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OPTIMAL LOCATION OF STEEL OUTRIGGER BRACING SYSTEM FOR TALL BUILDING

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ABSTRACT

The advancements in engineering and technology, development of high strength structural materials, rise in population and lack of land area available due to the raise in land prices and rapid urbanization have led to the development of high rise buildings in the modern era. The tall buildings are the most susceptible to the lateral loadings due to the wind and seismic forces. The trend of taller and slender structures makes it necessary to develop the structural configuration which can resist the lateral loads effectively with minimum cost. The outrigger bracing system provides the solution to control excessive drift and displacement in such buildings. In this study, the conventional structural model having the central core of reinforced cement concrete and the models with outrigger at different heights of the building are modeled for the 20, 40 and 60 storey building heights. The aim of this paper is to suggest a suitable location of outrigger bracing system to control excessive top storey displacement.

Key words: Outrigger system, lateral loads, displacement, drift, optimal location

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1. INTRODUCTION

The outrigger system consists of relatively stiff outrigger beams or trusses which connect the shear wall core of the building with the peripheral columns and the peripheral columns are connected with one another through the belt beams or trusses. The core can also be of the reinforced concrete section or may be constructed with the stiff steel trusses. The outriggers engage the peripheral columns with the core of the structure through stiff beams or trusses. When lateral loads act on the building, the central core tends to rotate which at the outrigger levels mutates a tension – compression couple in the peripheral columns. Columns on the windward side are subjected to tensile forces and columns on the leeward side are subjected to compressive forces. Consequently a restoring moment is induced in the central core.

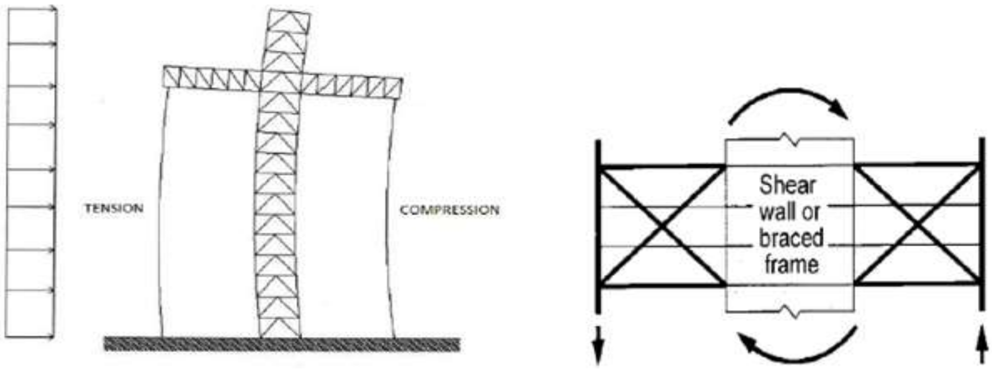

Figure 1 Mechanism of outrigger system

The couple due to axial forces in the peripheral columns resists the rotation in central core. The moment in central shear wall or core reduces due to the reverse moment induced at the outrigger locations. The peripheral columns are thus converted to the lateral force resisting system which otherwise are just the gravity columns and this leads to better economic solution.

2. RELATED WORK

Chan and Kuang [1] started the studies on stiffening the structure by employing stiff beams at arbitrary locations in the structure. They stated that location of stiff beams affects the performance of high rise structure against lateral loads. Taranath [2] worked on finding the optimal position of belt-truss along the height that decreased lateral sway under the wind loadings and found middle location of building as optimum for single outrigger. McNabb [3] carried the study of Taranath ahead and used two outriggers for finding out the reduction in lateral drift and also verified the work done by Taranath. Qi and Chen [4] worked with two-dimensional models to study the suitability of outriggers. Their model comprised of the core in form of channel and two columns connected with the series of outriggers beams to the core. They found that three outriggers reduce lateral displacement significantly. Kian and Siahaan [5] worked on increasing the stiffness to make the structure capable of resisting the wind load and seismic load by using the diagonal outrigger along with belt trusses. The researchers have found that in the case of two-dimensional models, a single outrigger incorporated at mid height of structural model reduces the lateral drift by around 56% while two outriggers, one at top and the other one at the mid height of structure reduces displacement by around 65%. Junais Ahmed AK and Yamini Sreevalli [6] have worked on investigating the variation in fundamental time period of the structure with outriggers placed at different storey levels of the building. The time period of the structure is remarkably decreased by using outriggers at one-third the building height from top as well as from the bottom. Su et al [7] worked on determining load transfer mechanism of outrigger bracing system with central core. They used “strut-and-tie method” to analyse the structural models. Hoenderkamp et al [8] gave a simple analysis technique for fundamental designing of the outriggers coupled with the shear walls. He also proved that location of outrigger significantly affects the lateral displacement of the building.

3. METHODOLOGY

3.1. Structural Modelling

For this study, the structural models of three different storey heights i.e. 20 storey, 40 storey and 60 storey are prepared for the comparative study. The bay width is kept constant along both the longitudinal as well as the transverse direction. A symmetrical structural model is thus obtained for simplicity in analysis. But the bay width is changed for the models of different heights so as to maintain the slenderness ratio of structural models as per the IS code guidelines. Table 1 depicts the details of dimensions of the structural models.

Table 1 Dimensions of structural models

Parameter	20 Storey	40 Storey	60 Storey
Bay Width	3m	4m	5m
No. of Bays	5	5	5
Plan Dimensions	15m x15m	20m x 20m	25m x 25m
Storey Height	3m	3m	3m
Height of structure	60m	120m	180m
Slenderness Ratio	4	6	7.2

Further five types of the structural configurations are modelled for each case of the storey heights. Total fifteen models (five for each storey height) are prepared. ETABS 2017 software is used for analysis. A conventional model in each case is modelled having the shear wall central core. This is compared with the models prepared with the steel outrigger bracing systems incorporated at the different locations in the model. Types of structural models considered for the study are as mentioned below.

Type I Conventional model with central core
Type II Central core with outrigger system at top
Type III Central core with outrigger system at top and 0.75 times the height of building (0.75H)
Type IV Central core with outrigger system at top and 0.5 times the height of building (0.5H)
Type V Central core with outrigger system at top and 0.25 times the height of building (0.25H)

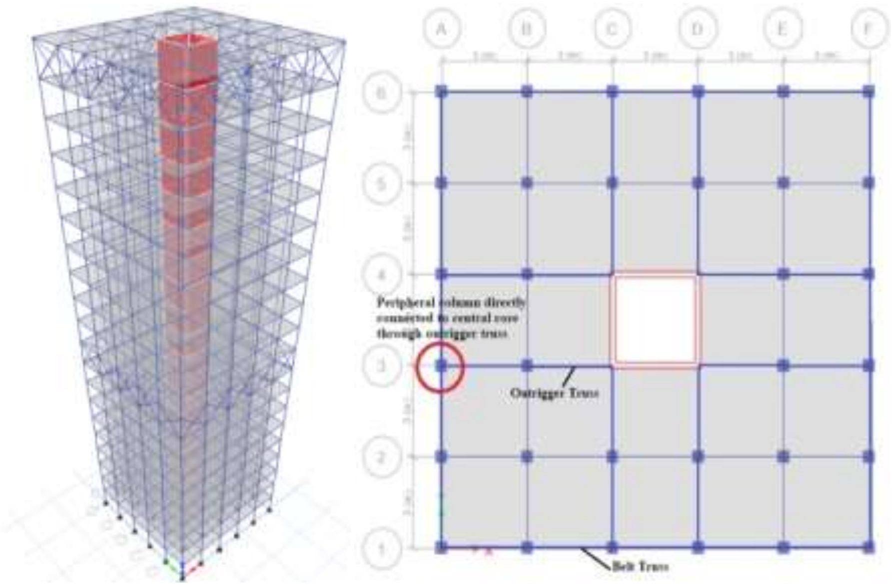

Figure 2 3D model and plan of the 20 storey building in ETABS software

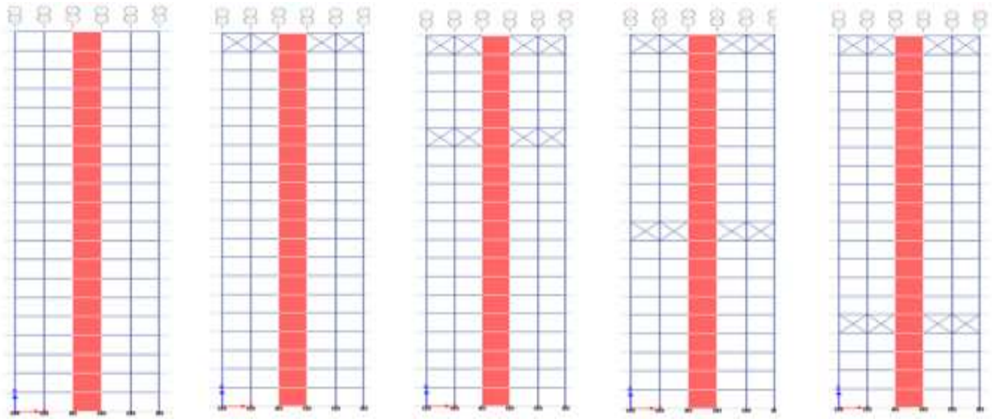

Figure 3 Elevation of the different 20 storey structural configurations

The structural members of the various models under consideration are designed according to IS 456:2000 and IS 800:2007 using the ETABS 2017 software package.

Table 2 Section Properties of the Structural Members

20 Storey models	40 Storey models	60 Storey models
Beams – 300mm x 400mm (M30)	Beams – 300mm x 450mm (M30)	Beams – 300mm x 550mm (M30)
Columns – 400mm x 400mm (M40)	Columns – 750mm x 750mm (M40)	Columns– 1000mm x 1000mm
Slabs – 125mm thick (M25)	Slabs – 125mm thick (M25)	Slabs – 125mm thick (M25)
Shear walls – 200mm thickness	Shear walls – 250mm thickness	Shear walls - 300mm thickness
Outrigger Beams – ISHB450 (Fe250)	Outrigger Beams – ISHB450	Outrigger Beams – ISHB450
Outrigger Bracings – ISHB300	Outrigger Bracings – ISHB350	Outrigger Bracings – ISHB400

3.2. Loadings

The loads are applied to the structural models as per the standard guidelines mentioned in relevant IS codes. Self weight of structural members is automatically calculated by the ETABS software. Live load is considered as 3.5kN/m^2 on all floor slabs and 1.5kN/m^2 on roof slab. Floor finish load of 1.5kN/m^2 is considered on all the floors including the roof. A wall load of 9kN/m run is applied on all the framing beams. Seismic load is applied as per the guidelines of IS 1893 (Part 1) – 2016 [9] considering seismic zone IV. Seismic zone factor of 0.24, response reduction factor of 5 and importance factor of 1 is taken considering the building to be SMRF. The soil type is medium soil (Type II). The load combinations are formed as per the Indian standard codes.

3.3. Analysis

The structural models are analysed in ETABS 2017 by three different analysis techniques namely Equivalent Static Method (ESM), Response Spectrum Method (RSM) and Non-Linear Time History Analysis (THA). Damping of 5% is considered for defining response spectrum function according to IS 1893 (Part 1) – 2016. Modes are combined by Complete Quadratic Combination (CQC) method as it is the best suited for combining the responses of the closely spaced modes. An eccentricity of 0.05 is taken for all the diaphragms for any accidental eccentricity arising in the structure. Time history analysis is performed to evaluate response of structural models for a ground motion with time. Time history analysis is performed for all fifteen models using 1940 Imperial Valley (El Centro) earthquake data having the PGA of 341.69 cm/s^2 and PGV of 33.45 cm/s obtained from peer ground motion database. The modal damping of 0.05 is considered in THA. The various parameters are studied by the results obtained from the three analyses.

4. RESULTS

4.1. Displacement

The lateral displacements of 20, 40 and 60 storey models are presented in Fig.(4), Fig.(5) and Fig.(6) respectively by different analysis approaches and the top storey displacement for different configurations is depicted in Table 3. The least displacement is found with outriggers at top and 0.5H (mid height) level of structural models. A reduction in lateral displacements of 22.3%, 26.5% and 26.3% for 20, 40 and 60 storeys models respectively have been found by equivalent static method for outriggers at top and 0.5H. RSM shows a reduction of 18.53%, 30.45% and 28.73% for 20, 40 and 60 storey respectively and THA shows a reduction in lateral displacements of 30.72%, 33.87% and 31.39% for 20, 40 and 60 storey models respectively.

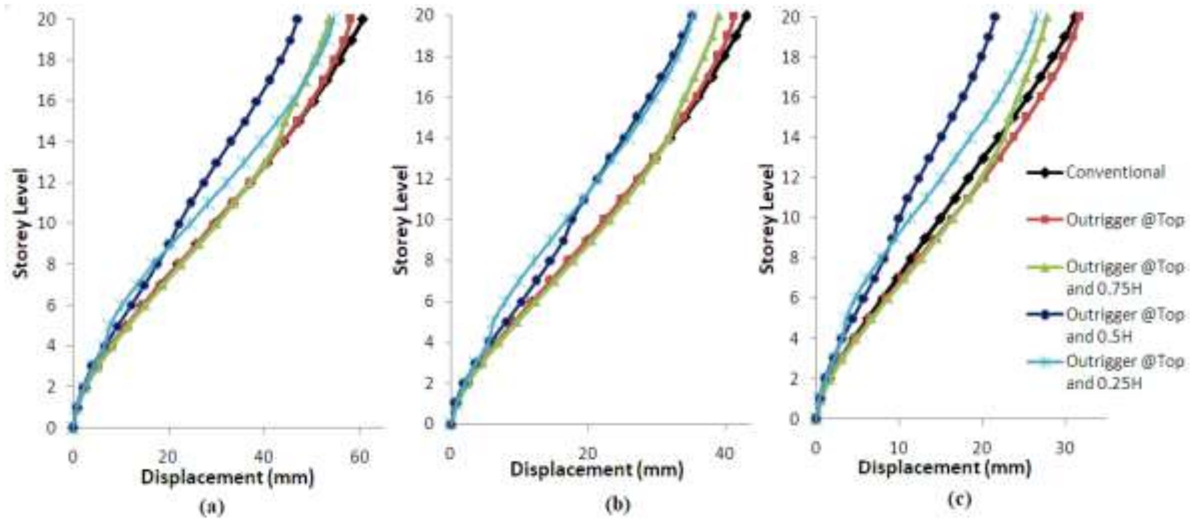

Figure 4 Lateral Displacement for 20 storey models by (a) ESM (b) RSM (c) THA

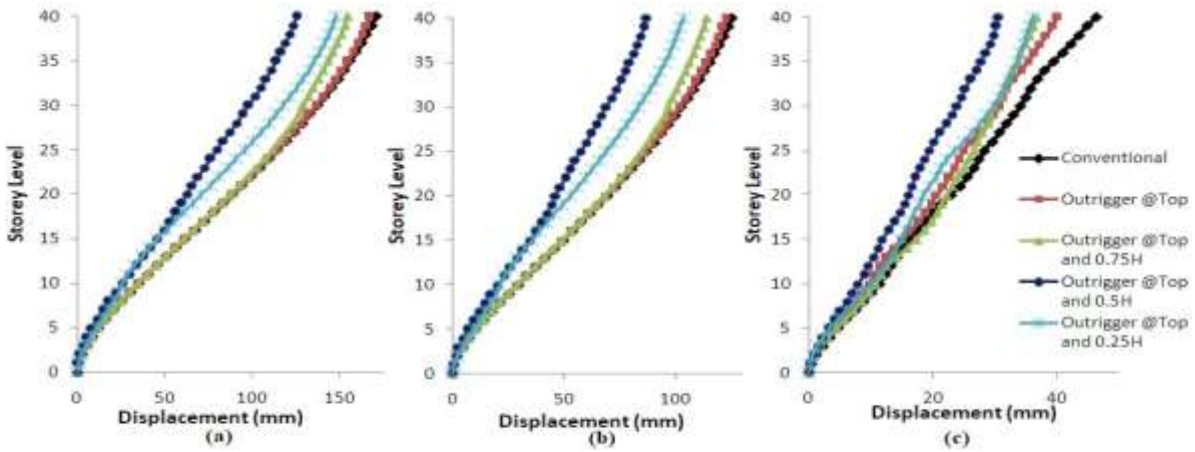

Figure 5 Lateral Displacement for 40 storey models by (a) ESM (b) RSM (c) THA

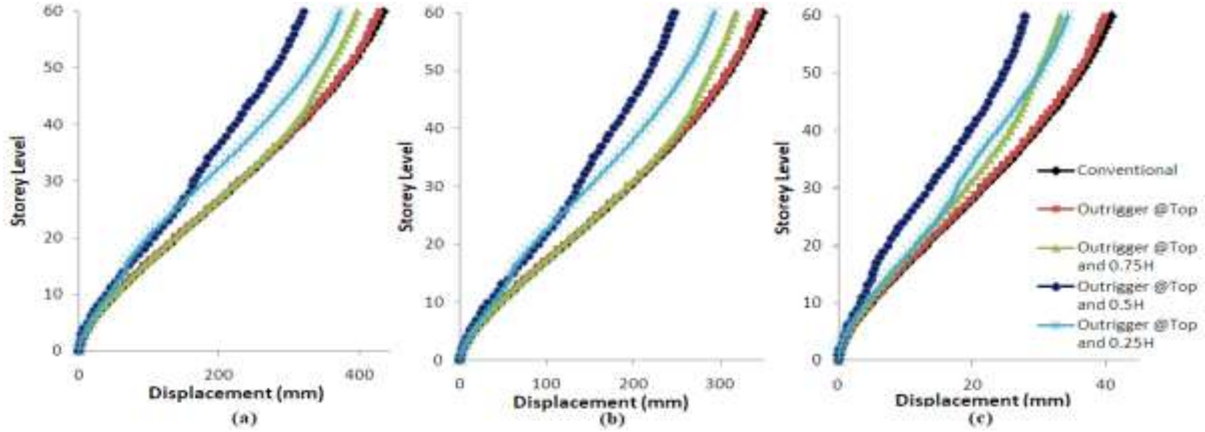

Figure 6 Lateral Displacement for 60 storey models by (a) ESM (b) RSM (c) THA

Table 3 Maximum displacement (in mm) at the top storey

Model	Equivalent Static Method (ESM)			Response Spectrum Method (RSM)			Time History Analysis (THA)		
	20 Storey	40 Storey	60 Storey	20 Storey	40 Storey	60 Storey	20 Storey	40 Storey	60 Storey
Conventional	60.56	170.62	434.62	43.2	125.28	347.99	31.23	46.35	40.89
Outrigger at Top	58.08	166.72	427.70	41.39	122.28	342.76	31.69	40.07	39.87
Outrigger at Top and 0.75H	53.62	154.64	396.55	39.10	113.85	318.24	27.82	36.70	33.23
Outrigger at Top and 0.5H	47.06	125.33	320.32	35.20	87.12	248.02	21.63	30.65	28.05
Outrigger at Top and 0.25H	54.53	147.67	372.58	35.27	103.36	293.16	26.53	36.14	34.4

4.2. Storey Drift

Storey drifts of 20, 40 and 60 storey models are presented in Fig.(7), Fig.(8) and Fig.(9) respectively. The minimum drift is found in outriggers at top and 0.5H models by all the analyses as depicted in Table 4.

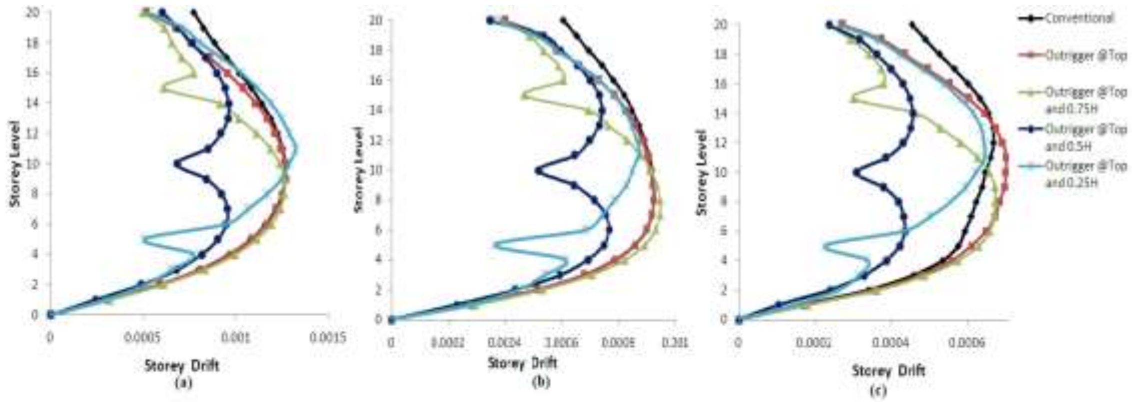

Figure 7 Storey drift for 20 storey models by (a) ESM (b) RSM (c) THA

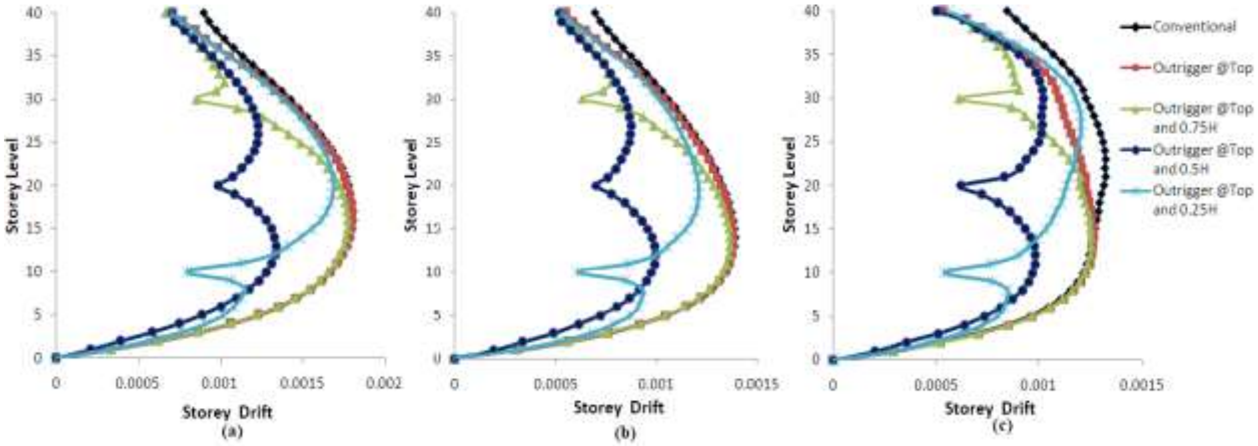

Figure 8 Storey drift for 40 storey models by (a) ESM (b) RSM (c) THA

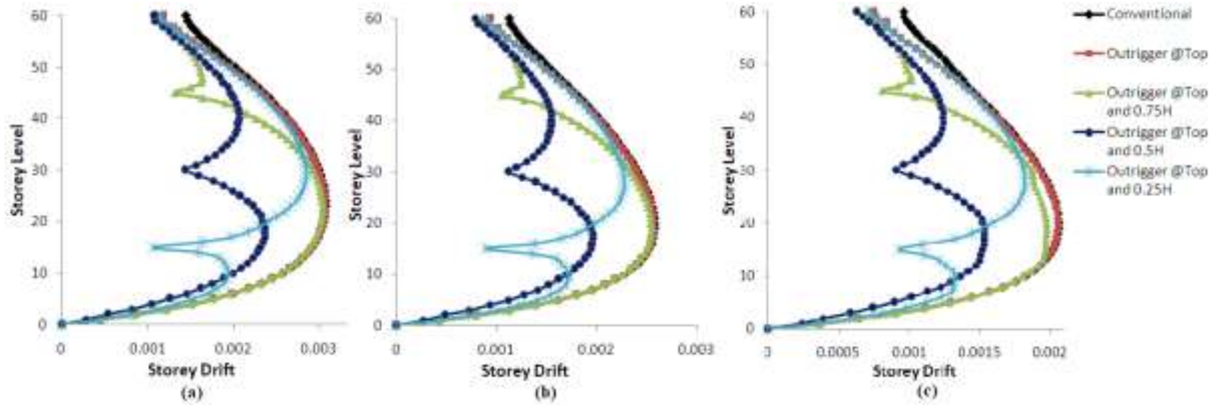

Figure 9 Storey drift for 60 storey models by (a) ESM (b) RSM (c) THA

Table 4 Maximum storey drift ratio

Model	Equivalent Static Method (ESM)			Response Spectrum Method (RSM)			Time History Analysis (THA)		
	20 Storey	40 Storey	60 Storey	20 Storey	40 Storey	60 Storey	20 Storey	40 Storey	60 Storey
Conventional	0.00127	0.00181	0.00307	0.00092	0.00139	0.00258	0.00067	0.00132	0.00206
Outrigger at Top	0.00127	0.0018	0.00307	0.00092	0.00138	0.00257	0.0007	0.00127	0.00206
Outrigger at Top and 0.75H	0.00126	0.00178	0.00304	0.00095	0.00137	0.00255	0.00067	0.00126	0.00198
Outrigger at Top and 0.5H	0.00096	0.00134	0.00237	0.00077	0.001	0.00196	0.00045	0.00102	0.00154
Outrigger at Top and 0.25H	0.00132	0.00169	0.00285	0.00087	0.00121	0.00228	0.00064	0.00121	0.00182

4.3. Fundamental Time Period

Fundamental time period of all the models under consideration is depicted in Table 5. It is evident that the minimum time period is found with outriggers at top and 0.5H in all the cases. Fundamental time period of conventional 20, 40 and 60 storey models reduces from 2.314s, 5.139s and 8.221s respectively to 1.769s, 4.342s and 6.995s for the structural models with the outriggers at top and 0.5H locations. This means that providing outrigger system at top and 0.5H locations makes a stiff structural configuration and hence the time period reduces.

Table 5 Fundamental Time Period (s) of various structural models

Model	20 Storey	40 Storey	60 Storey
Conventional	2.314	5.139	8.221
Outrigger at Top	2.285	5.116	8.206
Outrigger at Top and 0.75H	2.192	5.002	8.034
Outrigger at Top and 0.5H	1.769	4.342	6.995
Outrigger at Top and 0.25H	2.055	4.71	7.468

4.4. Roof Acceleration and Velocity

Table 6 shows the maximum roof acceleration and maximum roof velocity of all the models under consideration from THA. It is evident from the results that the minimum roof acceleration and velocity is experienced by the structural model with outriggers at top and 0.5H in all the cases.

Table 6 Roof Acceleration and Roof Velocity by Time History Analysis

Model	Roof Acceleration (m/s^2)			Roof Velocity (m/s)		
	20 Storey	40 Storey	60 Storey	20 Storey	40 Storey	60 Storey
Conventional	0.694	1.154	0.939	0.105	0.129	0.166
Outrigger at Top	0.673	1.05	0.736	0.108	0.116	0.144
Outrigger at Top and 0.75H	0.627	0.92	0.695	0.092	0.112	0.137
Outrigger at Top and 0.5H	0.617	0.64	0.544	0.077	0.082	0.113
Outrigger at Top and 0.25H	0.703	0.774	0.764	0.086	0.126	0.125

4.5. Base Shear

The base shear for 20, 40 and 60 storey conventional models by ESM is found to be 1705.19 kN, 3630.22 kN and 8770.1 kN respectively. The base shear for 20, 40 and 60 storey with outriggers at top and 0.5H models is 1657.32 kN, 3539.23 kN and 8403.6 kN respectively. The base shear for 20, 40 and 60 storey conventional models by RSM is found to be 1869.69 kN, 3519.72 kN and 8482.9 respectively where as the base shears for models with outriggers at top and 0.5H models are 1681.53 kN, 3491.34 kN and 8148.79 kN respectively. There is marginal decrease in base shear in models with outriggers at top and mid height level.

4.6. Moment at Base of the Central Core

Fig.(10) shows the variation in overturning moment in the central core along the height for different models of 20 storeys by the Equivalent Static Method. Similar variation is also found in the 40 storeys and 60 storeys models and by RSM and THA methods also. It is found from this comparison that the moment is reduced drastically at the outrigger locations and also changes the nature. At the locations of outrigger a counter moment due to tension compression couple in peripheral columns is developed and a remarkable magnitude of moment is resisted by the peripheral columns which are engaged with the outrigger system thereby reducing the moments in the core. Table 7 depicts the maximum moment at base of central core of structural models under consideration. It is found that the minimum moment at the base of core is in the structural models with outriggers at top and 0.5H levels.

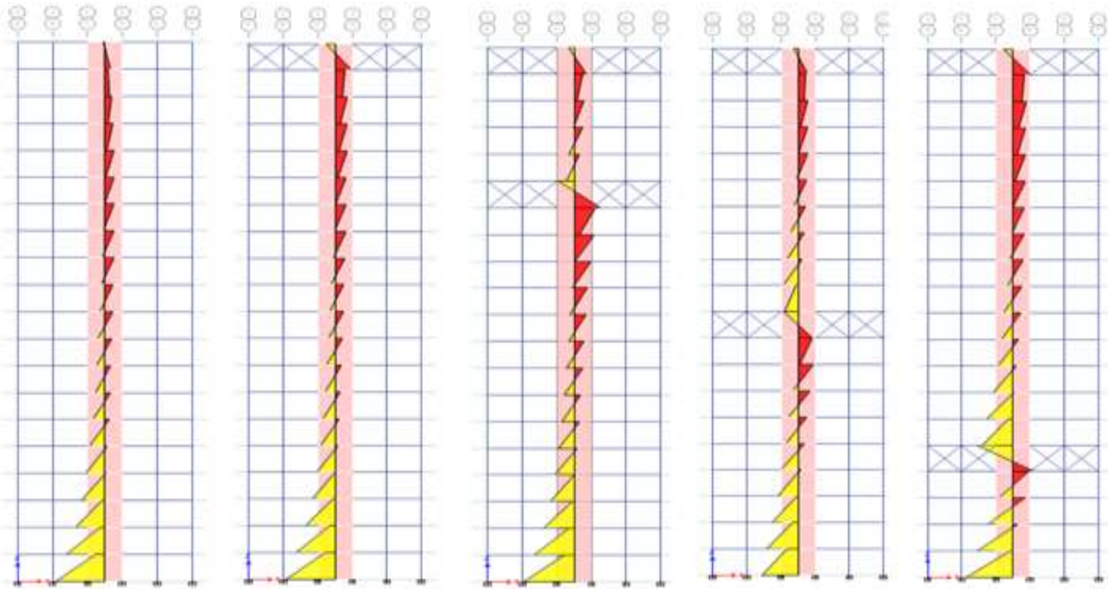

Figure 10 Variation of moment in the central core along the height for different structural configurations of 20 storey by Equivalent Static Method

Table 7 Maximum Moment (kNm) at base of central core

Model	Equivalent Static Method			Response Spectrum Method			Time History Analysis		
	20 Storey	40 Storey	60 Storey	20 Storey	40 Storey	60 Storey	20 Storey	40 Storey	60 Storey
Conventional	1688	4123	11626	1536	3730	10794	1522	2908	6719
Outrigger at Top	1702	4114	11622	1546	3718	10785	1596	2578	6595
Outrigger at Top and 0.75H	1759	4031	11569	1607	3643	10739	1615	2360	5756
Outrigger at Top and 0.5H	1288	2415	7115	1181	2079	6385	958	1690	3461
Outrigger at Top and 0.25H	1503	3759	10573	1503	3425	9859	1351	1947	5254

4.7. Axial Force in Peripheral Column

For comparing axial forces in column in various models, a peripheral column connected directly with core through outrigger trusses as shown in plan (Fig.2) is selected. Table 8 shows the maximum axial force (tensile) in periphery column of different structural models under consideration. As compared to the conventional models, the models with outriggers at top and mid height show higher axial forces in the peripheral columns. As discussed earlier, the external lateral load resisting couple formed by the tension and compression in peripheral columns results in higher axial forces.

Table 8 Axial Force (kN) in Periphery Column

Model	Equivalent Static Method			Response Spectrum Method			Time History Analysis		
	20 Storey	40 Storey	60 Storey	20 Storey	40 Storey	60 Storey	20 Storey	40 Storey	60 Storey
Conventional	368	1244	3859	263	921	2904	282	495	570
Outrigger at Top	366	1234	3673	260	910	2885	298	459	557
Outrigger at Top and 0.75H	377	1324	3841	274	962	2994	292	515	653
Outrigger at Top and 0.5H	458	1426	4220	344	989	3295	315	620	713
Outrigger at Top and 0.25H	433	1342	3827	284	971	3018	304	528	514

5. CONCLUSIONS

- The optimized location of double outriggers is when provided at top and mid height level of structure. Significant decrease in lateral displacement and drift is seen in providing outriggers at these locations.
- Marginal reduction in base shear is found in structures with outriggers.
- Roof acceleration and roof velocity is least in models with outriggers at top and mid height.
- Time period is found to be the least in this case due to the increase in stiffness of the structure.
- The moment at base of central core decreases and axial force increases in the columns at periphery connected directly to the core through the outrigger truss with outriggers at top and 0.5H.
- Peripheral columns take part in resisting lateral load more efficiently along with central core.

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