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Optimum location of Virtual outriggers in high rise buildings for seismic and wind responses

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Abstract - *Outriggers have been used in construction of high rises since late 20th century. Outriggers provide lateral stability against wind and seismic loads. Virtual outriggers are a type of outrigger using floor diaphragms instead of deep beams which ensures space optimization. Virtual outriggers are located at suitable storeys (height) to ensure efficient performance. Parameters used for study are lateral displacement due to seismic and wind forces in X and Y direction, storey drift, base reaction, maximum overturning moment and top storey acceleration. Optimum location as determined by analyzing and comparing these parameters when outriggers are located at different heights for models of 50, 60 and 70 storeys. Models are analyzed for one, two and three outrigger systems.*

Key Words: Outrigger, Virtual outrigger, wind load, seismic load, single outrigger system, multi outrigger system, lateral displacement, storey drift, overturning moment, top storey acceleration, base shear.

1. INTRODUCTION

Tall buildings form an integral part of human society and Outriggers have become an ideal structural solution to the problem of lateral instability caused in tall buildings due to winds and seismic forces. Outriggers are rigid and horizontal beams/trusses which connect the central core of the building to external peripheral columns. This improves the building strength and overturning stiffness. In spite of being structurally efficient, outriggers pose a few architectural and economic constraints which can be conveniently overcome by using Virtual outriggers.

2. LITERATURE

A number of researchers in the past have worked on the concept of outriggers and virtual outriggers as well.

R Shankar Nair (1998) in his paper gave a brief on the conventional outrigger system and problems associated with its installation and also outlined the concept of virtual outrigger system. The paper explains the virtual outrigger system with its advantages over the conventional outrigger system. The paper also gives example of Plaza Rakyat Tower in Kuala Lumpur which has two virtual outriggers.

Z. Bayati, et al (2008) worked on optimum number of outrigger systems in a building. The paper presents the results of an investigation on drift reduction in uniform belted structure with rigid outriggers, through the analysis of a model structure of 80 storeys.

S. Fawzia, et al (2011) studied the effects of cyclonic winds on 28, 42 and 47 storey buildings of L – shaped layout. The results showed that the plan dimensions have vital impact on structural heights. Increase in height with same plan dimensions, leads to reduction in lateral rigidity.

Msc. Rafael Shehu (2015) analysed the aspects of building performance designed or retrofitted by the means of conventional or virtual outrigger. The paper highlights ductile characteristics of structures post elastic phase and during seismic events. Structures of 25, 30 and 35 storeys are used to study rigid outrigger, vierendel outrigger and bracing outrigger.

Prajyot A. Kakde and Ravindra Desai (2017) used a 70 storeys building to study lateral stability and sway in case of winds. The building was modelled in ETABs 2016. The paper compares drift caused due to wind and seismic forces on tall buildings without outrigger and multiple outrigger system at located at varied heights.

The papers published conclude to the fact that use of outriggers in high rise buildings increases the stiffness by 20-30%. Optimum location of single outrigger system is at approximately mid height of the building. Also, virtual outriggers are equally structurally efficient as conventional outriggers.

3. VIRTUAL OUTRIGGER

In virtual outriggers, there is no direct connection between core and peripheral columns. The load is transferred to peripheral columns via floor diaphragms which are stiffer than usual slabs.

Virtual outriggers have a similar function to that of a conventional outrigger but the method employed varies. The working of virtual outriggers can be explained with the following two concepts.

3.1 Belt trusses as Virtual Outriggers

The overturning moment in the core is converted into a vertical couple at the exterior columns. Rotation of the core is resisted by the floor diaphragms at the top and bottom of the belt trusses; thus, part of the moment in the core is converted into a horizontal couple in the floors. The horizontal couple, transferred through the two floors to the truss chords, is converted by the truss into vertical forces at exterior columns.

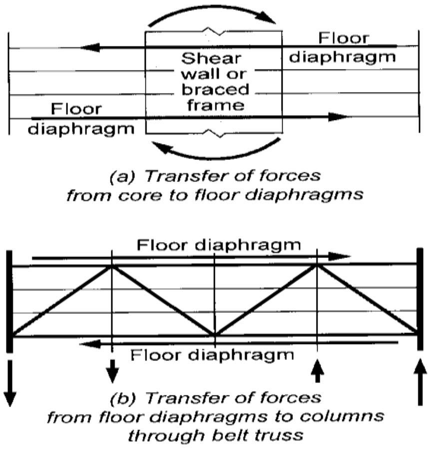

Fig -1: Working of belt truss as Virtual Outrigger

3.2 Basements as Virtual Outriggers

The principle is same as when belt trusses are used as virtual outriggers. Some fraction of the moment in the core is converted into a horizontal couple in the floors at the top and the bottom of the basement. This horizontal couple is transmitted through the floor diaphragms to the side walls of the basement, which convert the horizontal couple into a vertical couple at the ends.

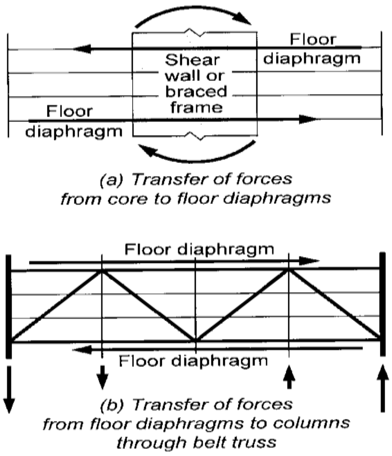

Fig -2: Working of basements as Virtual Outrigger

The concept of virtual outriggers presents a reasonably unique solution to the problems posed by conventional outrigger system.

4. MODEL

Models of a structure of 50, 60 and 70 storeys are made in ETABS software. The plan is triangular in shape with each side measuring 36 m. The shape is chosen to take into consideration the critical loads at the edges. The plan with location of columns at the bottom storey is shown in the figure below.

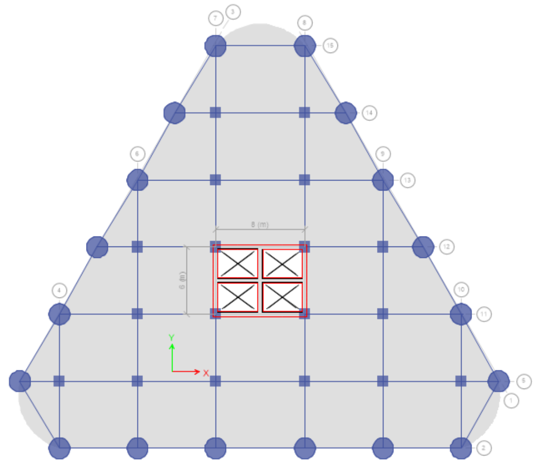

Fig -3: Model plan used for analysis

The building is assumed to be a commercial building located in Mumbai, India, with floor to floor height of 4 m.

4.1 Structural configuration

The structural configuration of the structure is as follows:

Type of Structure	Special R.C. Moment resisting frame				
Number for storeys	50, 60, 70				
Slab Thickness	150 mm				
Slab thickness at Virtual outrigger level	200 mm				
Frame elements	Storey range	Exterior peripheral column (Cp)	Interior columns (Ci)	Perimeter Beam Size (Bp)	Interior Beam Size (Bi)
	(All dimensions are in m)				
	61 – 70	0.8 m φ	0.8 x 0.8	0.6 x 0.7	0.45 x 0.5
	51 – 60	0.8 m φ	0.8 x 0.8	0.6 x 0.7	0.55 x 0.6
	41 – 50	1.0 m φ	0.8 x 0.8	0.6 x 0.7	0.65 x 0.7
	31 – 40	1.2 m φ	0.9 x 0.9	0.7 x 0.8	0.75 x 0.8
	21 – 30	1.4 m φ	0.9 x 0.9	0.7 x 0.8	0.75 x 0.8
	11 – 20	1.6 m φ	1.0 x 1.0	0.8 x 0.9	0.75 x 0.8
	Base – 10	1.9 m φ	1.0 x 1.0	0.8 x 0.9	0.75 x 0.8
Bean dimensions at outrigger level	0.8 x 1.0 m				
Thickness of internal wall	150mm				
Thickness of shear core	450 mm				
Grade of reinforcing steel	Fe500				
Grade of concrete	M50				

4.2 Loading

The loads considered for the structure are as follows:

1] Dead load: Unit weight of concrete : 25 kN/m³
Unit weight of floor finish: 1 kN/m³

Unit weight of masonry : 20 kN/m^3

2] Live load: Commercial are : 4 kN/m^2
Staircase : 3 kN/m^2
Terrace : 2 kN/m^2

3] Seismic load: Zone factor : 0.16 (Zone III)
Response reduction factor: 5
Importance factor : 1.5
Frame type : SMRF

4] Wind load: Basic wind speed : 44 m/s
Design wind speed : Vb * k1 * k2 * k3
Probability factor : k1 = 1
Terrain factor : k2 (category 2)
Topography factor : k3 (class C)

4.3 Virtual outrigger storey configuration

The model works on the principle of using belt trusses as virtual outrigger. The core moment is transferred to peripheral columns using floor diaphragms. The peripheral columns which are connected by a belt truss or belt walls then equally transmit the moment to the foundation.

Thickness of floor diaphragms	:	200 mm
Grade of concrete	:	M50
Reinforcement	:	Fe 550
Size of perimeter beams	:	0.8 x 1 m

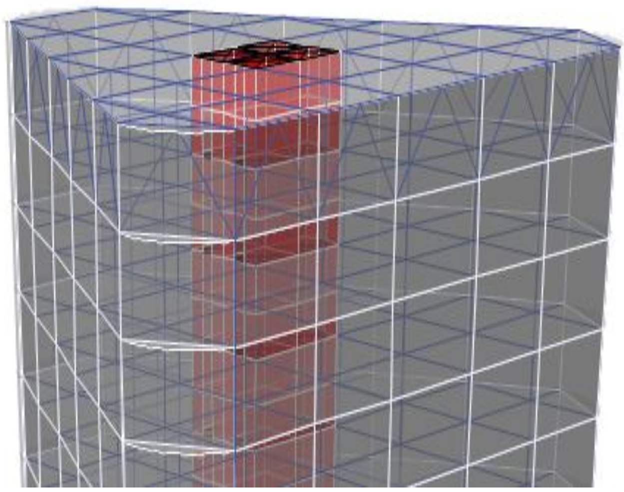

Fig -4: 3D Model for virtual outrigger storey at top

5. ANALYSIS

Models of 50, 60 and 70 storeys are subjected to seismic and wind loads. The models are analysed for one-outrigger system, two-outrigger system and three-outrigger system. The placement of virtual outriggers in each of the system is based on work of past researchers. The details of models are as follows:

1] One outrigger system

#	Details	Virtual outrigger @ storey		
	In case of models of:	50 storey	60 storey	70 storey
1a	Virtual outrigger @ top	50	60	70
1b	Virtual outrigger @ 3/4th height	38	45	53
1c	Virtual outrigger @ 2/3rd height	34	40	47
1d	Virtual outrigger @ mid height	25	30	35

2] Two outrigger system

#	Details	50 storey	60 storey	70 storey
		Virtual Outrigger located @ storey		
2a	Virtual Outrigger @ top & 3/4th height	50 & 38	60 & 45	70 & 53
2b	Virtual Outrigger @ top & 2/3rd height	50 & 34	60 & 40	70 & 47
2c	Virtual Outrigger @ top & mid height	50 & 25	60 & 30	70 & 35
2d	Virtual Outrigger @ 3/4th & mid height	38 & 25	45 & 30	53 & 35
2e	Virtual Outrigger @ 3/4th & 1/4th height	38 & 13	45 & 15	53 & 18
2f	Virtual Outrigger 2/3rd & mid height	34 & 25	40 & 30	47 & 35
2g	Virtual Outrigger 2/3rd & 1/3rd height	34 & 17	40 & 20	47 & 24

3] Three outrigger system

#	Details	Virtual Outrigger @		
		50 storey	60 storey	70 storey
3a	Virtual Outrigger at top, 3-4th and mid height	50, 38 & 25	60, 45 & 30	70, 53 & 35
3b	Virtual Outrigger at 3-4th, mid and 1-4th height	38, 25 & 13	45, 30 & 15	53, 35 & 18
3c	Virtual Outrigger at 2-3rd, mid and 1-3rd height	34, 25 & 17	40, 30 & 20	47, 35 & 24

Each of the above models are analysed for the following parameters:

- Lateral displacement for seismic and wind loads in X and Y direction
    - Top storey displacement
    - Floor wise displacement
    - Average displacement
- Storey drift for seismic and wind forces in X and Y direction
    - Maximum drift
    - Floor wise drift
    - Average drift
- Top storey acceleration
- Base shear
- Maximum overturning moment

The given parameters form the base to draw patterns and variations so that results can be concluded.

6. RESULTS

The following results are obtained in each of the outrigger system cases.

Lateral displacement due to seismic forces in X direction for 50, 60 and 70 storey models is shown and analyzed below.

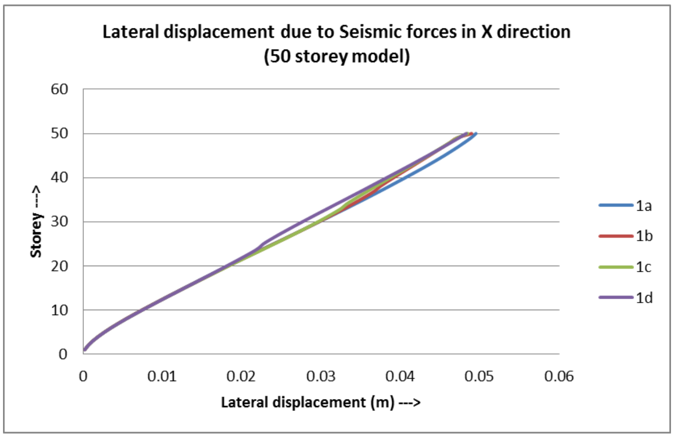

Chart -1: Lateral displacement for 50 storey model

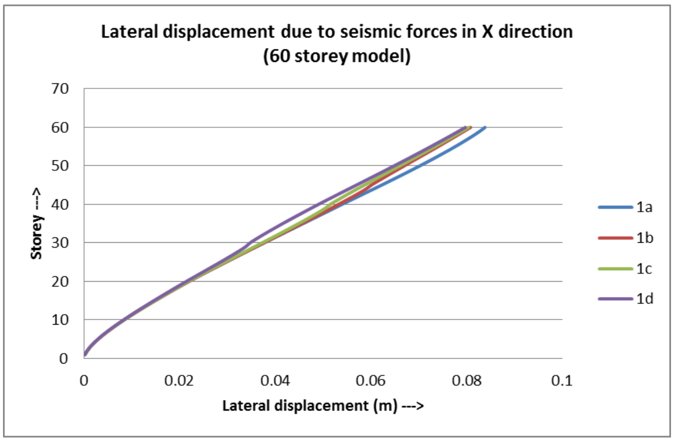

Chart -2: Lateral displacement for 60 storey model

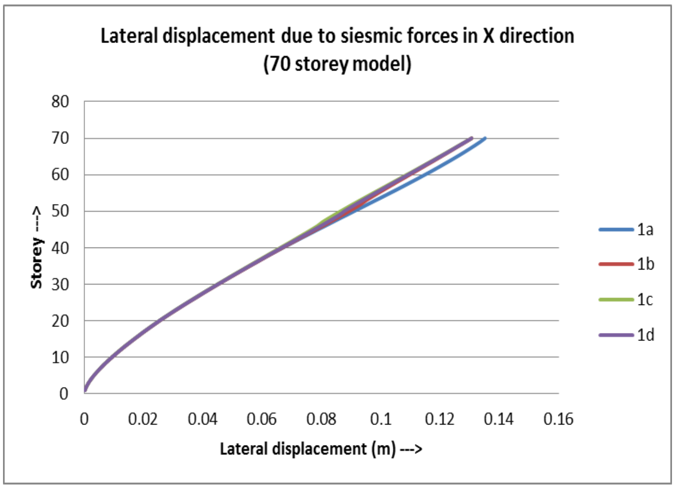

Chart -3: Lateral displacement for 70 storey model

The contents of the graph are analyzed in the following table. The displacements with least vales are highlighted.

Model	Condition	Lateral displacement in X direction (seismic) when Virtual Outrigger is located @			
		#1a	#1b	#1c	#1d
50 storey	Top storey	0.049532	0.048992	0.048504	0.048316
	Average	0.024593	0.024128	0.024013	0.023509
60 storey	Top storey	0.083828	0.080816	0.080409	0.079733
	Average	0.039593	0.038611	0.038082	0.036889
70 storey	Top storey	0.135226	0.13073	0.130689	0.130667
	Average	0.060808	0.059436	0.058743	0.059105

Storey drifts due to wind forces in Y direction for 50, 60 and 70 storey models are shown in the charts below.

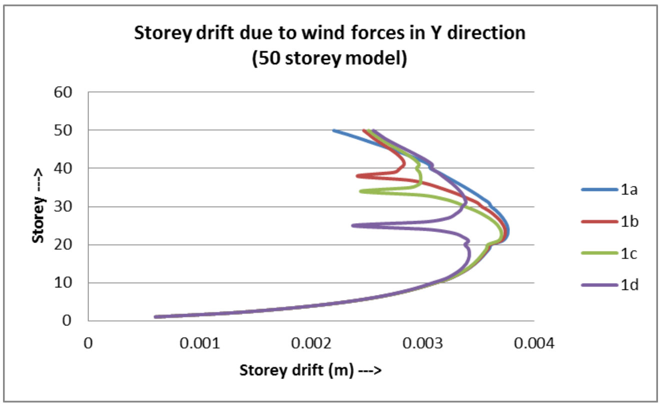

Chart -4: Storey drift for 50 storey model

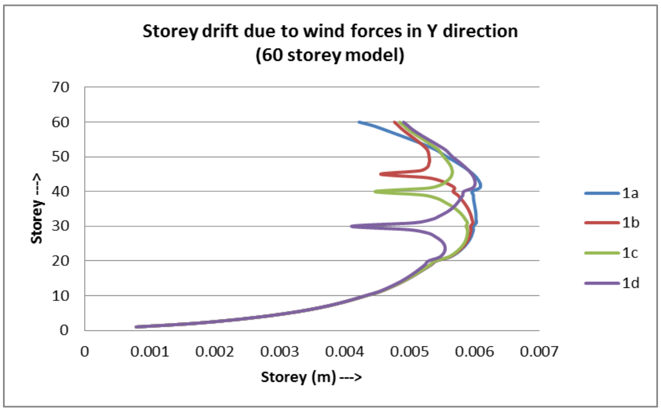

Chart -5: Storey drift for 60 storey model

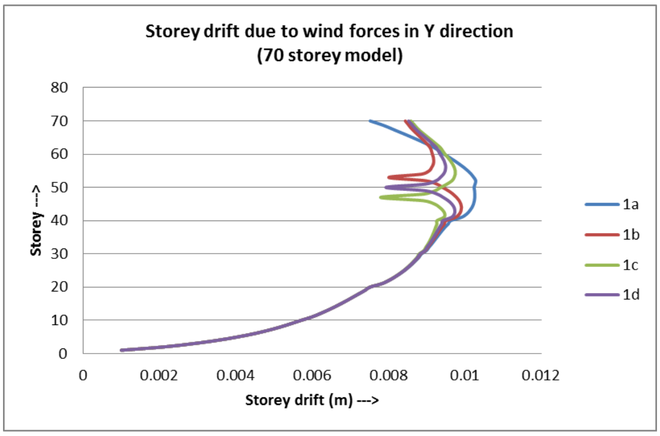

Chart -6: Storey drift for 70 storey model

The table below analyses the data for storey drift.

Model	Condition	Storey drift in Y direction (wind) when Virtual Outrigger is located @			
		#1a	#1b	#1c	#1d
50 storey	Max. Value	0.003765	0.00374	0.003707	0.003411
	Average	0.003082	0.0030161	0.0029995	0.002965
60 storey	Max. Value	0.006028	0.005976	0.005892	0.006008
	Average	0.00512141	0.0050135	0.0050170	0.005000
70 storey	Max. Value	0.10261	0.009912	0.00975	0.009499
	Average	0.00815894	0.0079928	0.0080019	0.0079296

Top storey acceleration in Ux direction analysis is as follows:

Model	Condition	Top storey acceleration in Ux direction(in m/s2) when Virtual Outrigger is Located @			
		#1a	#1b	#1c	#1d
50 storey	Spec X	0.3357	0.4263	0.3608	0.4309
	Spec Y	0.1298	0.164	0.1507	0.1093
60 storey	Spec X	0.2994	0.3767	0.3347	0.3712
	Spec Y	0.1336	0.1344	0.0976	0.1146
70 storey	Spec X	0.2708	0.3349	0.3099	0.3255
	Spec Y	0.1193	0.0944	0.1304	0.1159

The top storey acceleration is analyzed for Uy and Uz direction as well.

The table below shows base reaction due to seismic forces in X direction.

Model	Spec X	Base Reaction (in kN) when Virtual Outrigger is located @			
		#1a	#1b	#1c	#1d
50 storey	Fx	6381.76	6366.77	6824.49	6518.47
	Fy	2027.97	2501.91	827.39	2519.56
	Resultant	6696.23	6840.71	6874.46	6984.86
60 storey	Fx	6882.45	6978.28	8345.39	6906.99
	Fy	3084.16	3133.02	398.366	3259.32
	Resultant	7541.89	7649.32	8354.89	7640.1
70 storey	Fx	7402.24	7842.28	8864.67	7684.72
	Fy	3955.15	3293.19	1862.12	3788.05
	Resultant	8392.63	8505.67	9058.13	8567.62

Base reactions due to seismic forces in Y direction are also analyzed.

The table below presents maximum overturning moment.

Model	Moment	Maximum overturning moment (in kNm) when Virtual outrigger is located @			
		#1a	#1b	#1c	#1d
50 storey	Spec X	527108	532261	538303	547184
	Spec Y	541741	540949	540868	542541
60 storey	Spec X	704130	706247	705138	699969
	Spec Y	721743	723244	721207	717157
70 storey	Spec X	893548	897735	897057	897270
	Spec Y	913380	916823	915220	916086

Similar analysis is done for all the models in two-outrigger system and three outrigger system.

7. CONCLUSION

The following conclusions can be drawn for each of the outrigger systems.

7.1 One-Outrigger system

For each parameter, optimum location varies. This is mainly due to variation in height, impact of seismic and wind loads and layout of the structure.

Lateral displacement : Mid-height
Storey drift : Mid height
Top storey acceleration : No clear interpretation
Base reaction : 2-3rd height
Maximum overturning moment : No clear interpretation

7.2 Two-Outrigger system

The optimum locations in case of two outrigger system are:

Lateral displacement : 2-3rd and 1-3rd height
Storey drift : 3-4th and 1-4th height
Top storey acceleration : 2-3rd and mid-height
Base reaction : No clear interpretation
Maximum overturning moment : 3-4th and 1-4th height

7.3 Three-Outrigger system

The optimum locations in case of three outrigger system are:

Lateral displacement : 3-4th, mid and 1-4th heights
Storey drift : 3-4th, mid and 1-4th heights
Top storey acceleration : No clear interpretation
Base reaction : Top, 3-4th and mid-height
Maximum overturning moment : 3-4th, mid and 1-4th height

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