan and Elevation Views of Case III Model

4.9.4 Case IV: Reinforced Concrete Building with Shear Core and Single Outrigger Brace

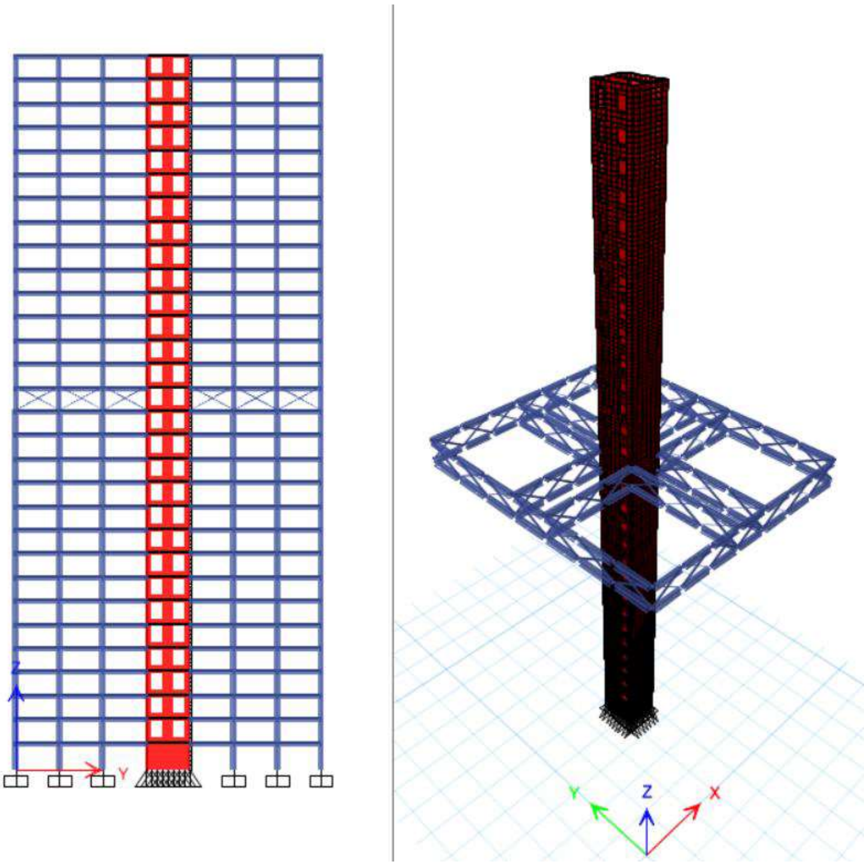


Figure 4. 8 Structural Plan and Elevation Views of Case IV Model

4.9.5 Case V: Reinforced Concrete Building with Shear Core and Double Outrigger Brace

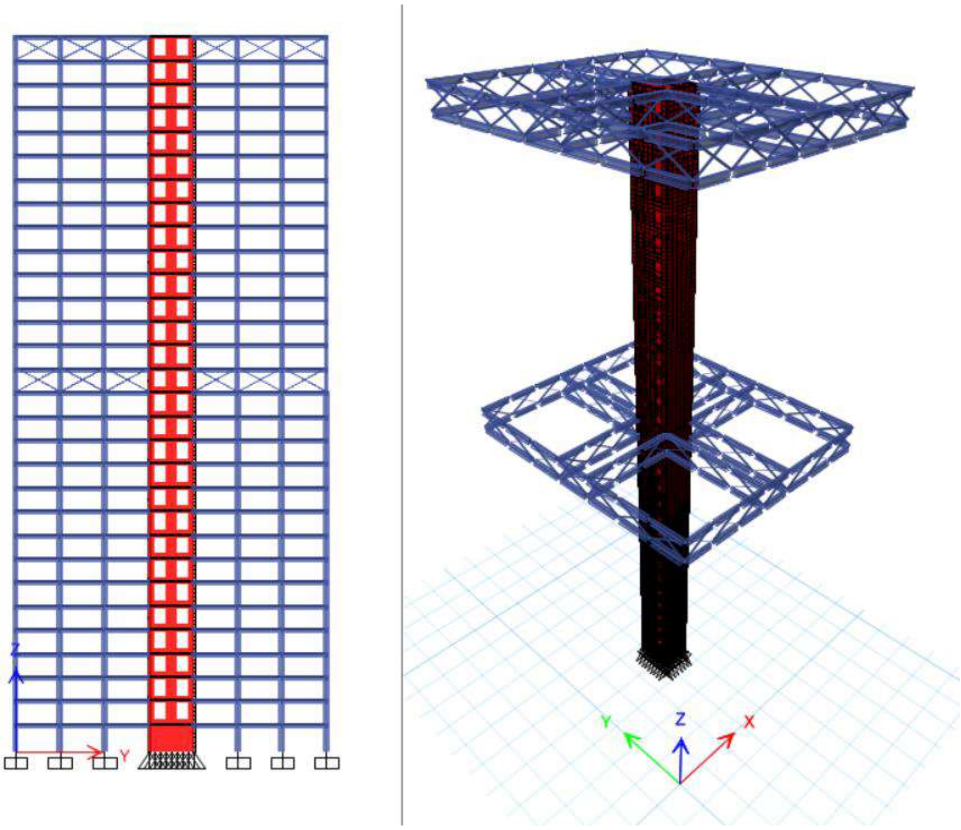


Figure 4. 9 Structural Plan and Elevation Views of Case V Model

4.10 EVALUATION FOR STRUCTURAL MODELS

For this study, the structural model has been analyzed using ETABS. In zone IV, evaluation involves two methods: an equivalent static and a dynamic analytical method specifically using the response spectrum technique. This software calculates lateral loads on the model based on the analysis method selected, and these calculations are then applied to the model assessment. The results are presented by summarizing the behavior of the structural systems assessed. This study focuses on a structure that experiences lateral loads, implementing the Equivalent Static Method and the Response Spectrum Approach due to the symmetry inherent in the structure.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 EVALUATION OF MAXIMUM DISPLACEMENT UNDER VARIOUS LOAD PATTERNS

The maximum storey displacement is a critical parameter in evaluating a structure's lateral stability, especially under seismic and wind loading. In this study, all five structural configurations-Case I (SMRF), Case II (Shear Wall), Case III (Shear Core), Case IV (Single Outrigger), and Case V (Double Outrigger) were analyzed using various load patterns including lateral seismic loads (EQX, EQY) and wind loads (WL-X, WL-Y), as per IS 1893 (Part 1): 2016.

Permissible limit value - Maximum Displacement at Terrace (Top Storey)

Total building height H = 99,700 mm

Table 5. 1 Permissible Limit Criteria for displacement

Load case	**Limit expression**	**Limit Value**
Earthquake (EQ) -Total sway check	H/250	99,700 / 250 = **398.8 mm**
Wind (WL) **-** serviceability check	H/500	99,700 / 500 = **199.4 mm**

The table below summarizes the peak displacement values obtained at the top storey (roof level) for each case and load pattern. It is observed that Case I, the bare frame model, recorded the highest displacement under both seismic and wind loads, indicating relatively low lateral stiffness. Case II and III showed moderate improvements due to the inclusion of shear walls and shear core, respectively. Notably, Case IV and Case V demonstrated significant reductions in lateral displacement, with the double outrigger system (Case V) being the most effective in controlling deflection. This trend confirms that the introduction of outrigger systems enhances lateral stiffness and improves displacement control in tall buildings.

Table 5. 2 Max Storey Displacement for Different Load Patterns

LOAD PATTERN	DISPLACEMENT VALUES FOR RC BUILDING WITH DIFFERENT CASES				
	SMRF (mm)	Corner Shear Walls (mm)	Central Shear Core (mm)	Shear Core and Single Outrigger Brace (mm)	Shear Core and Double Outrigger Brace (mm)
Linear static EQ-X	188	169	164	146	143
Linear static EQ-Y	213	183	176	154	149
Wind load WL- X	112	99	96	85	84
Wind load WL- Y	97	82	77	68	66
Response spectrum SPEC- X	152	99	108	112	102
Response spectrum SPEC-Y	162	101	109	108	95

5.2 DISPLACEMENT RESPONSE COMPARISON THROUGH GRAPHICAL INTERPRETATION

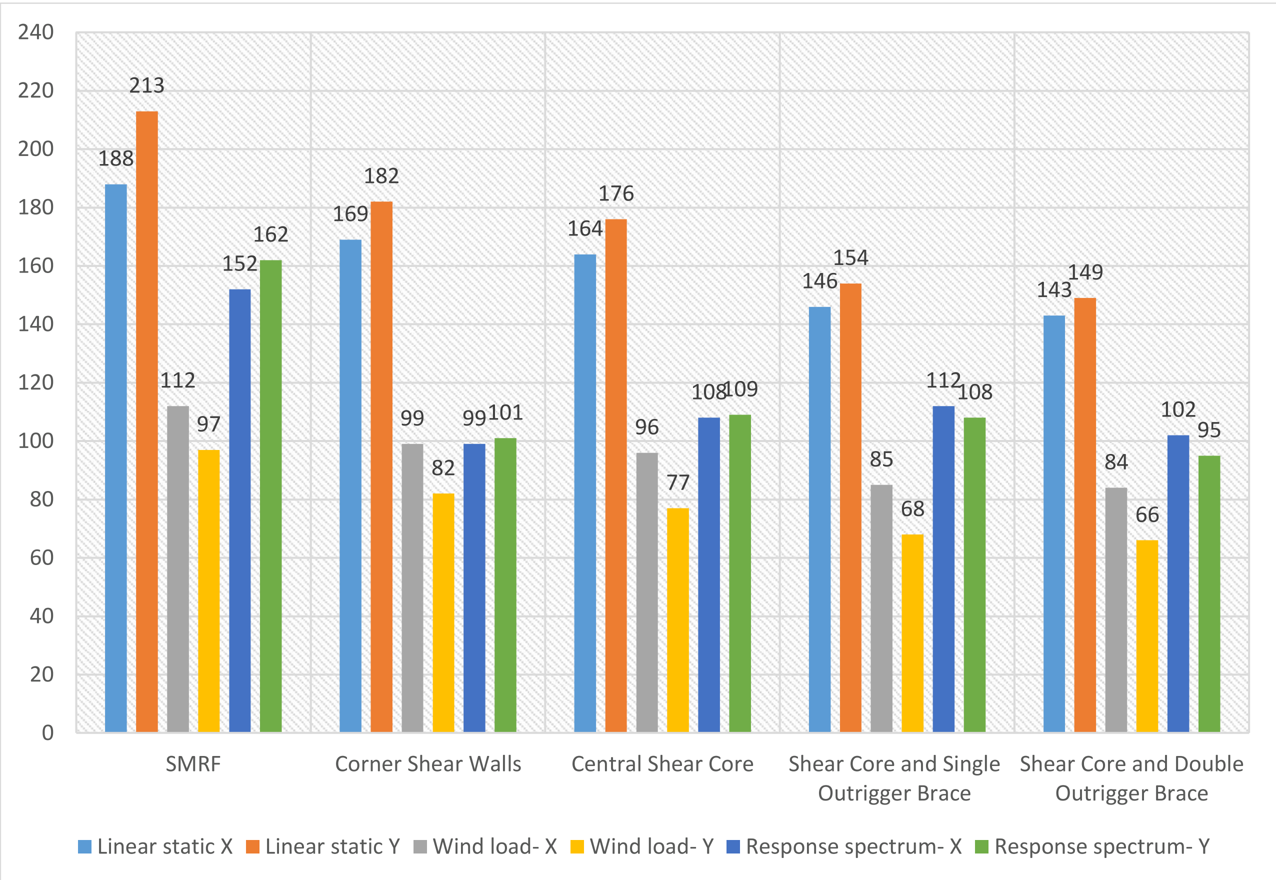


Figure 5. 1 Graphical representation of Max. Story Displacement with respective Load Type

5.2.1 RC Building (SMRF) Story Displacement for Different Load Patterns

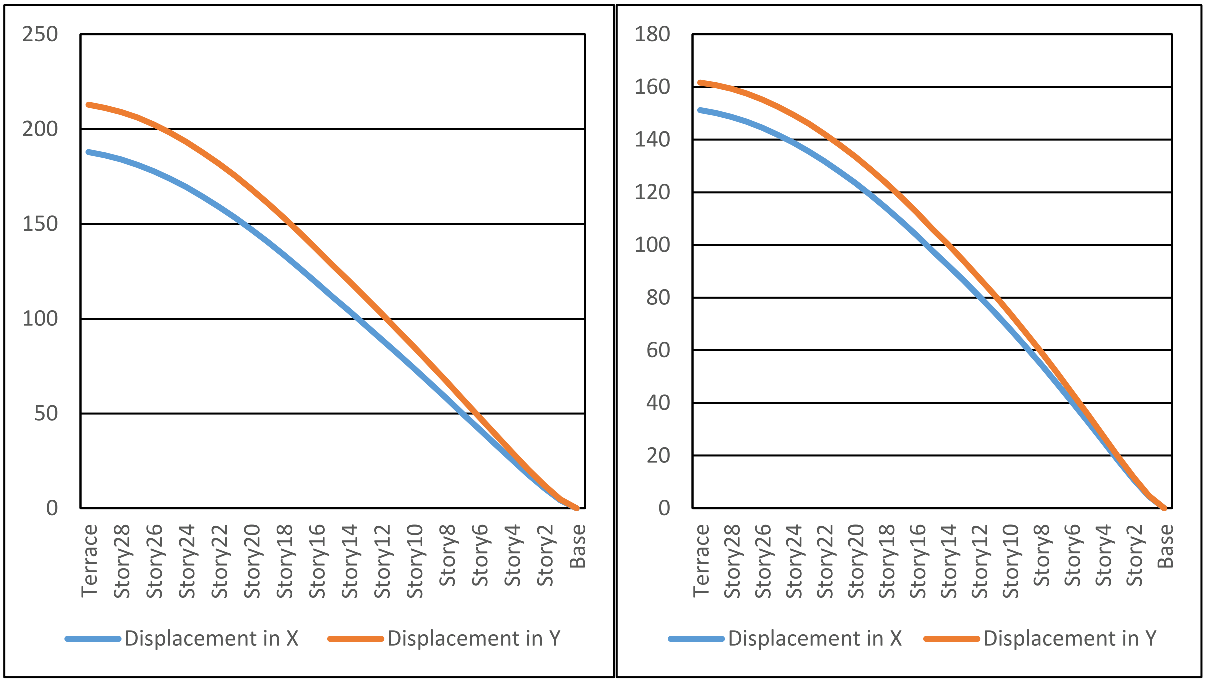


Figure 5. 2 Linear Static and Response Spectrum Analysis Results in X and Y Directions

5.2.2 RC Building with Corner Shear Wall Story Displacement for Various Load Patterns

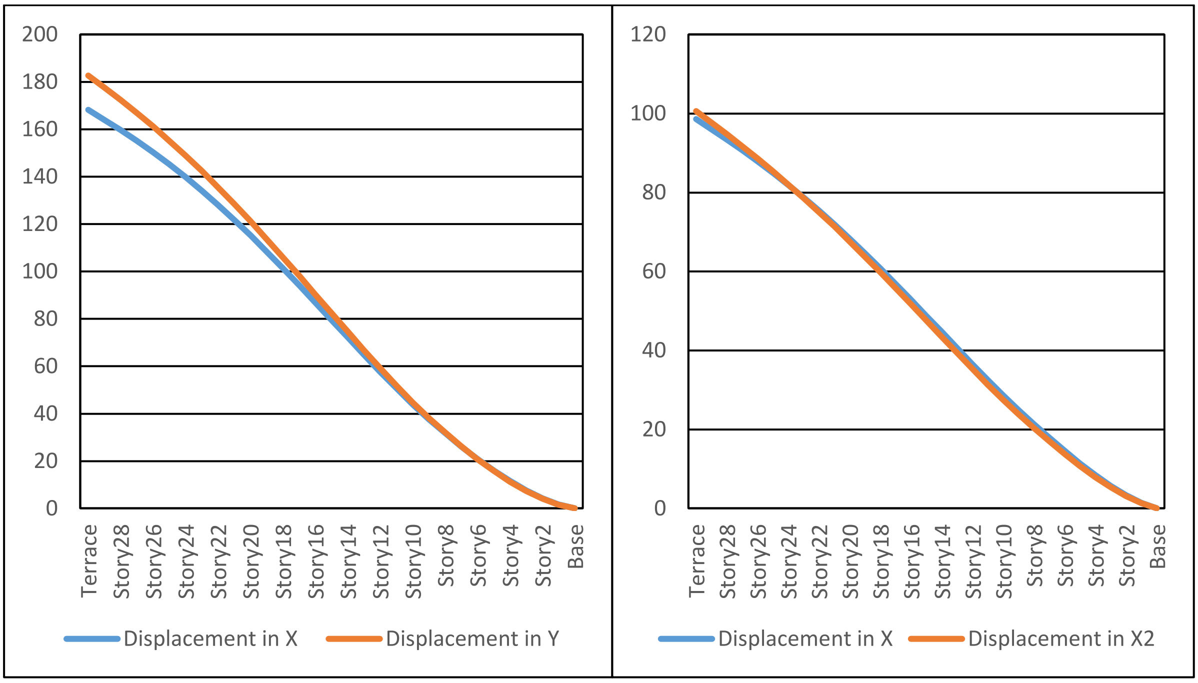


Figure 5. 3 Linear Static and Response Spectrum Analysis Results in X and Y Directions

5.2.3 Storey-wise Lateral Displacement Assessment of an RC Structure with Centralized Core Under Diverse Loads

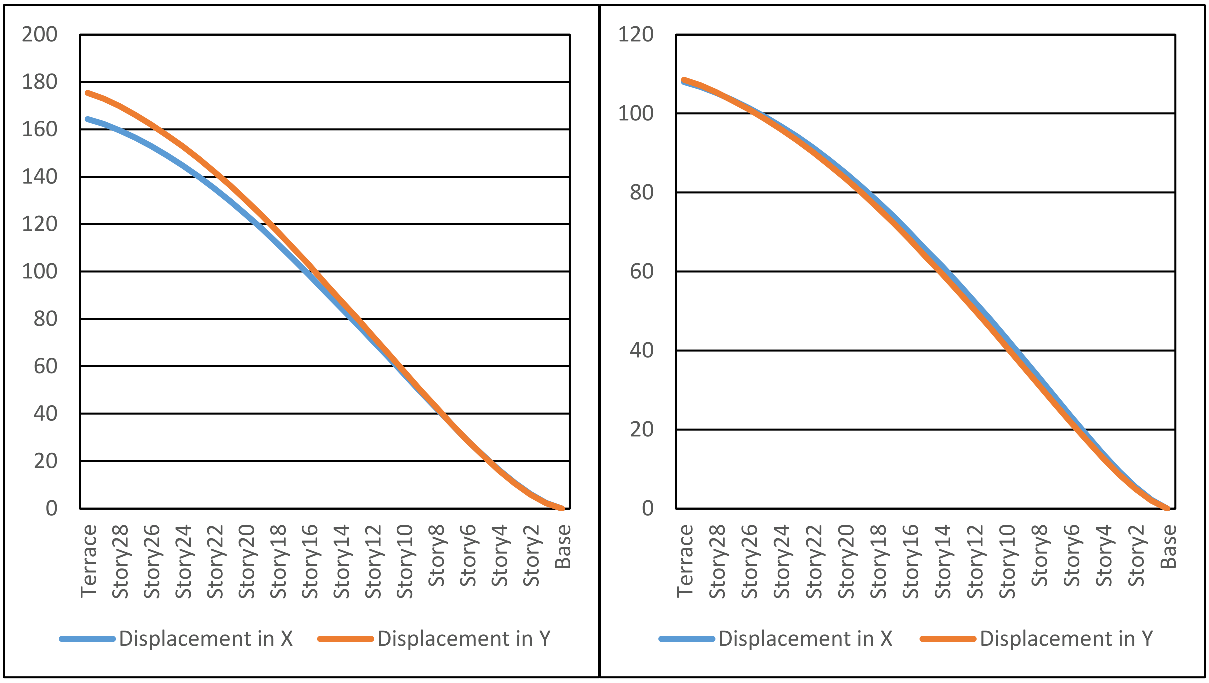


Figure 5. 4 Linear Static and Response Spectrum Analysis Results in X and Y Directions

5.2.4 Storey-wise Lateral Displacement Assessment of an RC Structure with Centralized Core and Single Outrigger under Diverse Loads

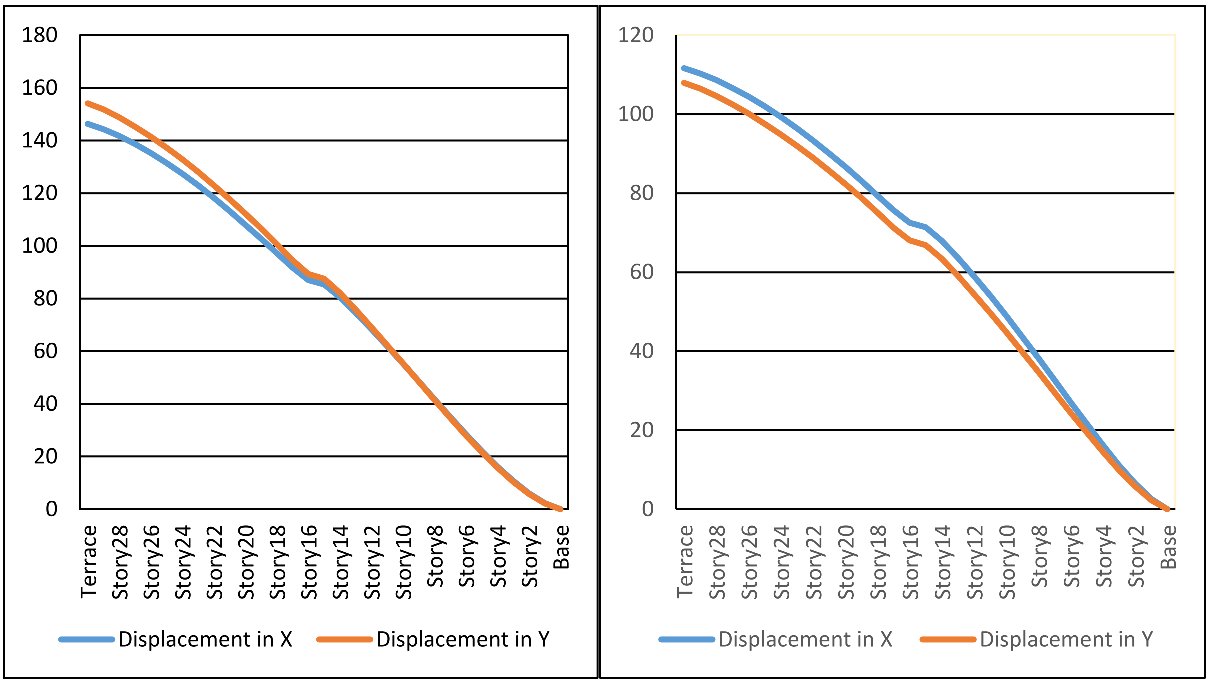


Figure 5. 5 Linear Static and Response Spectrum Analysis Results in X and Y Directions

5.2.5 Storey-wise Lateral Displacement Assessment of an RC Structure with Centralized Core and Double Outrigger under Diverse Loads

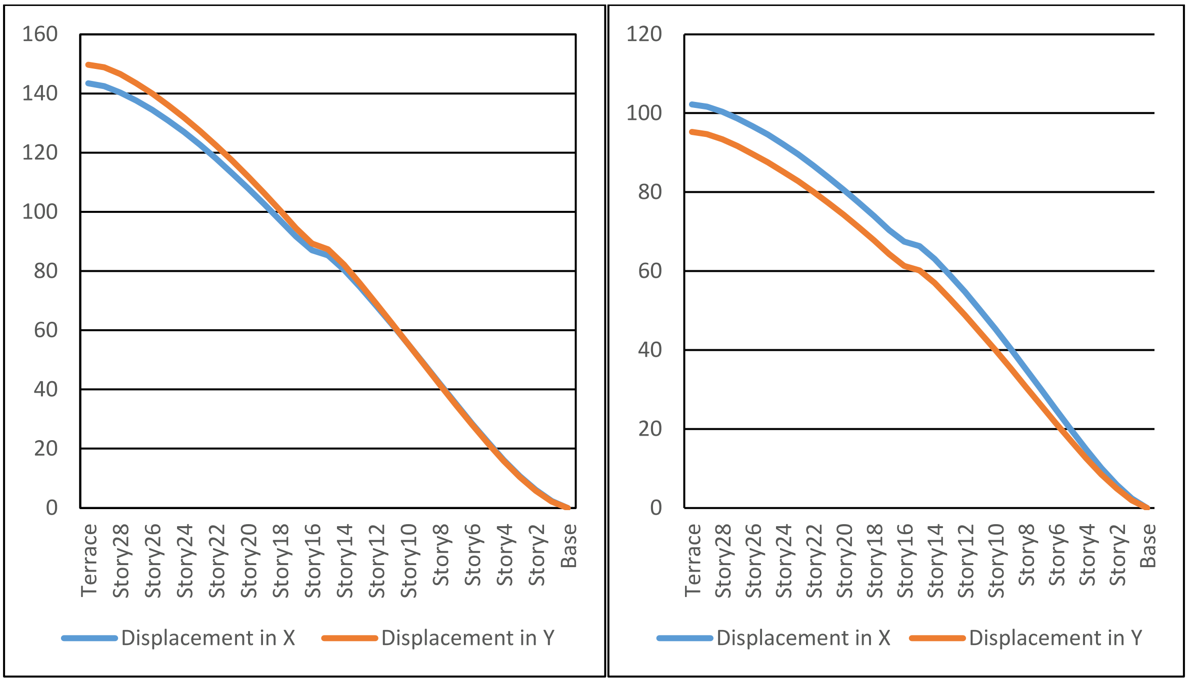


Figure 5. 6 Linear Static and Response Spectrum Analysis Results in X and Y Directions

5.3 MAXIMUM STORY SHEAR ACROSS DIFFERENT STRUCTURAL MODELS

Storey shear is a critical parameter in evaluating the seismic response of a structure, as it represents the horizontal force acting on each level due to ground acceleration. In this study, five different structural configurations were analyzed to observe how each system affects the maximum storey shear distribution under seismic loading. These models include: Case I – a regular RC frame structure with SMRF; Case II – a structure with corner shear walls; Case III - a centrally located shear core; Case IV – a shear core combined with a single outrigger-braced system; and Case V - a centre shear core incorporated double outrigger-braced truss,in which results were obtained by the methods of both static analysis & response spectrum analysis conducted under compliance with code IS 1893 (Part 1): 2016.

The comparative results are presented in the table and graph below, which clearly illustrate that Case I recorded the highest storey shear values across most levels. This can be attributed to the absence of any specialized lateral-road-resisting system in this model. The structure lacks stiffness, particularly at upper levels, which leads to greater lateral force accumulation. Case II and Case III exhibited moderate reductions in storey shear due to existence of shear walls with a central shear core, respectively. These systems provide additional stiffness and reduce the lateral force demand on beams and columns.

Among all configurations, the lowest maximum storey shear was observed in Case V. The double outrigger system, coupled with a central shear core, significantly improved the lateral stiffness and redistributed internal forces more effectively throughout the height of the building. This system not only resisted the overturning moment but also engaged the peripheral columns in absorbing lateral forces, thereby reducing the shear at intermediate levels. Case IV, with a single outrigger, showed improvement over Cases I–III but was still slightly less efficient than the dual outrigger system in minimizing storey shear. It is also notable from the graph that the shear demand gradually increases along building height and peaks at lower storeys, where lateral loads accumulate from the upper levels. The sharp contrast in values between Case I and Case V emphasizes the importance of incorporating lateral load-resisting system in tall buildings, especially within the seismic zones.

The comparative analysis confirms that the inclusion of outrigger systems, particularly the double outrigger configuration, plays a vital role in reducing storey shear forces in high-rise buildings. This directly contributes to improved seismic performance and structural safety, validating its application in modern high-rise construction.

Table 5. 3 Story Shear Force Comparison Across Different Models

STORY	Conventional RC Frame Structure with SMRF (kN)	RC Structure Featuring Corner Shear Walls (kN)	RC Structure with Central Shear Core (kN)	RC Structure with Central Shear Core and Single Outrigger Bracing (kN)	RC Structure with Central Shear Core and Double Outrigger Bracing (kN)
Terrace	801.8731	1130.7389	1081.8329	1052.4142	969.3365
Story29	1764.4558	2381.6184	2288.5106	2227.2854	2138.4168
Story28	2646.0695	3382.4284	3298.5403	3210.9875	3152.4416
Story27	3423.0515	4122.4627	4097.3006	3989.3891	3986.3791
Story26	4082.9462	4621.1338	4693.8897	4572.4836	4631.7455
Story25	4627.703	4923.7312	5120.336	4993.418	5105.5597
Story24	5074.0821	5097.5012	5429.0868	5305.4146	5448.7281
Story23	5450.8032	5221.225	5684.2383	5572.1406	5719.2895
Story22	5791.9512	5365.8235	5945.1084	5850.7124	5977.8841
Story21	6127.5353	5571.5032	6247.1502	6173.2987	6268.6437
Story20	6474.3813	5837.6203	6591.1652	6538.3856	6605.0555
Story19	6831.7778	6127.6327	6948.7136	6917.919	6970.0894
Story18	7184.5138	6393.3114	7280.3557	7275.2133	7330.2791
Story17	7512.1083	6604.0889	7556.361	7585.0214	7656.3356
Story16	7800.1841	6759.1062	7771.3267	7865.3285	7958.5047

Story15	8055.219	6889.071	7952.3473	8177.0944	8290.8721
Story14	8302.6943	7041.7767	8151.1756	8467.5722	8593.946
Story13	8559.4736	7251.569	8399.5965	8726.9183	8854.014
Story12	8842.5414	7520.4265	8704.2024	8967.8007	9085.7466
Story11	9150.1585	7812.3482	9033.1948	9197.4588	9303.025
Story10	9458.5062	8099.5146	9332.5764	9410.7865	9508.1872
Story9	9734.1232	8355.002	9561.4424	9600.8826	9698.2589
Story8	9959.8518	8582.8154	9727.9629	9779.9013	9883.7481
Story7	10160.2568	8842.9111	9901.8694	9990.7502	10101.996
Story6	10398.9461	9215.9922	10177.3658	10285.6756	10400.5481
Story5	10718.3058	9730.4138	10587.2598	10669.6802	10785.0722
Story4	11046.856	10305.5138	11042.0029	11061.7215	11179.0642
Story3	11232.5005	10805.5481	11414.8452	11374.0935	11493.2456
Story2	11507.6504	11330.3823	11873.9467	11822.514	11921.1267
Story1	13462.5843	12924.3562	13461.0506	13474.5196	13487.9904

5.3.1 Comparison Of Maximum Story Shear: Graphical View

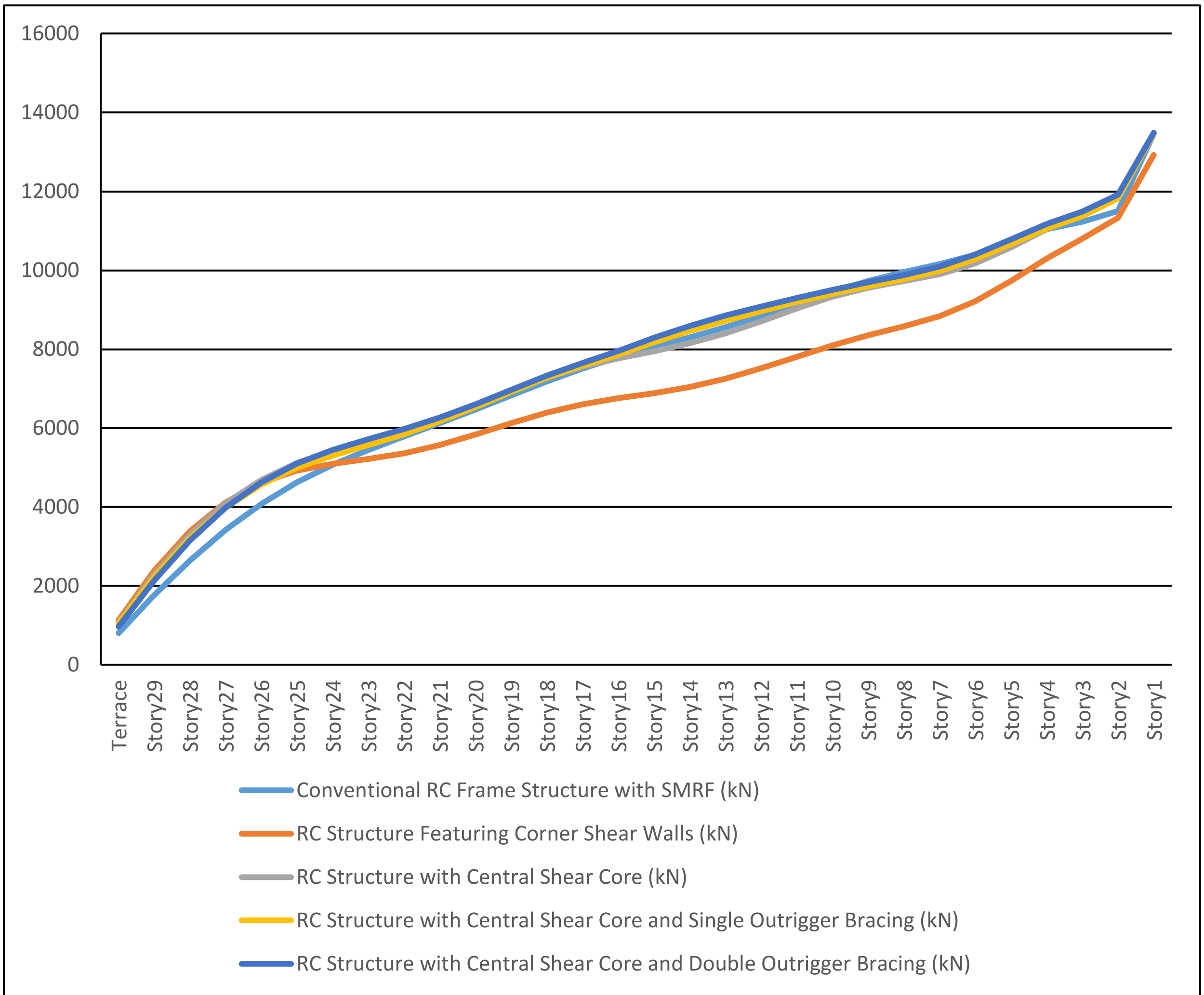


Figure 5. 7 Story Shear force graphical curve comparison for different model case.

5.4 EVALUATION MODEL FOR SERVICEABILITY CRITERIA

5.4.1 Structural Stability Assessment of Various Model Cases

- ❖ According to Clause 7.11.1 of IS 1893:2016, the inter-storey drift ratio should not exceed 0.004.

i) <u>CASE I: STABILITY ASSESSMENT</u>

The maximum inter-storey drift obtained from the Response Spectrum analysis is 0.0023 in the X-direction and 0.0025 in the Y-direction.

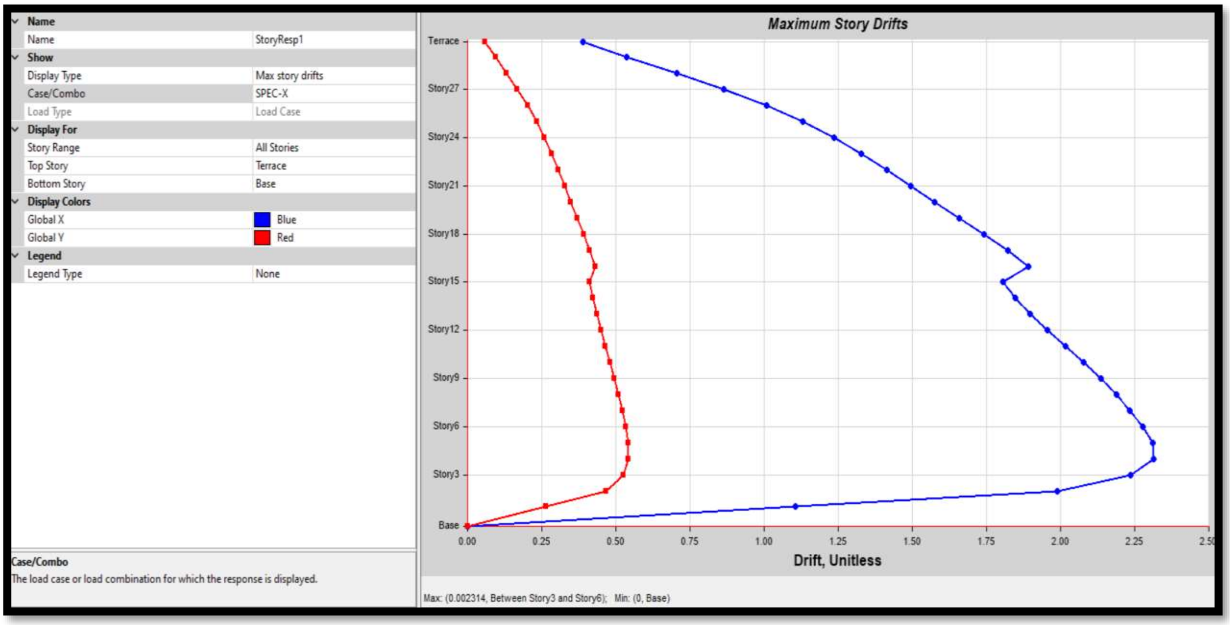


Figure 5. 8 Peak story-level drift ratio response in the X-direction

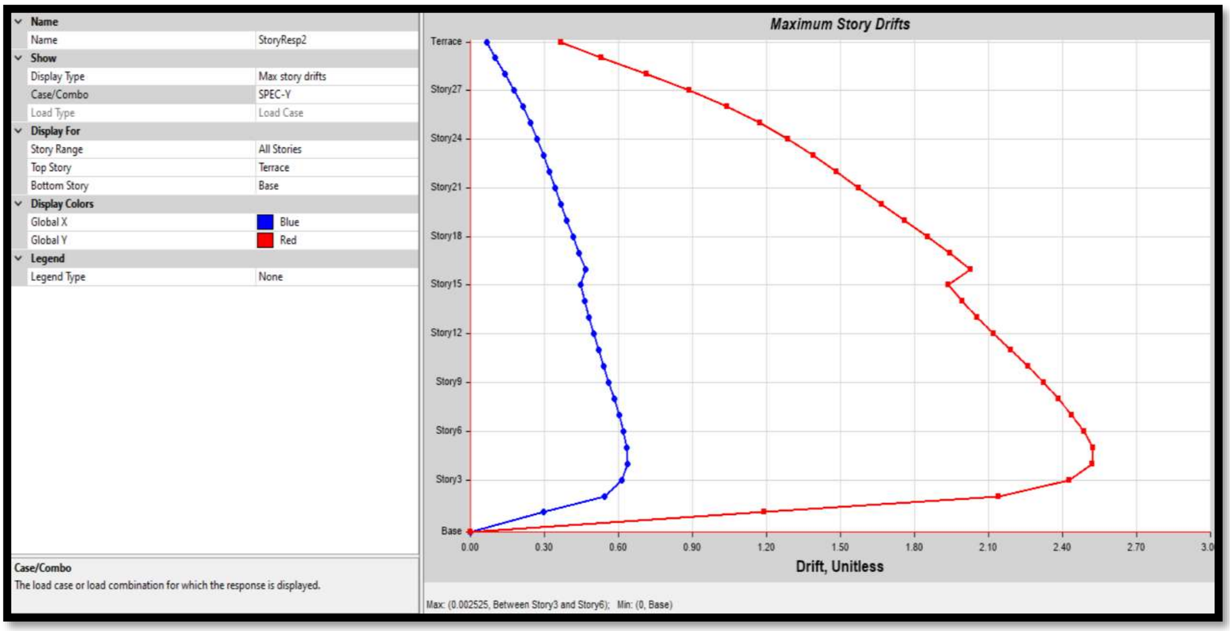


Figure 5. 9 Peak story-level drift ratio response in the Y-direction

ii) <u>CASE II: STABILITY ASSESSMENT</u>

The maximum inter-storey drift obtained from the Response Spectrum analysis is 0.0013 in the X-direction and 0.0013 in the Y-direction.

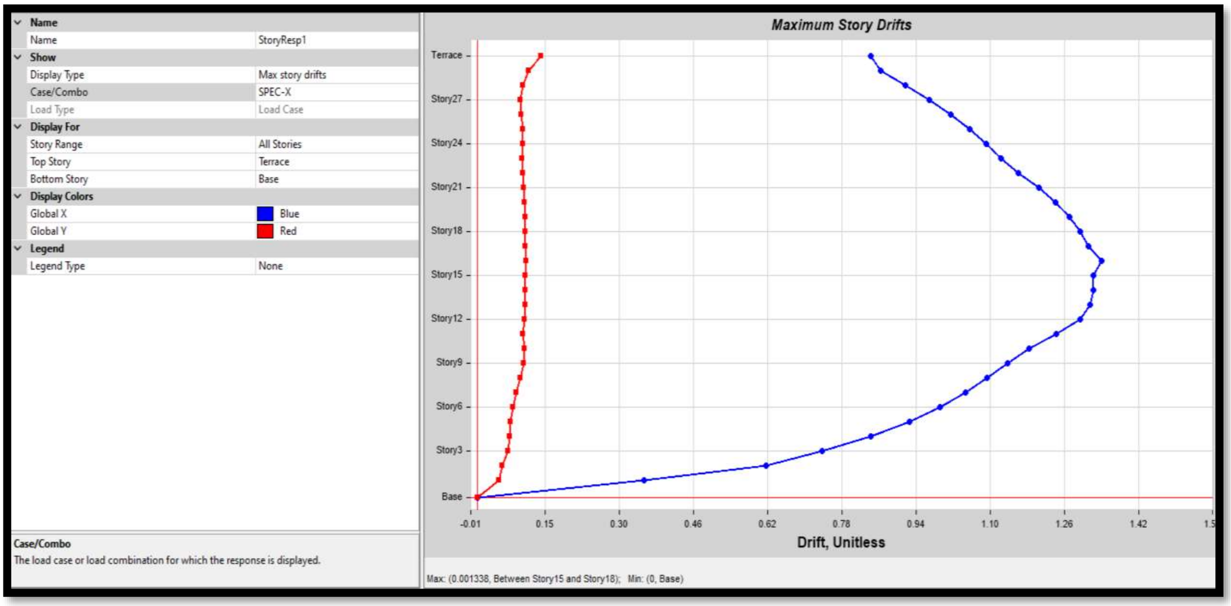


Figure 5. 10 Peak story-level drift ratio response in the X-direction

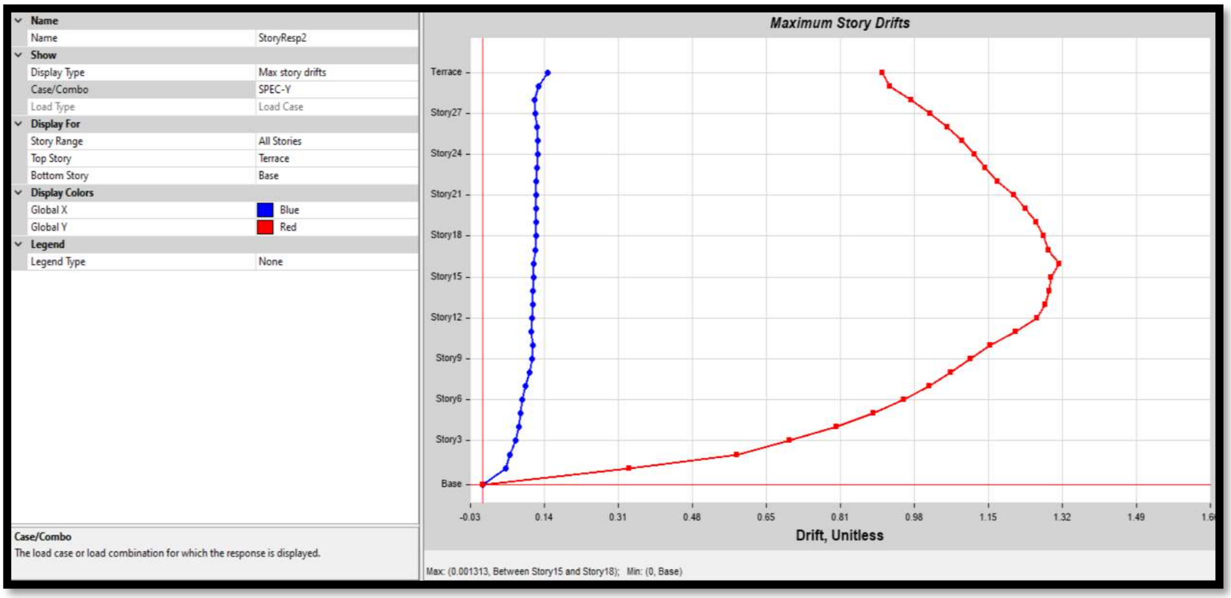


Figure 5. 11 Peak story-level drift ratio response in the Y-direction

iii) CASE III: STABILITY ASSESSMENT

The maximum inter-storey drift obtained from the Response Spectrum analysis is 0.00155 in the X-direction and 0.00152 in the Y-direction.

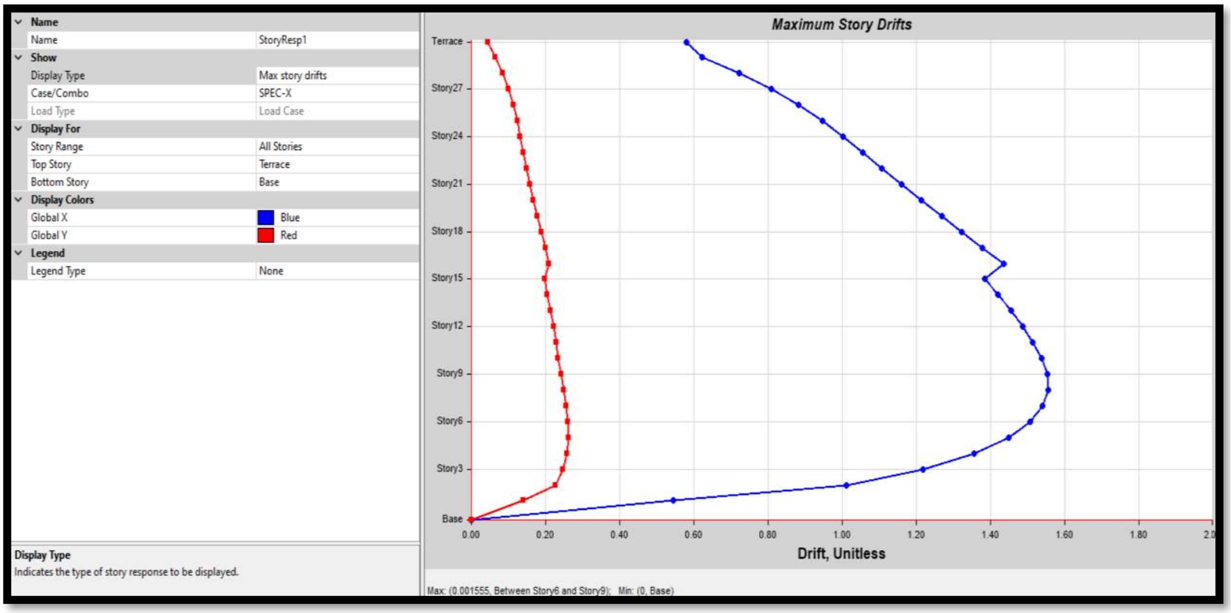


Figure 5. 12 Peak story-level drift ratio response in the X-direction

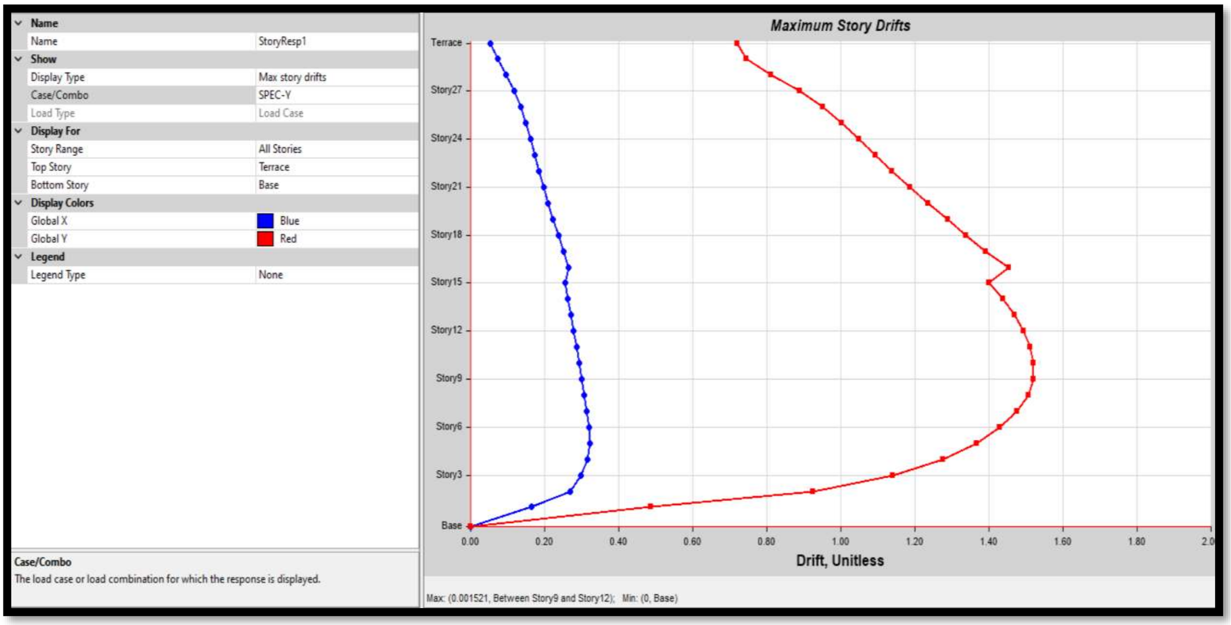


Figure 5. 13 Peak story-level drift ratio response in the Y-direction

iv) CASE IV: STABILITY ASSESSMENT

The maximum inter-storey drift obtained from the Response Spectrum analysis is 0.00172 in the X-direction and 0.00160 in the Y-direction.

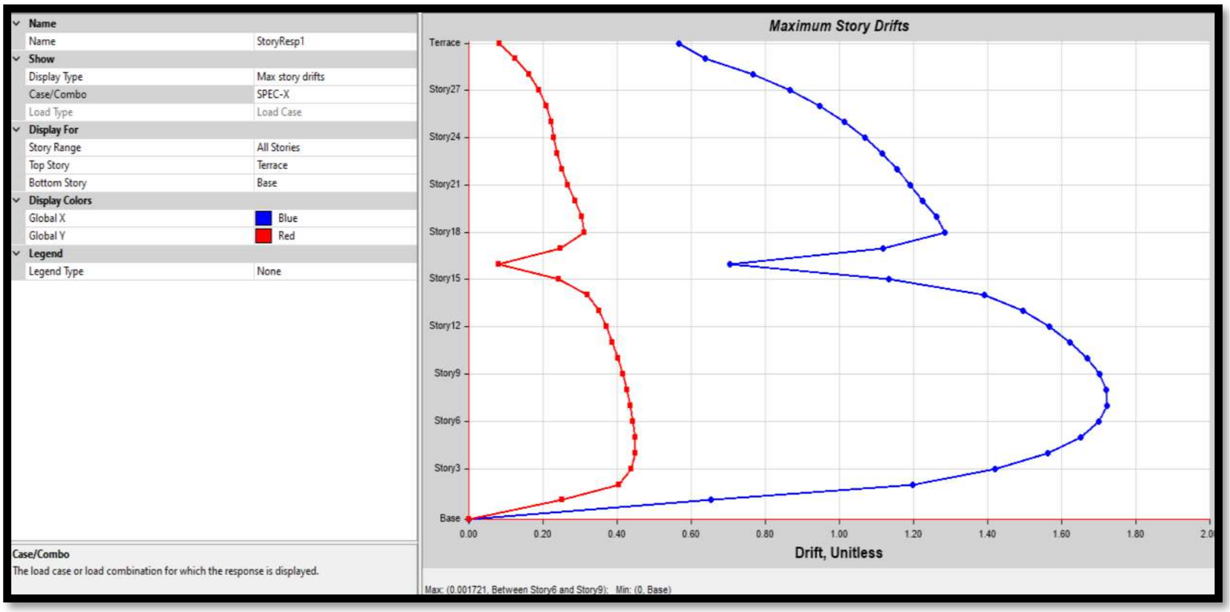


Figure 5. 14 Peak story-level drift ratio response in the X-direction

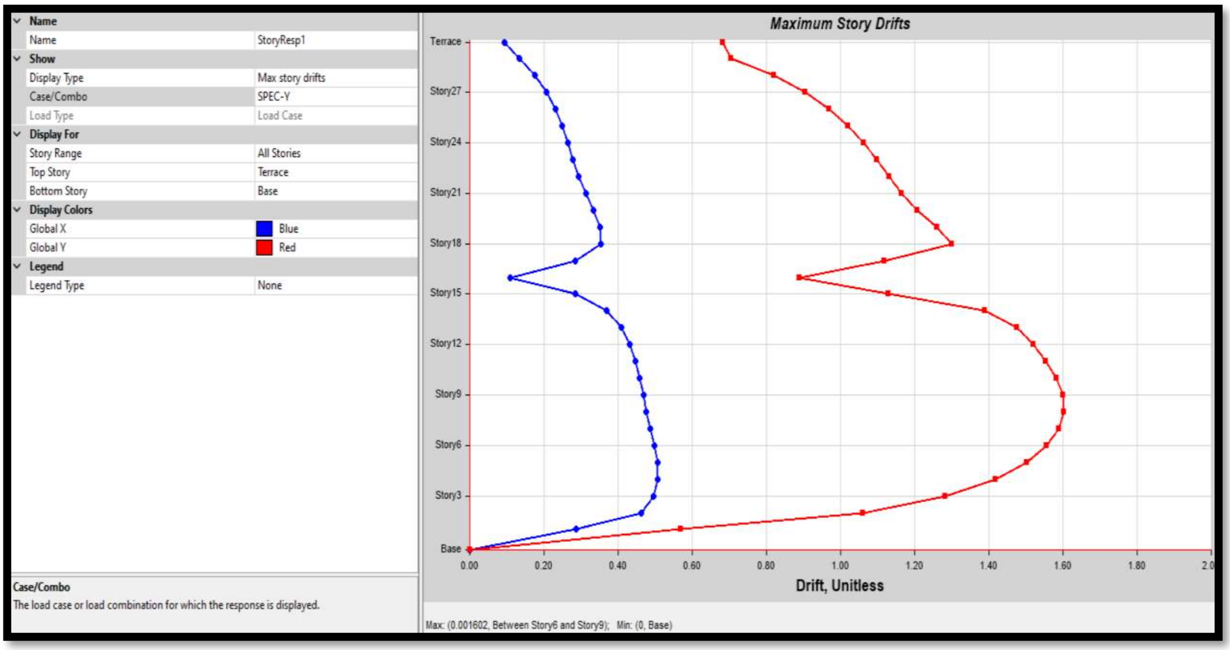


Figure 5. 15 Peak story-level drift ratio response in the Y-direction

v) CASE V: STABILITY ASSESSMENT

The maximum inter-storey drift obtained from the Response Spectrum analysis is 0.00161 in the X-direction and 0.00146 in the Y-direction.

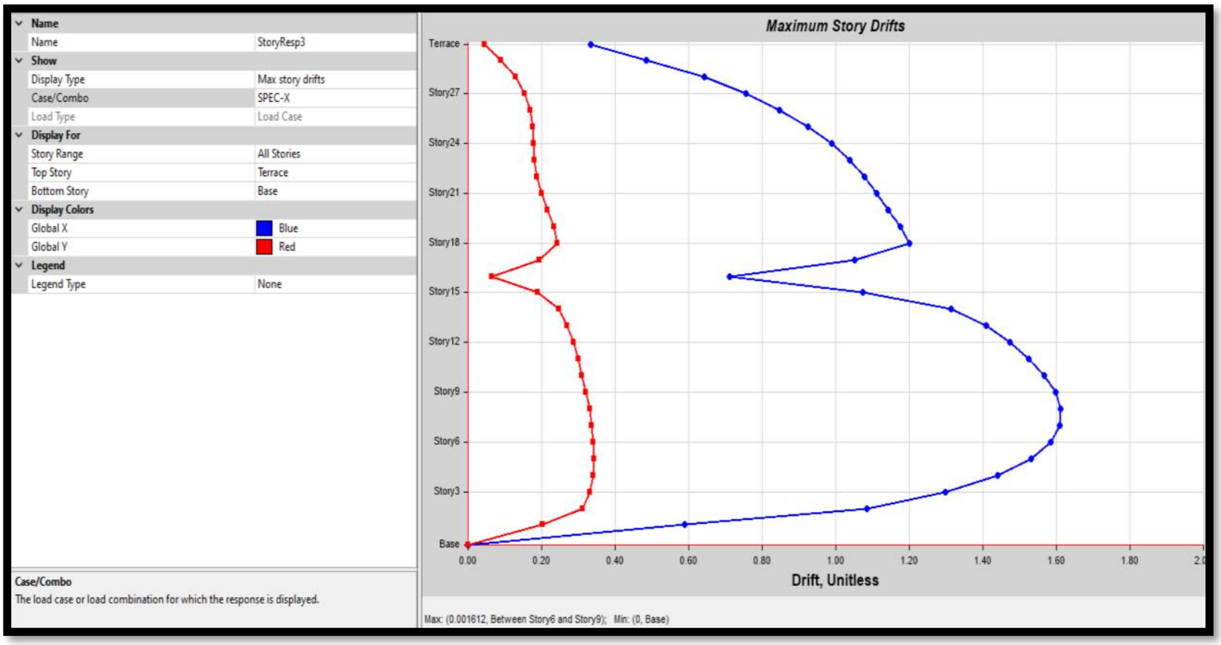


Figure 5. 16 Peak story-level drift ratio response in the X-direction

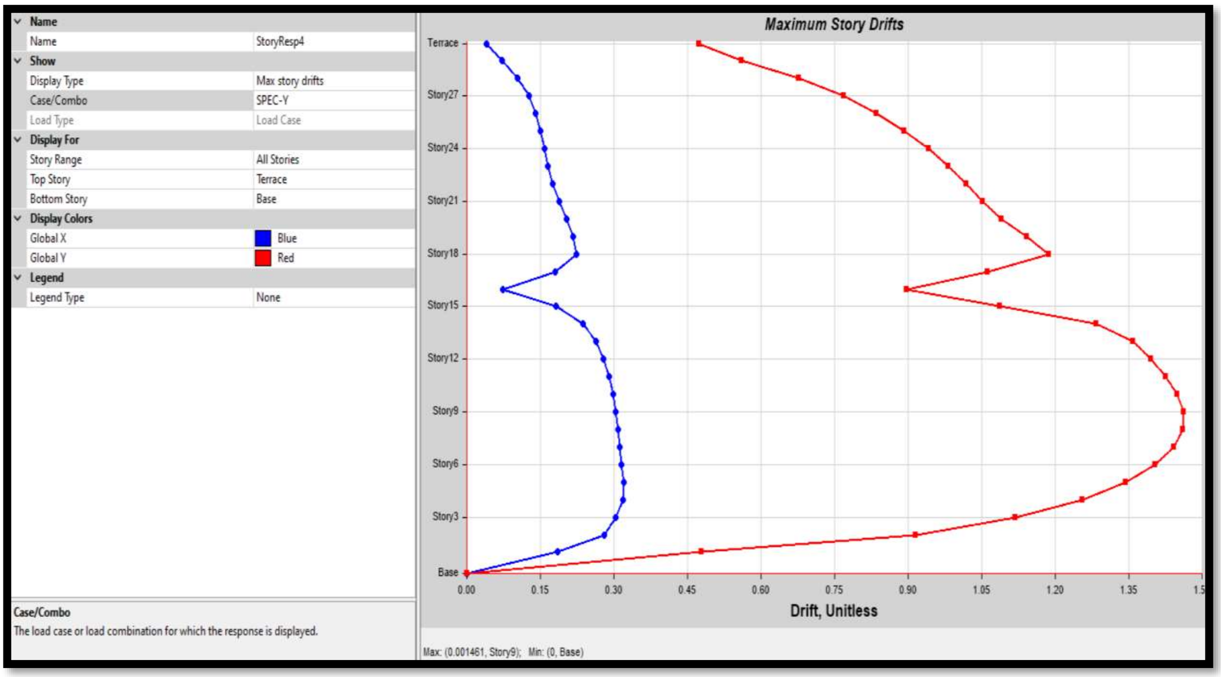


Figure 5. 17 Peak story-level drift ratio response in the Y-direction

CHAPTER 6

CONCLUSIONS AND FUTURE SCOPES

6.1 CONCLUSIONS

- Based on the conducted analysis, the following conclusions are made:

- ❖ The analyses involve evaluating multiple model instances and hard soil types for Zone IV. To evaluate the performance of both Equivalent Static and Response Spectrum methods, key responses like lateral load, drift, displacement, and base shear are graphically compared
- ❖ The adoption of a robust shear core with a dual outrigger system is the most effective structural configuration relative to other options.
- ❖ In both the Equivalent Static and Response Spectrum analyses, the configuration incorporating a shear core along with double outriggers consistently yields the lowest lateral displacement when compared to alternative structural systems under varied loading conditions
- ❖ The maximum storey shear is observed to be the lowest in the double outrigger-braced structure, with the exception of conventional SMRF buildings. This indicates that incorporating a double outrigger system resulted highly effective in reducing impact of seismic and lateral loads.
- ❖ In comparison to standard buildings, those utilizing a double outrigger-braced system exhibit a minimum base shear, indicating that the double outrigger-braced system is the most efficient configuration for this parameter (base shear).
- ❖ The results are consistent with prior studies such as Bayati et al. (2008), who concluded that multi-outrigger systems significantly reduce lateral displacement and improve overall building stiffness under seismic loading. This supports the effectiveness of such double outrigger system observed in the present study.
- ❖ The incorporation of shear core in all configurations showed noticeable improvement in controlling lateral displacement and storey drift, as also confirmed by Santhosh and Mathew (2017), who found centrally placed shear cores to be effective in tall buildings.
- ❖ The reduction in time period with the addition of outriggers demonstrates improved structural rigidity, which agrees with findings by Kurzekar et al. (2020), who observed up to 64% reduction in fundamental time period using outrigger systems.

- ❖ It is observed that models with shear walls (Case II) or shear cores (Case III) alone are less effective in reducing base shear compared to models with integrated outrigger systems, highlighting the need for hybrid systems in high-seismic zones, as supported by Dangi and Jamle (2019).
- ❖ Double outriggers at ideal sites (15th and 29th floors) produced better structural performance in all respects. This fits the strategy advised by Dahake and Azghar (2019), who underlined the need of outrigger placement in improving earthquake protection.

6.2 FUTURE SCOPE

This study offers important insights into the performance of tall, reinforced concrete (RC) buildings subjected to lateral loads by evaluating various structural systems. However, there is still potential for further research and improvement in the following areas:

1. **Soil-Structure Interaction (SSI):** This study assumes a fixed-base condition. Incorporating flexible soil properties through SSI analysis can give more realistic results, especially for soft or variable soil types.
2. **Material Variations:** Future studies can explore the use of high-strength concrete, steel-concrete composite elements, or dampers integrated with outriggers to enhance seismic resistance.
3. **Performance-Based Design (PBD):** A more advanced approach such as non-linear time history analysis or pushover analysis could be adopted to study real-life behavior under major earthquake scenarios.
4. **Construction Feasibility and Cost Analysis:** Though structural performance is considered here, future work can include the practicality of construction, cost implications, and architectural limitations of implementing outrigger and shear core systems.
5. **Wind Tunnel Testing and CFD Simulation:** While ETABS provides effective earthquake modeling, future work can involve detailed wind load simulation using the concept Computational Fluid Dynamics (CFD) or wind tunnel experiments for more accuracy.

6. **Irregular Buildings and Torsion Effects:** This study focuses on regular-plan structures. Further studies may extend the analysis to buildings with vertical or plan irregularities to investigate torsional behavior.
7. **Hybrid and Smart Systems:** Research can be expanded by integrating energy-dissipating devices or adaptive outrigger systems (such as damped outriggers or active control systems) for enhanced resilience.
8. **Different Seismic Zones and Building Heights:** Extending the analysis to include other seismic zones and comparing performance across different height ranges (e.g., G+20 to G+50) would help generalize the findings

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Arpit GOYAL

Assessment of Seismic Parameters in Reinforced Concrete Tall Structures Utilizing Shear Cores

Gaurav ME Thesis

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