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Structural Behaviour of High-Rise Buildings with Different Outrigger Configurations under Dynamic Loading

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***Abstract* - The increasing demand for high-rise buildings in urban settings requires effective structural systems capable of enduring significant lateral forces from wind and seismic events. This study analyses and compares the performance of tall structures using outrigger systems to those lacking such systems. The primary aim is to understand the behaviour of different structural configurations specifically typical bare frames, frames with core walls, and those featuring outrigger and belt truss systems under lateral forces. The study entails thorough modelling and dynamic analysis of established design codes to determine displacement, drift, stiffness, and stability for the evaluation of overall structural effectiveness.**

A model of a 50-story reinforced concrete edifice is developed for four separate situations, preserving a uniform plan and elevation design. Each case is analysed using both comparable static and response spectrum methods for seismic evaluation, with wind loads applied per IS 875 Part 3. The strategic implementation of outriggers is analysed for their efficacy in reducing top story displacement and inter-story drifts. Comparative studies indicate that outrigger systems markedly improve the lateral stiffness and performance of tall structures by effectively dispersing moments and shear stresses throughout structural sections, hence reducing overall deformation under lateral loads.

The research indicates that while bare frames and core walls offer no resistance to considerable lateral stresses, the incorporation of outriggers and belt trusses significantly enhances structural stability and serviceability. Such systems are particularly beneficial in regions prone to seismic activity or strong winds, where controlling displacement and drift is crucial. The findings improve the understanding of optimal structural configurations for skyscrapers and offer practical recommendations for future high-rise designs, promoting both safety and structural effectiveness.

Keywords: Tall Buildings, Lateral Load Resistance. Outrigger Systems, Non-Outrigger Systems. Structural Stability, Seismic activity.

I. INTRODUCTION

The rapid urban expansion and the increasing population density have made the urban land scarce, which has caused the growing need for vertical construction. A response to the limitations of space for commercial and residential purposes, the development of high-rise and skyscraper buildings has been propelled by breakthroughs in structural engineering, material development, and computer design. The city's vertical growth creates a huge technological challenge in maximising usable floor area and ensuring the safety of occupants in fire events. Tall buildings are subjected to large lateral pressures owing to wind and seismic activity, which can cause considerable sway, resulting in discomfort to occupants and possible damage to structural and non-structural components. Thus, it is necessary to build structural systems that can handle such stresses efficiently in terms of space. High-rise buildings require stability and strength against lateral loads. In an effort to satisfy this requirement, different structural systems have been developed by engineers. These systems include braced frames, rigid frames, wall-frame systems, shear walls, tube structures and outrigger systems. Each system has its own advantages in terms of rigidity, cost and ease of construction.

The core and outrigger structural system has been extensively studied for its efficiency in improving the stiffness and managing the deflections of high-rise buildings. The economical design consists of a central core, usually shear walls or braced frames and outlying columns coupled with stiff horizontal outrigger sections. Outriggers are essentially stiff arms that transfer moments from the core to the outer columns that act as compression and tension members, thus increasing the resistance of the building to lateral forces and overturning moments. This strategy increases the utilisation of internal space by reducing the demand of closely spaced structural members. It is applicable to commercial and

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residential high-rise buildings. The method was originally developed in bridge engineering and was adapted for tall buildings, initially with deep steel or concrete trusses at mechanical levels, so as not to interfere with useable space. Development of construction technology makes it possible to install a multi-tiered outrigger at different levels of the building with accurate modelling, greatly improving the control of inter-story drifts and lowering the total lateral displacement.

Today, outrigger systems are used in several applications, including the traditional steel or concrete outriggers, and new possibilities including damped outriggers, belt trusses, and hybrid materials. Today, structural engineers use computer-aided design and simulation techniques to optimise the placement of outriggers for best performance under dynamic loads. The tech affords greater freedom to architectural design, with open floor plans and less internal structural barriers. With the development of skyscrapers above 200 meters, the outrigger system became more and more popular for its economic and structural efficiency. It is now one of the recommended systems for mid and high-rise projects in seismic and wind sensitive areas. The aim of this study is to compare the response of buildings with and without outriggers to evaluate the performance, feasibility, and durability of different structural systems under lateral loadings in an effort to help in making the best design choices in modern high-rise construction.

II. LITERATURE REVIEW

Ahmed and Zhang (2025) performed a comparative analysis on the effectiveness of outrigger systems in alleviating lateral forces in super-tall structures. The study employed finite element analysis (FEA) to assess the performance of outrigger-supported and conventional moment-resisting frame structures under seismic and wind-induced lateral forces. The results demonstrated that outrigger systems can reduce lateral displacements by up to 40%, thereby substantially improving overall structural stability. The authors underscored that the strategic placement of outriggers, particularly at mid-height and elevated levels, is crucial for improving structural performance. While the augmented stiffness is advantageous, they also noted drawbacks, such as greater building complexity and coordination challenges. Their research concluded that outrigger systems are most effective and justified in buildings above 50 stories, when lateral displacements provide a significant challenge. The research highlights the necessity of good design integration to balance performance improvements with construction feasibility and cost factors.

Chen *et al.* (2024) focused on evaluating the economic and structural impacts of integrating outrigger systems in high-rise buildings. The study combined structural performance modelling with cost analysis to assess if the improvements in stiffness and stability offered by outriggers justify the extra material and manpower expenses. Their findings demonstrated that whereas outrigger systems markedly enhance lateral stiffness, they frequently lead to greater construction complexity and resource utilisation. The study indicated that in regions with moderate seismic activity, reinforced core wall systems lacking outriggers can achieve comparable lateral load resistance. Thus, they proposed a hybrid method that combines belt trusses with viscous dampers as a cost-efficient option for specific applications. This hybrid approach enhances structural durability while reducing material usage and construction difficulties. Chen et al. emphasised the necessity of aligning structural design choices with local seismic regulations and economical limitations, promoting tailored solutions for diverse high-rise building situations.

Wang and Li (2023) performed a comparative investigation of construction efficiency and time management challenges associated with outrigger and non-outrigger structural systems in high-rise buildings. Empirical case studies indicated that projects utilising outrigger installations saw extended timelines typically 15–20% longer mainly due to the necessity for meticulous coordination across structural, architectural, and MEP systems. The delays resulted from the complexity of integrating outriggers into building cores, especially at mechanical or transitional levels. Despite the prolonged construction period, the study found that outrigger systems offered lasting operational advantages. Structures equipped with outriggers exhibited improved serviceability, diminished maintenance expenses, and greater management of long-term deformations. Wang and Li suggested that in projects where long-term performance and minimised building sway are critical, the extra construction time could be a worthwhile investment. The decision on the two systems must reconcile immediate logistical efficiency with long-term operational benefits.

Kumar and Sharma (2022) assessed the environmental impacts of outrigger systems in high-rise buildings by a full life-cycle assessment (LCA). Their analysis examined the entire carbon footprint, encompassing material extraction, building, and long-term operational efficiency. The results demonstrated that while outrigger systems initially increased carbon emissions due to additional materials and complex construction techniques, they ultimately improved building performance over time. Structures supported by outriggers demonstrated increased control of dynamic sway, leading to reduced energy consumption in HVAC systems and improved overall thermal efficiency. This enhanced performance

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mitigated occupant discomfort and diminished mechanical system loads, leading to lower operational energy demands. The writers emphasised the necessity of harmonising current environmental impacts with long-term sustainability advantages. Their result suggested that although outrigger systems may appear environmentally wasteful during construction, their potential to improve building longevity and reduce operational emissions renders them a sustainable choice in high-rise design across the whole life cycle.

Johnson *et al.* (2021) conducted an extensive parametric analysis to investigate the influence of outrigger system spacing on lateral load distribution and overall structural performance in high-rise buildings. Modelling various spacing configurations with structural simulation tools shown that closely spaced outriggers markedly enhanced torsional resistance, hence increasing lateral stiffness and diminishing building twist during wind or seismic events. This design led to a substantial rise in axial forces transmitted to the core walls and perimeter columns. This trade-off underscored the necessity for precise structural specifications and reinforcement strategies, particularly in the core region, to accommodate increased stresses. The research emphasised the necessity of optimising outrigger placement—rather than merely incorporating them—by balancing lateral performance with internal force distribution. Johnson et al. established that although closely spaced outriggers improve torsional performance, their effect on vertical load paths necessitates meticulous evaluation to avoid overstressing core elements and compromising structural safety or serviceability.

Rodriguez and Kim (2020) evaluated the feasibility of alternative lateral load-resisting systems by comparing diagrid structures with conventional outrigger systems in high-rise buildings. Their research involved a comparative analysis utilising finite element modelling, focusing on factors such as lateral stiffness, drift control, and architectural flexibility. The results demonstrated that diagrid systems exhibited structural performance comparable to outrigger systems, especially in minimising lateral displacements and regulating dynamic response under wind loads. Furthermore, diagrids offer substantial architectural advantages by facilitating open interior areas and unique exterior aesthetics, which are occasionally constrained by traditional outrigger designs. The researchers noted that diagrids distributed lateral stresses more uniformly across the building's structure, possibly diminishing the necessity for complex internal reinforcement. While outriggers offer advantages under specific height and load circumstances, Rodriguez and Kim concluded that diagrid systems present a viable and cost-effective alternative, particularly where architectural innovation, spatial efficiency, and visual identity are essential project considerations.

Ibrahim *et al.* (2019) investigated the practical challenges of integrating outrigger systems into modular high-rise construction, a method that is becoming increasingly common for rapid and efficient urban development. Their research assessed the influence of outriggers on constructability, modular coordination, and on-site assembly timelines. They observed that while outrigger systems improved lateral stability, they also introduced significant complexity to modular connections, occasionally resulting in prolonged construction timeframes and more coordination across trades. The authors introduced prefabricated outrigger components designed for modular systems to improve construction efficiency while preserving structural integrity. Furthermore, they found that non-outrigger modular structures enabled rapid assembly but displayed insufficient lateral stiffness until enhanced with bracing or damping systems. The study emphasised that progress in modular outrigger integration is essential for optimising the benefits of modular efficiency and structural integrity in skyscrapers. Ibrahim et al. urged for further research on modular-compatible outrigger design alternatives.

Objectives

- To assess lateral load-resisting capacity of outrigger versus non-outrigger systems.
- To analyse drift, displacement, and base shear under loading conditions.
- To evaluate structural efficacy and global stability performance.
- To recommend optimal systems based on performance metrics.

III. METHODOLOGY

Structural design philosophy is based on resilience, connecting performance objectives to seismic event intensity and recurrence. It classifies the ground motion into small, moderate and major levels with different tolerable damage thresholds. Small earthquakes should keep the structures in full function with minimal or no maintenance costs. In the event of mild seismic occurrences, buildings may suffer damage and require repairs or strengthening of key structural elements before they can be reoccupied. In the event of major or great earthquakes, buildings might be momentarily uninhabitable but are likely to be sufficiently intact to permit a safe means of escape and future reconstruction. The idea is to save human life by preventing catastrophic structural collapses. In the standard design approach, it is acknowledged that structures can be designed to be sufficiently ductile. This permits energy absorption via controlled inelastic deformations while keeping the structure intact. The transition from elastic to inelastic design requires ductility reduction and

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overstrength factors indicative of the ability of the system to deform safely. The permissible deformation is controlled by inter-story drift limitations, which are typically on the order of 0.4%. Hence, structural systems should be designed not only for strength but also for appropriate control of displacement behaviour for improved seismic performance.

CASE A: Conventional Bare Frame

A symmetrical G+50 story structure featuring beams, columns, and slabs at the floor level. Each floor has a height of 3 meters, and there are 3 denied storeys at a total height of 45 meters. The structure's total height is 150 meters, categorising it as a high-rise building according to IS16700:2023.

Table 3.1: material and section properties of RC members for bare frame

S. No.	Material and Section Description	Specifications
1	Type of reinforcement used	High Yield Strength Deformed (HYSD) bar, Grade 550
2	Grade of concrete utilized	M30 grade concrete
3	Number of frames along X-axis	6 spans
4	Number of frames along Y-axis	6 spans
5	Building height	Ground floor plus 50 upper stories
6	Spacing between grid lines in X-direction	8 meters
7	Spacing between grid lines in Y-direction	8 meters
8	Dimensions of external RCC columns	1000 mm × 1000 mm
9	Cross-section of RCC beams	450 mm × 650 mm
10	Thickness of floor slab	250 mm

Property modifiers/stiffness modifiers

Sl No.	Structural Element	Serviceability Design		Strength Design	
		Cross-Sectional Area	Moment of Inertia	Cross-Sectional Area	Moment of Inertia
(1)	(2)	(3)	(4)	(5)	(6)
i)	Slabs	$1.0A_g$	$0.35I_g$	$1.00A_g$	$0.25\ I_g$
ii)	Beams	$1.0\ A_g$	$0.7\ I_g$	$1.00\ A_g$	$0.35\ I_g$
iii)	Columns	$1.0\ A_g$	$0.9\ I_g$	$1.00\ A_g$	$0.70\ I_g$
iv)	Walls	$1.0\ A_g$	$0.9\ I_g$	$1.00\ A_g$	$0.70\ I_g$

Figure 3.1: cracked section properties of RC members as per IS 16700:2023

CASE A Details

Start Modelling the elements after defining the material properties initially model the outer columns after that inner columns and then beams and core walls and then slab portion.

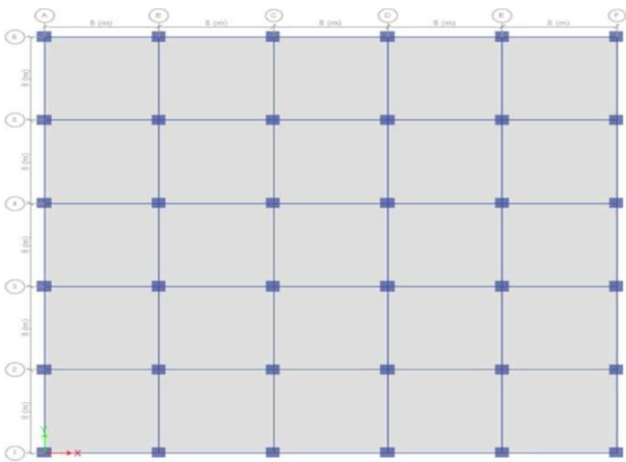

Figure 3.2: Plan view of framing

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After modelling, next we need to assign joint restraint to the support at the base as fixed. Next step is loading, before that we need to define all load cases in defining section.

Gravity loads and lateral loading definition

Table 3.2.1: loading pattern for the framing system

Load Types	Reference Standards
Self-weight	As per IS 875 (1987), Part 1 – Permanent Loads
Imposed load	Adjusted live load as per IS 875 (1987), Part 2
Lateral load (X)	Earthquake effect as per IS 1893 (2016) in X-axis
Lateral load (Y)	Earthquake effect as per IS 1893 (2016) in Y-axis
Wind action (X)	As per IS 875 (2015), Part 3 – Wind loading in X
Wind action (Y)	As per IS 875 (2015), Part 3 – Wind loading in Y

LOAD CALCULATIONS

Beam load calculation:

(density of light weight brick) X (height of floor) X (thickness of wall)

=10X(3.0-0.9)X0.2

=4.7KN/m

Slab load calculation:

Floor finisher: density of bedding material) X (thickness of filling) + (density of flooring tile) X (thickness of the flooring)

= (20X0.05) + (26.7 X 0.025)

=1.7 KN/m^2

LIVELOAD

As per IS875:1987 PART 2 for commercial buildings rooms without separate storage= 4KN/m^2.

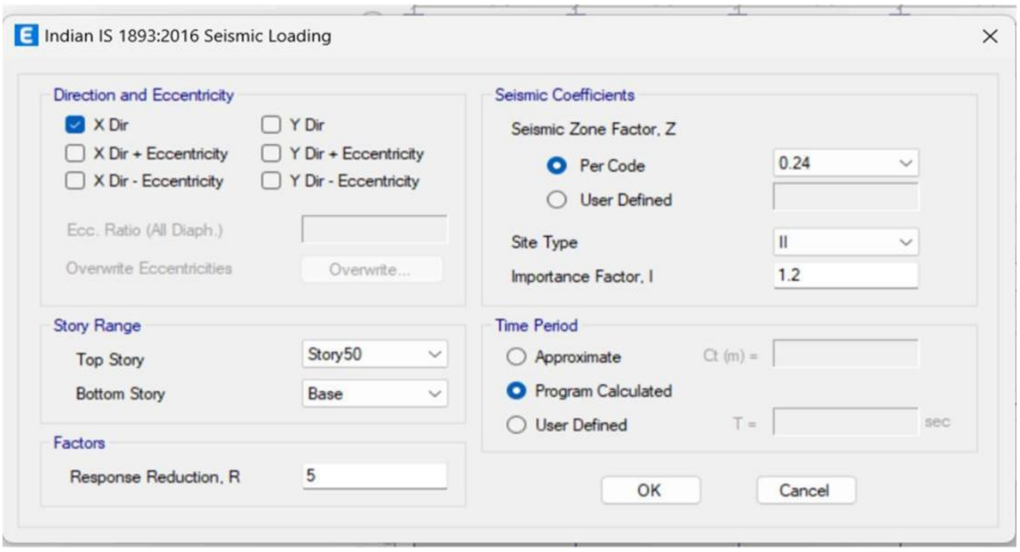

Figure 3.2.2: earthquake loading definition

After changing the required data software, it self-calculates time period value as per IS 1893:2016.

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ASSIGNING LOADS:

In CSI ETABS self-weight of the member is calculated by default no need to calculate separately. Beams are to be selected separately and assign the load as per calculation in gravity direction as distributed load. After the assigning of beam load floors are to be selected and dead weight and live load has to be assigned as distributed load.

WIND LOAD

There are four (4) methods for calculation of wind load.

- Pressure coefficient method.
- Force coefficient method.
- Gust factor method.
- Wind tunnel analysis method.

Here I have fallowed pressure coefficient method for calculating wind force.

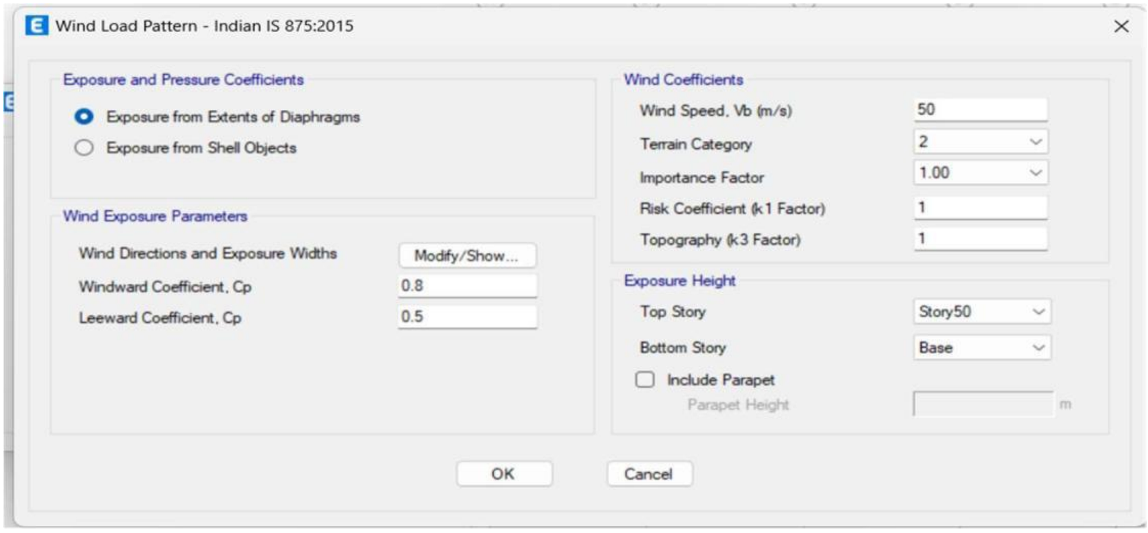

Figure 3.2.2.1: Wind load definition

Change direction angle to 0 degree because it is in windward direction, after that in leeward direction change direction value to 90 degrees.

MASS SOURCE

In structural engineering software like ETABS, mass sources are used to define additional masses for dynamic analysis that are not part of the structural elements. These can include concentrated or distributed masses such as equipment and partitions, contributing to the building's overall mass. By accurately modelling these non- structural components, engineers can better predict the structure's response to dynamic forces like seismic or wind loads. This allows for a comprehensive analysis of the building's behaviour under various conditions, ensuring it meets safety and performance standards. In ETABS, mass sources are specified by defining the mass value, location, and direction, integrating them into the finite element model for precise dynamic analysis.

After mass source we need to define type of dynamic analysis which we are going to performed.

I have chosen "Response spectrum analysis" method for my analysis.

RESPONSE SPECTRUM ANALYSIS

Response spectrum analysis is a method used in structural engineering to evaluate the seismic response of a structure. It involves the conversion of ground motion data into a graphical representation known as the response spectrum, which illustrates

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how a structure will react to seismic forces at different frequencies. Unlike time history analysis, response spectrum analysis simplifies complex seismic inputs into a single curve, making it a powerful tool for seismic design and evaluation.

By comparing the structure's response spectrum with predefined design spectra, engineers can assess its performance and make necessary adjustments to ensure structural safety against seismic events. This analysis is crucial for designing earthquake-resistant structures, especially in regions prone to seismic activity.

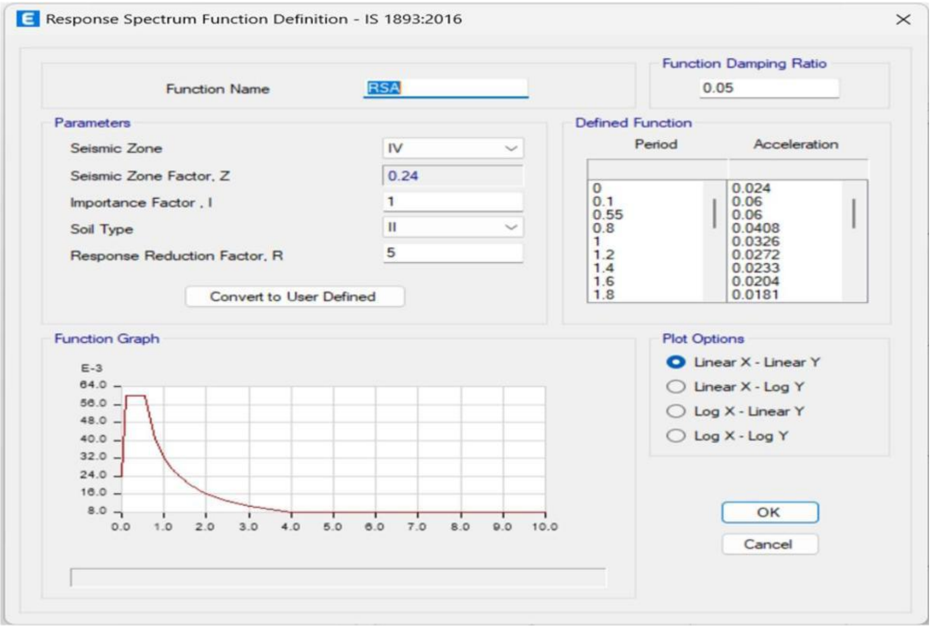

Figure 3.2.3: Response spectrum definition

MODEL ANALYSIS

After defying response spectrum analysis go for modifying the modal analysis. Model analysis studies the deformed shape of the structure within 60 seconds. This free vibration response is a sum of simple harmonic motions where the shape of each harmonic motion is called mode shapes. Model analysis gives InSite of the structure in respect of the frequencies under deflection and from there we get torsional irregularity of the proposed structure.

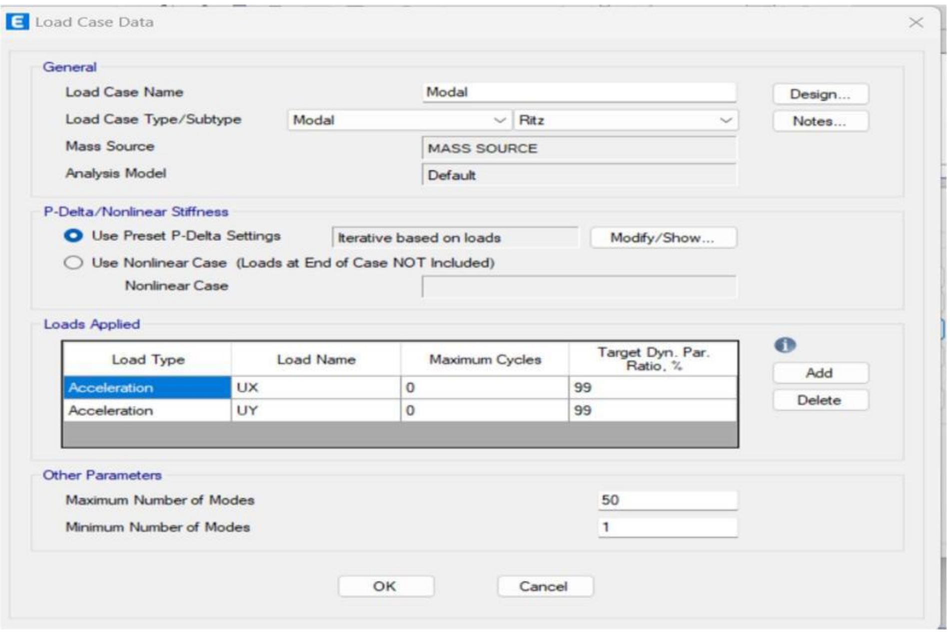

Figure 3.2.4: Model analysis definition

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IV. ANALYSIS RESULT

CASE A:

The analysis of all the cases considered are carried for both response spectrum and equivalent static method of analysis and the results obtained are for the parameters like storey displacement, storey drifts and overturning moment and check for the torsional irregularity. Storey displacement: Storey displacement in high-rise buildings under lateral loading (wind pressure and seismic activity), lateral forces act upon the building, individual storeys experience horizontal movement, with lower storeys generally exhibiting less displacement compared to upper levels. Advanced computational tools aid in simulating and predicting storey displacements, ensuring compliance with building codes and standards that prescribe maximum allowable drift ratios or deflection limits. Ultimately, managing storey displacement is essential for maintaining structural integrity, occupant comfort, and safety in high rise building buildings subjected to lateral loading. Maximum is 1019 mm at top story (50th floor) under the response spectrum analysis in the global-X direction.

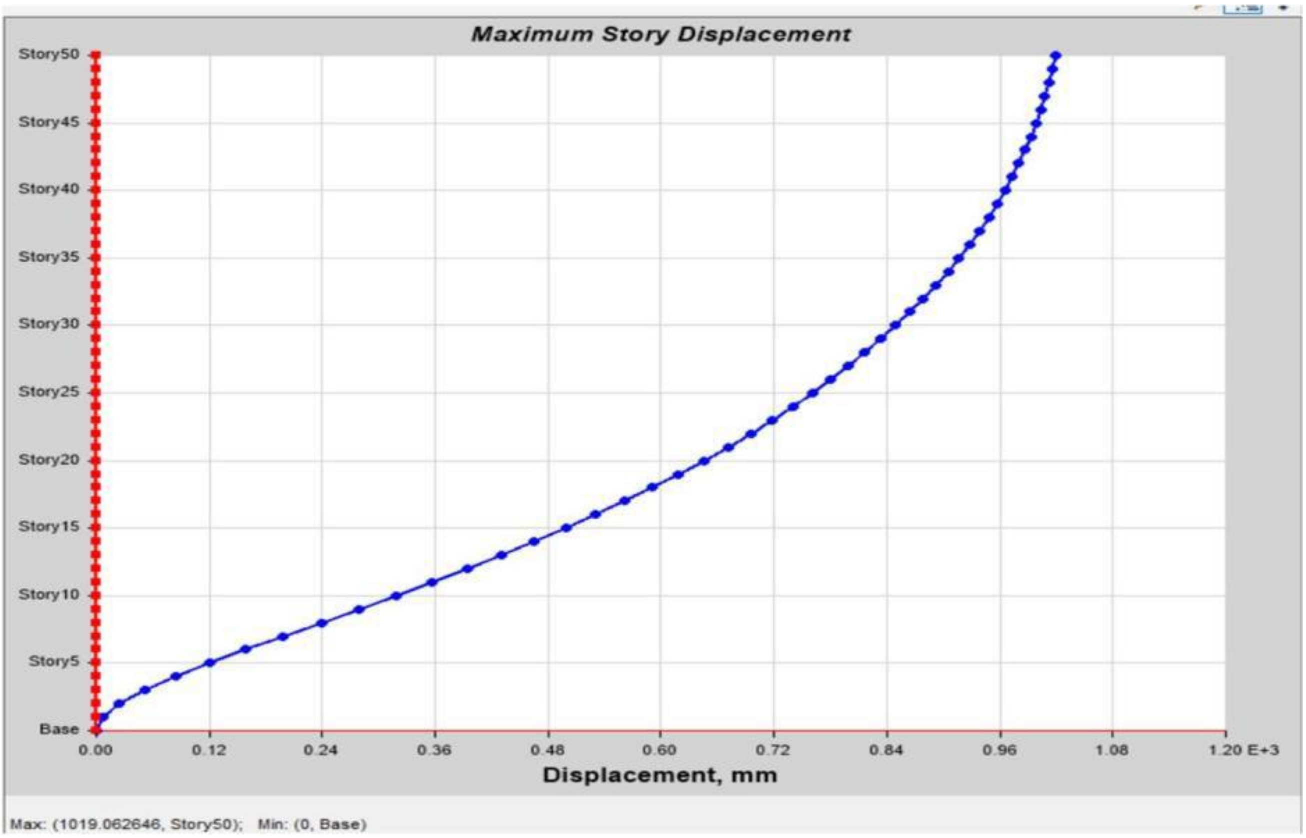

Figure 4.1.1: Maximum storey displacement of CASE A

Storey drift: Storey drift in high-rise buildings under lateral loading refers to the relative displacement between adjacent storeys due to horizontal forces such as wind or seismic activity. As these forces act upon the structure, each storey undergoes horizontal movement, resulting in differential displacements along the building height. Typically, lower storeys experience lesser drift compared to upper levels due to their proximity to the building's foundation. The phenomenon of storey drift is a critical consideration in structural design to ensure that displacements remain within acceptable limits to maintain occupant comfort, structural stability, and safety. Engineers employ various techniques such as selecting appropriate structural systems, optimizing building materials, and incorporating damping devices or bracing systems to mitigate excessive drift. Maximum storey drift is 0.013465 between the storey 5 and 10, exactly at storey 8.

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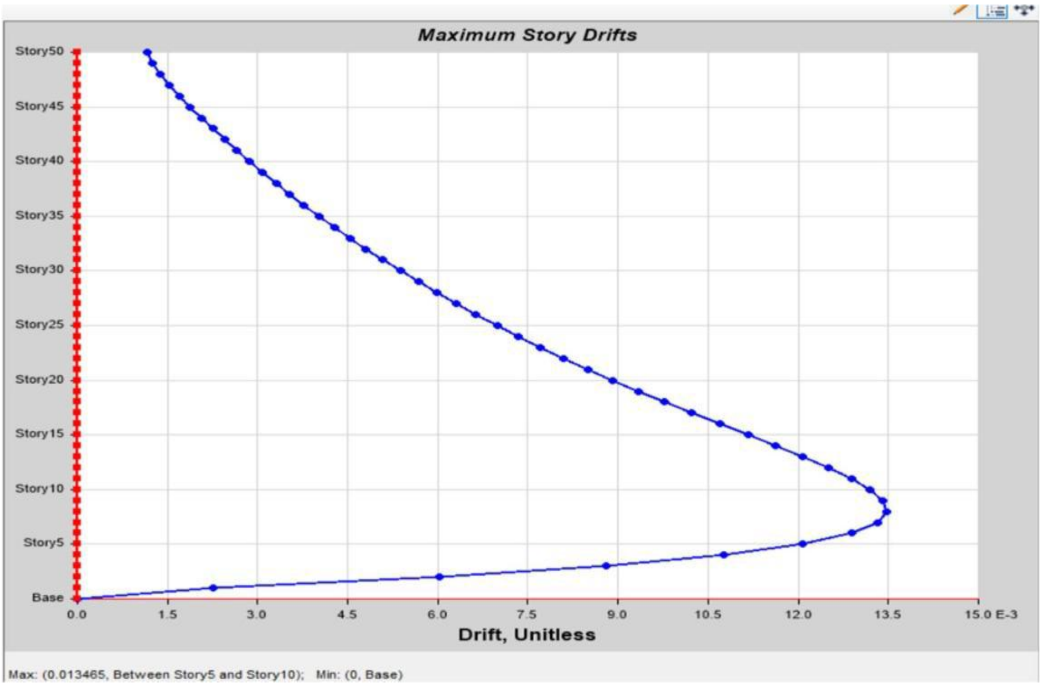

Figure 4.1.2: Maximum storey drifts of CASE A

Story stiffness: Story stiffness It is the proportion of storey force to storey drift and is only applicable to shear buildings, or structures with infinitely stiff floor beams. In these situations, a building's lateral stiffness matrix adopts a tridiagonal shape. On the other hand, the stiffness matrix is fully populated in buildings with finite beam stiffness. Storey stiffness is almost non-existent in this situation, yet it is necessary to determine its approximate value for early seismic design. Consequently, it is necessary to redefine the storey stiffness, which was also necessary for the building's seismic design. The stiffness of a building is like the rigidity of a spine, determining its ability to resist external forces and maintain its structural integrity, core and framework engineered to withstand wind, earthquakes, and other stresses. This stiffness is achieved through a careful balance of analysis and required structural system techniques, ensuring that the building can sway and flex within safe limits without compromising its stability.

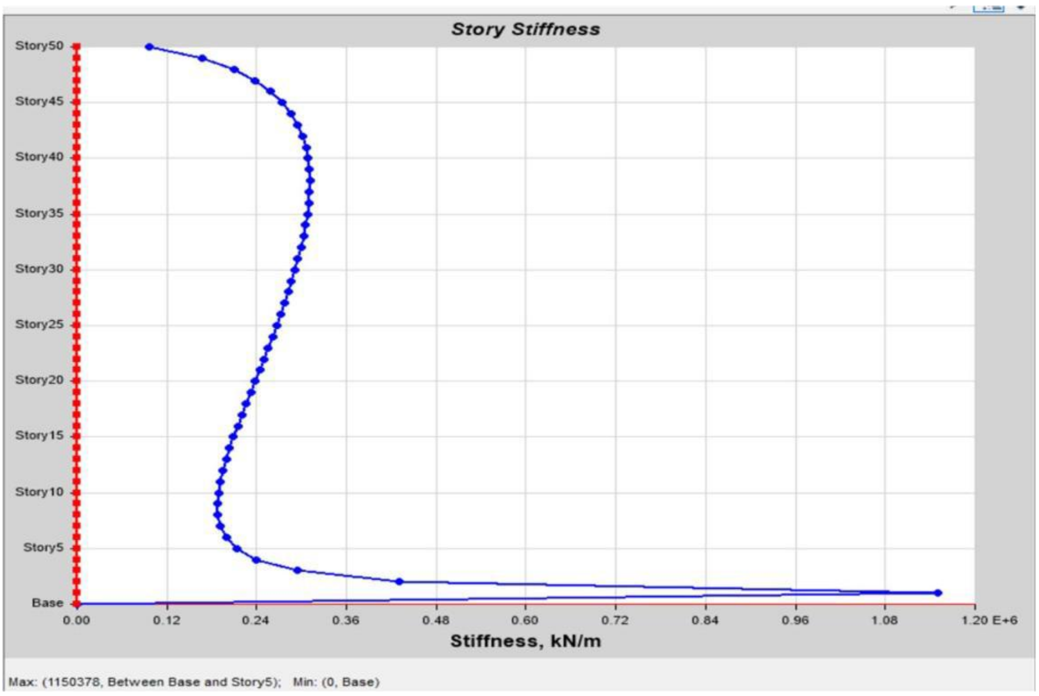

Figure 4.1.3: Storey Stiffness of Case A

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Torsional irregularity: Torsional irregularity in high-rise buildings under lateral loading refers to the uneven distribution of stiffness or mass along different axes of the structure, leading to torsional or twisting effects. This irregularity can arise due to asymmetrical floor layouts, setbacks in the building's profile, or variations in structural elements such as columns and walls. When subjected to lateral forces like wind or seismic activity, torsional irregularities can cause the building to rotate or twist about its vertical axis, potentially leading to structural instability and increased drift. Structural engineers carefully analyse and mitigate torsional irregularities during the design phase by implementing strategies such as redistributing mass or stiffness, incorporating torsional bracing systems, or optimizing the building's geometry. Advanced computational techniques enable engineers to simulate and assess the torsional behaviour of high-rise structures, ensuring compliance with regulatory requirements and enhancing overall structural performance and safety under lateral loading conditions.

Table 4.1: Mass participation ratio with modes in Case A

Mode	Time Period (sec)	X1	Y1	Z1	X2	Y2	Z2	X3	Y3
1	20.093	0.2649	0.5506	0	0.2649	0.5506	0	0.1078	0.0519
2	20.091	0.5506	0.2649	0	0.8155	0.8155	0	0.0519	0.1078
3	14.048	0	0	0	0.8155	0.8155	0	0	0.8174
4	5.605	0.0251	0.0515	0	0.8407	0.867	0	0.3529	0.1723
5	5.604	0.0515	0.0251	0	0.8407	0.867	0	0.1723	0.3529
6	4.193	0	0	0	0.8921	0.8921	0	0	0.0745
7	3.088	0.0094	0.0178	0	0.9015	0.9099	0	0.0171	0.009
8	3.088	0.0178	0.0094	0	0.9015	0.9099	0	0.009	0.0171
9	2.406	0	0	0	0.9193	0.9193	0	0	0.0285
10	2.075	0.0055	0.0103	0	0.9206	0.9206	0	0.0369	0.0198
11	2.075	0.0103	0.0055	0	0.9351	0.9351	0	0.0198	0.0369
12	1.64	0	0	0	0.9351	0.9351	0	0	0.016
13	1.511	0.0037	0.0068	0	0.9388	0.9419	0	0.0114	0.0062
14	1.511	0.0068	0.0037	0	0.9388	0.9419	0	0.0062	0.0114
15	1.209	0	0	0	0.9456	0.9456	0	0	0.0107
16	1.157	0.0027	0.0051	0	0.9484	0.9507	0	0.0157	0.0084
17	1.157	0.0051	0.0027	0	0.9484	0.9507	0	0.0084	0.0157
18	0.915	0.0027	0.0049	0	0.9555	0.9577	0	0.0041	0.0075
19	0.915	0.0049	0.0027	0	0.9555	0.9577	0	0.0075	0.0041
20	0.743	0.0011	0.0038	0	0.9606	0.9633	0	0.0105	0.0023

V. CONCLUSION

Outrigger systems are a very effective structural solution in high-rise construction that increases the lateral stiffness and redistributes moment demands from the core to the outer columns. Though widely used, there is a lack of study on their seismic performance and the present Indian and US building standards do not provide any explicit guidelines for multi-objective design techniques. This work simplifies the outriggers model by classifying them as reinforced concrete beams and belt trusses as traditional RCC members. The analysis of four architectural configurations shows the considerable enhancement of the resistance of lateral loads by the use of outriggers and the response spectrum analysis shows a significant reduction in the tale’s displacement and drift without the addition of other dampening techniques. The study establishes that outrigger systems may be optimised for different levels of seismic danger and can maintain the structural integrity by greatly minimising the lateral deformations for different load cases and guaranteeing compliance with Indian code standards. The proposed modelling approach aids the design process without compromising accuracy. Results show that the structures with outriggers perform better with reduced inter-story drift and more stability under dynamic loading. This study emphasises the efficiency of outrigger systems to achieve multi-level performance objectives with uniform and trustworthy earthquake response at diverse hazard levels, without requiring sophisticated modifications. The simplified RCC-based modelling methodology will ensure the tool’s accessibility to the engineers and will promote its extensive adoption in the Indian building industry. The key findings

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indicate that the outriggers inherently improve the lateral stiffness and reduce the need for additional energy dissipating devices. The solutions show strong collapse prevention ability in accordance with the life-safety objectives of the Indian seismic code, making outriggers a cheap and code compliant choice for tall buildings in seismic regions. This study gives useful information to engineers involved in the construction of high-rise buildings in India. This study gives the design framework that addresses the weaknesses in prescriptive standards, and thus, allows engineers to safely use outrigger systems to boost structural resilience and performance.

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