Performance Assessment of Outrigger System for High Rise Slender Structures

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Abstract. High-rise slender structures have become increasingly prevalent in modern urban landscapes due to the demand for efficient land use and sustainable development. However, these tall and slender buildings are susceptible to various structural challenges, including wind-induced vibrations and lateral deformations. To mitigate these issues and ensure the safety and comfort of occupants, outrigger systems have emerged as a popular structural solution. Through a thorough examination of their structural performance, the outrigger systems used in high-rise, slender structures are examined in this study to determine how they behave and how successful they are. In this way, the design base shear for the entire structure is calculated and distributed over its height. Response spectrum analysis employs eigen value analysis to identify natural frequencies and mode shapes. While time history analysis is a method for figuring out the precise reaction of a structure as a function of time, it is used to compute the peak response. The equation of motion is typically numerically integrated step by step to calculate the response history. This paper explores the impact of earthquakes on outrigger systems in high-rise slender structures. Outrigger systems, which typically consist of horizontal beams connecting the core and the perimeter of the building, play a crucial role in mitigating the effects of seismic activity. These systems provide stiffness and strength to the structure, limiting lateral sway and reducing damage during an earthquake. This paper innovative technologies and construction techniques that enhance the earthquake resilience of outrigger systems. This includes the use of advanced materials, base isolators, and dampers to improve the performance of high-rise slender structures during seismic events.

Keywords. Outrigger Systems, High-Rise Buildings, Slender Structures, Structural Behavior, Lateral Stability, Wind-Induced Vibrations, Structural Analysis.

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1 Introduction

In the ever-evolving realm of urban architecture and construction, the pursuit of taller and more slender high-rise structures has become a defining characteristic of contemporary cityscapes worldwide. These iconic skyscrapers are emblematic of modern innovation, boasting breathtaking aesthetics and remarkable feats of engineering. However, their towering heights and slender profiles introduce a unique set of structural challenges that necessitate innovative solutions to ensure the safety, stability, and comfort of both occupants and the surrounding environment [1].

The idea of an outrigger was first applied to canoe-style boats. The principle is understood in terms of the feedback mechanism, and the outriggers were used to reinforce and avoid boat overturn [2]. The feedback process is effective, i.e., when the boat's stability is increased, it gives unfavourable feedback because it is a different component of the boat. Boats are shown in Figure. 1 coupled with outriggers.

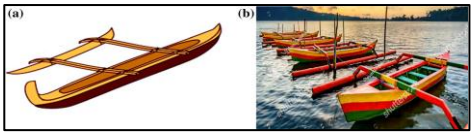

Fig. 1. Canoe with Single & Double Outrigger

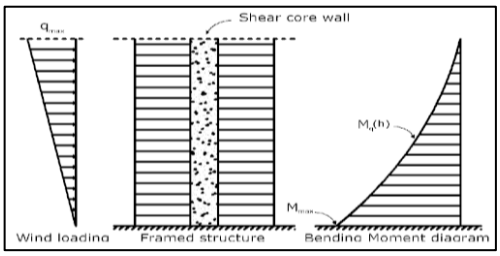

Fig. 2: The reduction in bending moments because of outriggers

When a high-rise building is narrow, especially one with shear walls, it is more susceptible to strong overturning moments caused by wind or earthquakes. This behaviour is depicted in Figure 1, which shows a person standing on one leg without any support. Figure 2 illustrates the forces that a shear wall resists and how the shear wall responds to these extremely strong forces [3].

One of the most prominent structural innovations employed in high-rise slender structures is the outrigger system. These systems, designed to redistribute lateral forces and control deformations, play a pivotal role in enhancing the structural performance of these tall and often architecturally ambitious buildings. Understanding the behavior and effectiveness of outrigger systems in the context of high-rise slender structures is not only a matter of engineering curiosity but is essential for the continued advancement of urban development. This paper delves into the multifaceted domain of outrigger systems, focusing on their behavior and effectiveness in the context of high-rise slender structures. By examining the intricate interplay of architectural design, engineering principles, and material science, we aim to unravel the key factors that influence the performance of outrigger systems in such complex environments.

Moreover, this research extends its reach beyond the confines of academic inquiry by examining the practical implications of outrigger systems through a thorough review of global case studies. These case studies span a range of geographical locations, architectural designs, and structural challenges, allowing us to glean insights into the versatility and adaptability of outrigger systems in different contexts. In essence, this paper strives to contribute to the ever-evolving body of knowledge in structural engineering, with the ultimate goal of offering valuable guidance to architects, engineers, and developers who are tasked with the design and construction of high-rise slender structures. By doing so, we aim

to foster safer, more sustainable, and aesthetically captivating urban landscapes that embrace the limitless possibilities of high-rise architecture.

In this research EATAP (Earthquake Analysis Tool for Outrigger Systems) software is used for anlayis of parameters which is a powerful and specialized tool designed to analyze and assess the performance of outrigger systems in high-rise slender structures under seismic loads. This software is instrumental in the field of structural engineering, offering engineers and designers the capability to simulate and evaluate the dynamic behavior of outrigger systems during earthquakes. It employs advanced numerical methods and algorithms to calculate critical factors such as lateral displacements, inter-story drifts, and stresses within the outrigger components. Additionally, EATAP enables engineers to explore different outrigger configurations and assess their effectiveness in enhancing the structural stability and seismic performance of high-rise slender buildings.

Han-so Kim et al [4] studied two-purpose outriggers in high structures to minimize lateral displacement (LAT) and alternate axial shortening (DAS). Outrigger systems have been shown to be effective in reducing side migration to high-rise buildings and air and earthquakes. The exact position of the outriggers affects the performance of the building control. Rehineh Tavakoli et al. [5] investigated the impact of explosions on buildings to determine the best location for belt truss systems in high-rise buildings. The authors report that if there is an explosive cost within 5 meters of a building, the post-buckling effect of truss elements is greater than that of the cost of exploding ions within 1 meter. Wind-induced vibrations are a significant concern in tall and slender buildings. Lin and Cai [6] conducted wind tunnel experiments and numerical simulations to evaluate the effectiveness of outriggers in mitigating wind-induced vibrations. Their work demonstrated that well-designed outriggers can substantially reduce wind-induced accelerations and sway. Ibrahim Mousleh [7] studied this model using a 35-story two-story building, this studied this model using a dual plan of a 35-story building, a reinforced concrete wall and a solid metal frame using the 3D and line extension. vertical analysis. The authors suggest that the model of the study of the impact of earthquakes instead of wind effect controls the structure of the structure. Viren P. Ganatra et al. [8] Weakness of a 50-storey building to an earthquake and wind load is discussed by changing its depth with the help of exits. Comparisons of the structure with the cut walls were also made. The storytelling and the flow of the story are greatly reduced as there are motives for the height of the whole story. The integration of outrigger systems with architectural design is crucial for achieving both structural and aesthetic goals. Stochetti et al. [9] discussed the architectural possibilities and constraints associated with outriggers, emphasizing the need for collaboration between architects and engineers to optimize design outcomes. Analytical and computational models play a critical role in understanding outrigger systems. Wang and Li [10] utilized finite element analysis to study the dynamic response of a high-rise building with an outrigger system subjected to seismic loading. Their findings underscored the effectiveness of outriggers in reducing lateral displacements and enhancing structural resilience. The organization of the paper is as follows. In Section 2, building analysis are elaborated. The load analysis is described in Section 3 and methodology is elaborate in section 4. Firefly optimization algorithm (FFA) is also explained. Here, the result analysis is done in in Section 5. Finally, Section 6 provides the concluding remarks.

2 Building Analysis

In this paper, a 100-storey building 3 m high and below is analysed by the Finite Element Method ETABS v19 software. The selected plan is rectangular. 3D analysis is done because the building system behaves like a straight cantilever when under a plane bend. The structure is analysed for both wind power and earthquakes [11]. The building is

studied by the outriggers provided during the height of the building at different levels to determine the migration and erosion of the floor. The efficiency of the outrigger is calculated based on the percentage reduction in lateral removal. Equal dry load is assessed in accordance with IS 1893 (2016) in Zone 4 with a solid soil structure.

Methods Used for Building Analysis:

- Response Spectrum Analysis
- Air Cargo Analysis

2.1 Spectrum Response Analysis:

A dynamic mathematical analytical technique called response-spectrum analysis (RSA) examines the contribution from each natural vibration mode to reveal the amplitude of an earthquake reaction that might be a significant limiting structure. By measuring pseudo-spectral acceleration, speed, or displacement as a structural activity of a specific period of time history and level of wetness, response-spectrum analysis offers insight into dynamic behavior[12]. The smooth curve indicates the highest possible response to each building phase thanks to the way the envelope response operates.

Response scope analysis is helpful in designing decisions because it is related to the choice of type of structure and flexibility. Short-term structures receive greater acceleration, while long-term ones receive greater migration. The functional objectives of the structure should be considered during the initial design and analysis of the reaction spectrum.

2.2 Air Upload Analysis

Buildings are under horizontal loads due to the pressure of the air working on the buildings. Air load is calculated in accordance with IS 875 (Part III) -2015. Horizontal air presses operate on vertical exterior walls and exposed surface of buildings. Another pressure applied to exposed areas of walls and columns of a building directly counteracts the bending of these elements [13]. The filling walls act as a vertical plate supported by the upper and lower planks, thus transferring loads to the slab level. The parapet wall on the shelf transmits air loads instead of the slab by the action of a cantilever. For simplicity, the air load operating in the open space of a given floor is well done to support the floor up and down.

3 Load Analysis

The three types of loads that affect RCC buildings are as follows:

1) Gravitational loads (Dead load and Live load).

2) Earthquake-related lateral loads.

3. Lateral load brought on by wind.

3.1 Additional categories for gravity loads include:

1. According to IS 875 Part I, a structure's self-weight is a constant permanent load that acts vertically downward on the structure.
2. Weight of the slab: The structure's slabs range in thickness from 125 mm to 200 mm..
3. Wall shear weight: For the structure, the wall thickness ranges from 300 to 550 millimetres.

4. Wight of beam: - The structure's beams are 300 mm x 500 mm and 300 mm x 550 mm in size, with an ISLB 600 rating..
5. Weight of column: - The column that runs throughout the entire construction has various cross sectional sizes..
6. Live load: - The live load consists of a person's self-weight, which varies greatly depending on the use of the space but is considered for analysis to be 3 kN/m sq. and evenly distributed on a slab.

3.2 Lateral load due to earthquake as per IS 1893 (Part I) 2016:

1. Factor of zone: - In the current study, seismic zone IV behaviour of the model is examined in accordance with IS 1893 (Part I):2016. From Table-2, clause no. 6.4.2 of IS 1893 (Part I):2016, the zone factor value is assumed as Z=0.24.
2. Need of Structure: - The suggested model is based on the assumption that the structure is a generic building, and the important factor for the structure is taken as I=1.5 from Table 6, clause no. 6.4.2 of IS 1893(Part I):2016..
3. Type of soil: The type of soil that is taken into account when calculating seismic load makes it necessary to understand. The fundamental natural time period (Ta) is dependent on the kind of soil, as stated in clause no. 6.4.2 of IS 1893(Part I):2016, and the average response spectrum coefficient (Sa/g), as stated in clause no. 7.6.1 of IS 1893(Part I):2016..
4. Structure type: - The structure is taken to be a particular RC moment-resisting frame, hence clause 7.2 of IS 1893(Part I):2016 takes the response reduction factor value to be R.
5. Weight of seismic: - According to clause 7.3.1 of IS 1893(Part I):2016 and the complete dead load plus the proportion of live load, the earthquake force must be determined.
6. **D**efinition of mass source:- According to clause no. 7.3.1 and IS 1893(Part I):2016, "(Gravity loads with a factor of 100% + Live load with a factor of 50%)".[14]

3.3 Lateral Load due to wind as per IS Codes: 875 (part III)-2015:

1. Basic wind speed: 39 m/sec
2. Terrain category: III
3. Risk factor, Topography factor and Cyclonic factor: K1=K3=K4=1
4. Height Factor: K2

3.4 Load combinations: -In the limit state design of reinforced concrete structure, load combination is taken as per clause no. 6.3.1.2 of IS 1893(Part I):2016.

1.5 (DL+LL)
1.2 (DL+LL +SPECX)
1.2 (DL+ LL –SPECX)
1.2 (DL+ LL +SPECY)
1.2 (DL+ LL –SPECY)
1.5 (DL+SPECX)
1.5 (DL–SPECX)
1.5 (DL+SPECY)
1.2 (DL+LL +WX)
1.2 (DL+LL -WX)
1.2 (DL+LL +WY)
1.2 (DL+LL -WY)
1.5(DL+WX)
1.5(DL-WX)
1.5(DL+WY)
1.5(DL-WY)

1.5 (DL–SPECY)
0.9 DL+1.5SPECX
0.9 DL–1.5SPECX
0.9 DL+1.5SPECY
0.9 DL–1.5SPECY
0.9 DL+1.5WX
0.9 DL–1.5WX
0.9 DL+1.5WY
0.9 DL–1.5WY

SPECX / SPECY - Earthquake in X- direction and Y- direction
WX / WY - Wind in X- direction and Y- direction respectively

4. Methodology

In this research work, geometrical details, grade of the materials, gravity loads on structure, data for analysis and location of outriggers applied for make different shape of building.

4.1 Data for geometrical analysis:

Structure type: Commercial, Floor Dimensions: $36m \times 35m$, Height of the Structure: 310 m, Floor to Floor height: 3m, Storeys: 100, Thickness of slabs: SGEN =125mm, SPARK=175mm, SSTAIRS=200mm, SWC=200mm, SOR=300mm., Beams Dimension: 300mm x 500mm, 300 x 550mm, ISLB600. , Columns Dimension: 300mm x 800mm, 600mm x 1000mm, 700mm x 1000mm, 800mm x 12000mm.

Core walls thickness: 300mm, 400mm, 500mm., Dimension of Concrete Outrigger: 550mm.

4.2 Grade of the Materials

Grade of Concrete for Beams: M50 , Grade of Concrete for Slabs: M50, Grade of Concrete for Columns: M50, Grade of Concrete for Wall: M50, Grade of Rebar: 415N/mm2 , Grade of Structural Steel: 500 N/mm2 ,Density of Concrete: 25kN/m3

4.3 Weights on the structure

Live load on floor/terrace: 3kN/m2 / 1.5kN/ m2, Lift Machine load: 15kN/m2

Data for analysis: Seismic Zone: 1V, Seismic zone factor: 0.24, Importance factor: I = 1.5 , R = 5, the response reduction factor Hard-I soil type, III terrain classification 39 m/sec (for all zones) wind speed NRLL of the lift machine with load factor 1 and 1DL+0.5LL (excluding terrace live load) IS Codes: 1893 (part I)-2016; 875 (parts I, II, and III)-2015.

4.4 Location of Outriggers

The positions of various Outriggers for all the models are as follows:

1 Outrigger = Single OT - Mid = at 50th storey

2 Outriggers = Double OT – Mid & Top = at 50th and 100th storey

Outriggers = Three OT = at 25th – 50th – 75th storey

Outriggers = Four OT = at 20th – 40th – 60th – 80th storey

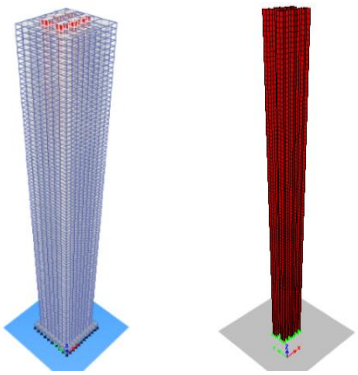

Fig. 3. 6. Bare Frame with Central Core

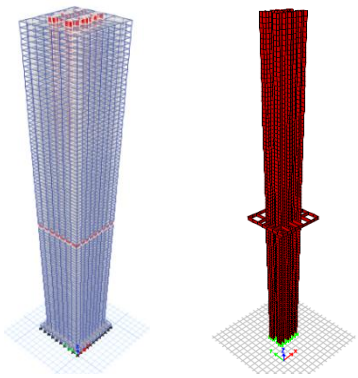

Fig. 4. Frame with Single Outrigger at 50th Storey

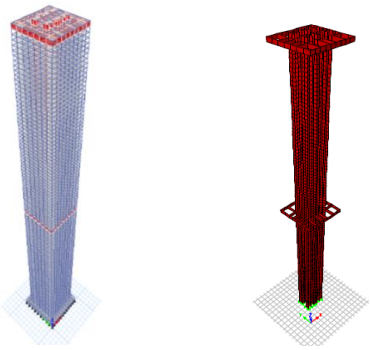

Fig. 5. Frame with Double Outrigger at 50th and 100th storey

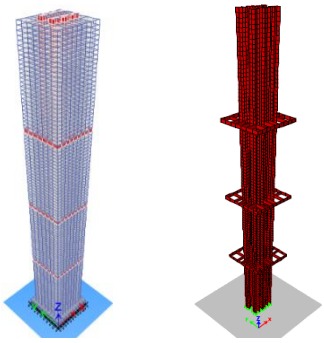

Fig. 6. Frame with triple Outrigger at 25th, 50th and 75th storey

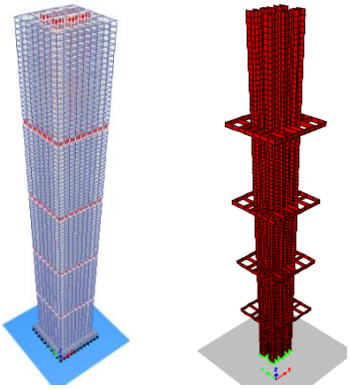

Fig. 7. Frame with Four Outrigger at 20th, 40th, 60th and 80th storey

A multistorey RC bare frame and frame tube buildings with core Figure.3, Figure.4, Figure.5, Figure.6 and Figure.7 shows that bare frame with central core , frame with single outrigger at 50th storey , frame with double outrigger at 50th and 100th storey, frame with

triple outrigger at 25th, 50th and 75th storey frame with four outrigger at 20th, 40th, 60th and 80th storey respectively are considered for computation and analysis work.

4 Results and Discussion

For analysis of load, Response Spectrum Analysis and Wind Analysis of models is carried out by applying uncracked property modifiers as per IS 16700:2017, IS 1893 (Part I): 2016 and IS 875 (part III):2015. The software used for analysis is ETABS V19. The comparison results of all the model are for lateral displacement and storey drift in X and Y direction respectively. The Lateral displacement and Storey drift checks are as:

4.1 Lateral Displacement check as per Indian code for Earthquake and Wind:

- Permissible displacement for earthquake H/250 … As per IS 1893:2016 (Part 1)
- Permissible displacement for wind H/500 ……. As Per IS 16700:2017

The difference between the lateral displacement of the core and core with outrigger system at any time equals the percentage reduction in lateral displacement of the core and with outrigger system. × 100.

4.2 Storey Drift Ratio check as per Indian code for Earthquake and Wind:

- Permissible drift ratio for earthquake 0.004h … As per IS 1893:2016 (Part 1)
- Permissible drift ratio for wind 0.002h ……. As Per IS 16700:2017

The difference between the Storey drift of the core and the core with outrigger divided by the Storey drift of the core alone determines the percentage reduction in the Storey Drift Ratio of the core and with outrigger system at every time. × 100.
Here, H is the height of the structure and h is the storey height in any storey.
In this study, the results of lateral displacement and storey drift ratio in X-direction and Y-direction both are considered.

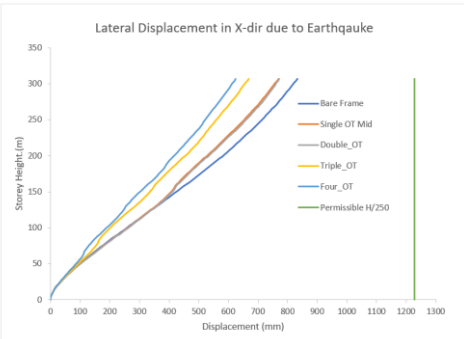

Fig. 8. Displacement due to Earthquake in X- Direction

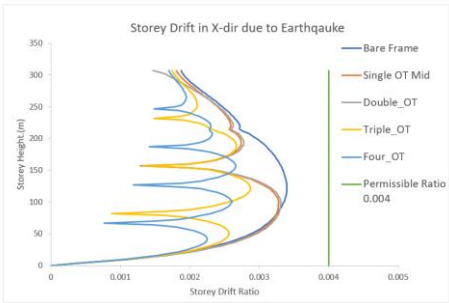

Fig. 9. Storey Drift due to Earthquake in X-Direction

Figure. 8 represent displacement due to earthquake in X direction, similarly Figure. 9 shows storey drift due to earthquake in X- Direction.

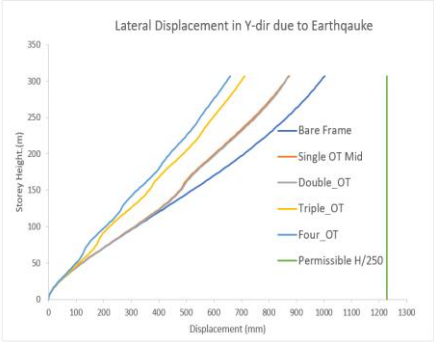

Fig. 10. Displacement due to Earthquake in Y- Direction

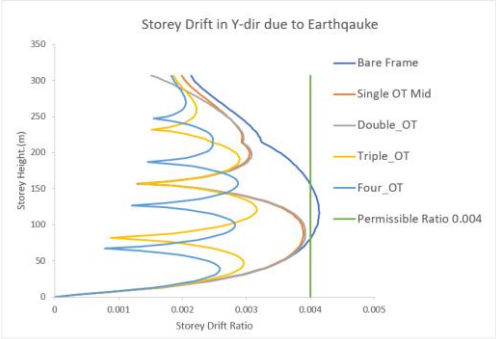

Fig. 11. Storey Drift due to Earthquake in Y-Direction

Figure. 10 represent displacement due to earthquake in Y direction, similarly Figure. 11 shows storey drift due to earthquake in Y- Direction.

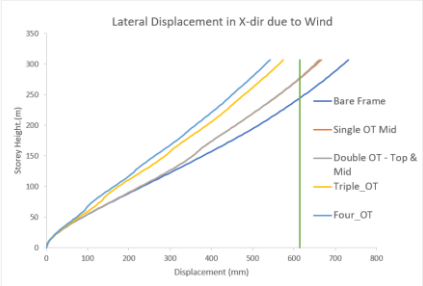

Fig. 12. Displacement due to Wind in X-Direction

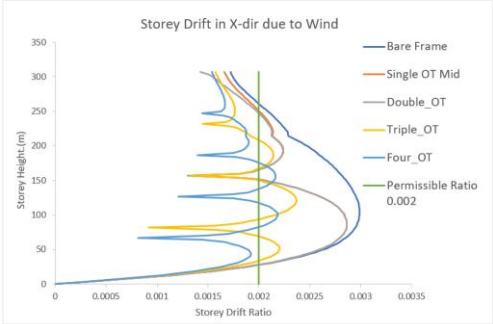

Fig. 13. Storey Drift due to Wind in X-Direction

Figure. 12 represent displacement due to wind in X direction, similarly Figure. 13 shows storey drift due to wind in X- Direction.

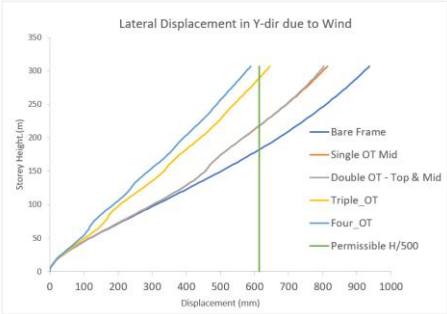

Fig. 14. Displacement due to Wind in Y-Direction

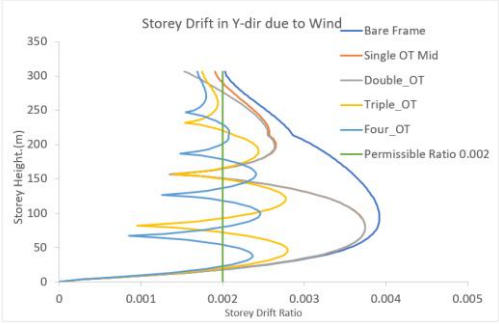

Fig. 15. Storey Drift due to Wind in Y-Direction

Figure. 14 represent displacement due to wind in Y direction, similarly Figure. 15 shows storey drift due to wind in Y- Direction.

Table 1. Displacement due to earthquake

Model Type	Displacement in X- Dir.		Displacement in Y- Dir.	
	Displacement (mm)	Percentage Reduction	Displacement (mm)	Percentage Reduction
Bare	833	--	1002	--
Single OT	769	8	873	13
Double OT	772	7	871	13
Triple OT	668	20	712	29
Four OT	625	25	659	34

Table 2. Displacement due to Wind

Model Type	Displacement in X- Dir.		Displacement in Y- Dir.	
	Displacement (mm)	Percentage Reduction	Displacement (mm)	Percentage Reduction
Bare	732	--	936	--
Single OT	667	9	814	13
Double OT	661	10	803	14
Triple OT	574	22	645	31
Four OT	542	26	589	37

The value of Lateral Displacement is compared in Table 1 and Table 2 for Earthquake and Wind analysis in X and Y direction respectively. It's noted that, maximum lateral displacement for Bare frame for EQ-X is 833 mm and for EQ-Y is 1002 mm which reduces as we increase the number of outriggers and even change the location to get the optimum results. The lateral displacement for structure with Four Outriggers at 20-40-60-80 storeys gives 625 mm and 659 mm in X and Y direction respectively. The percentage reduction is by 25% and 34% which is very significant decrease and with more effectiveness in Y-direction as this direction gives higher value of displacement as building is more flexible in this direction.

It's also noted that, maximum lateral displacement for Bare frame for Wind-X is 732 mm and for Wind-Y is 936 mm which reduces as we increase the number of outriggers and even the location to get the optimum results. The lateral displacement for structure with Four Outriggers at 20-40-60-80 storeys gives 542 mm and 589 mm in X and Y direction respectively. The percentage reduction is by 26% and 37% which is very significant decrease and with more effectiveness in Y-direction as in wind analysis this direction is subjected to more forces as it's more flexible in the same direction hence, gives higher value of displacement i.e. more design forces will be developed which are countered by outriggers. The Lateral displacement graph Fig. 14. shows that, in Y- direction, building with Four Outriggers the displacement is within the permissible limit (H/500) as per IS 16700:2017.

Table 3. Drift Ratio due to earthquake

Model Type	Drift Ratio in X- Dir.		Drift Ratio in Y- Dir.	
	Drift Ratio	Percentage Reduction	Drift Ratio	Percentage Reduction
Bare	0.0034	--	0.0041	--
Single OT	0.0033	3	0.0039	6
Double OT	0.0033	3	0.0039	5
Triple OT	0.0029	15	0.0032	24
Four OT	0.0027	22	0.0029	31

Table 4. Drift Ratio due to Wind

Model Type	Drift Ratio in X- Dir.		Drift Ratio in Y- Dir.	
	Drift Ratio	Percentage Reduction	Drift Ratio	Percentage Reduction
Bare	0.0030	--	0.0039	--
Single OT	0.0029	4	0.0037	4
Double OT	0.0029	4	0.0037	4
Triple OT	0.0024	21	0.0028	29
Four OT	0.0022	27	0.0025	37

The value of Storey Drift Ratio is compared in Table 3 and Table 4 for Earthquake and Wind analysis in X and Y direction respectively. It's found that, maximum storey drift ratio for Bare frame for Wind-Y is 0.0039 which reduces as we increase the number of outriggers and even change the location to get the optimum results. Hence, the storey drift ratio for structure with Four Outriggers at 20-40-60-80 storeys reduces to 0.0025 i.e., by 37% in Y direction which is very significant. The Storey Drift Graph Fig. 30.b. shows that, in Y- direction building with Four Outriggers the drift ratio is within the permissible limit (0.002) as per IS 16700:2017.

Table 5. Time Period for Modal Mass Participation

Percentage Reduction in Time Period		
Model Type	Time Period (sec)	Percentage Reduction
Bare	14.173	--
Single OT	13.99	7
Double OT	13.28	6
Triple OT	11.27	20
Four OT	11.18	21

The Time Period for Bare frame is 14.173 sec. which is reduced to 11.18 sec. for Four Outriggers at 20-40-60-80 storeys i.e., by 21% which is significant.

5 Conclusions

The 100-storey high rise structure is analysed for Response Spectrum Analysis and Wind Analysis methods without and with outrigger at different storey level and also with varying numbers. The following conclusions are made on the basis of results obtained:

1. On observing the analysis results of the 100-storey high rise structure for Lateral Displacement and Storey Drift Ratio shows that, there is a significant decrease in displacement and drift as we increase the number of outriggers to reach the optimum number and improve its effectiveness. Also, changing the location helps to get the location where the displacement and drift ratio results are significantly reduced.
2. The optimum location and effective number of outriggers will help in reducing the lateral design forces induced due to lateral displacement of the structure.
3. The reduction in design forces will reduce the member sizes of the structure and eventually the cost of the structure.
4. The stiffness and strength is increased on using outrigger against the Response Spectrum and Wind analysis, which eventually reduces lateral displacement and storey drift ratio in both directions for the said seismic analysis.
5. The building is observed to be more flexible in Y-direction as compared to X-direction, as more shear wall oriented in X-direction. Also, the orientation of columns is in one direction which is resisting more force in X-direction.
6. The plain structure (bare frame) is observed to be failing in overturning thus, by increasing the dimensions of podium level in X and Y, the building can be prevented from overturning and this provision will also decrease the flexibility of structure.

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