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Parametric Study Of Dynamic Analysis Of High-Rise Buildings With Outrigger Systems

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Abstract: Design of tall buildings have their own challenges, right from resisting lateral loads due to wind and earthquake forces to huge construction costs. In order to reduce the lateral displacement of tall buildings, outriggers are employed. The optimal positioning of these outriggers at various levels of the building results in economic design. Rearranging those optimally positioned outriggers at the same level of the building further reduces the parameters like fundamental time period, drift, lateral displacements, etc. and result in further economic design of the building. Three models each of G+10, G+20, G+30 with ordinary moment resisting frame, special moment resisting frame, special moment resisting frame with outriggers are modeled, analysed and designed as per IS codes using ETABS 2016. Parameters like modal participation mass ratio, storey drifts, maximum lateral displacements against earthquake and wind, minimum base shear, soft storey, maximum to average displacement ratio are checked and brought under control as per Indian codes for lateral stability of the structures. Value engineering is performed on the structures and the final results are compared.

Keywords: outrigger system, high-rise buildings, dynamic analysis, value engineering

1. INTRODUCTION

In this modern day life, it is a desire of every human to have his own shelter. This desire of human added to growing population has led to urbanization overcrowding of buildings and cities getting congested without having nominal space for greenery, space for recreational purposes which in turn is reducing the oxygen levels and increasing the content pollutants in the atmosphere, bringing abnormal climatic changes, causing a sense of distress and psychological impact on mental health of human beings. Added to this the governments both at the central and states are proposing housing schemes for low income groups and economically weaker sections of the society which requires large areas of land for construction, hardly leaving the land requires for agriculture, forests, etc. which are necessary to maintain ecological balance in the environment.

It is in this situation, the high-rise buildings come to the rescue of the engineers which can accommodate a greater number of people per a given base area. These tall buildings have their own engineering difficulties in terms of design and construction when it comes to the lateral stability of the structure. For mid-rise buildings, the braced frames provide lateral stability to the structure and are proved to be economical. But for high-rise buildings, braced frame design becomes complex uneconomical and cumbersome. In modern high-rise buildings, lateral loads due to wind and earthquake forces are often a cause of concern, more over other effects like storey drifts, large moments, lateral displacements, fundamental time period, etc. plays a crucial role in the lateral stability of the high-rise buildings. As the height of the building increases, the stiffness of the structure is of more importance. To improve the stiffness of the structure and overcome these complexities, structural engineers have introduced outrigger system for tall buildings to reduce the lateral movement of tall buildings by maintaining a reasonable quantity of steel.

Outriggers are horizontal rigid deep beams with depth almost equal to the storey height. They are designed to improve the stiffness and the strength of the building by connecting the core of the building to the peripheral columns of the building. However, there is a misconception that these outrigger systems of depth equivalent to storey height maybe uneconomical owing to its size. Effectively positioned outriggers in high-rise buildings show remarkable results of improved stiffness and reduced lateral displacements and also economical. To prove this, three models each of G+10, G+20, and G+30 are considered, one without outrigger and the other two with outriggers (except for G+10 models). The specimens are modeled, analysed and designed using a powerful tool called ETABS which is based on the principle of Finite Element Method.

Ahmed and Sreevalli (2014) reported the results of the study carried out on application of outrigger in slender high-rise buildings to reduce fundamental time period. The conclusion drawn from this study is that the 1/3rd distance from top and bottom of the building is the optimum position of the outrigger in slender high-rise building. Nanduri et al. (2013) reported the results of the study carried out on optimum position of outrigger system for high-rise reinforced concrete buildings under wind and earthquake loading. Results showed that the use of outrigger and belt truss system in high-rise buildings escalated the stiffness and made the structural system efficient under lateral load. The maximum drift at the top of structure when one core is employed is about 50.63 mm and this is reduced by suitably selecting the lateral system. When the outrigger is placed at top storey as a cap truss, the maximum drift is 48.20 mm and 47.63 mm with and without belt truss respectively. Therefore, there is not much decrease in drift value with belt truss. It is concluded that the optimum location of the outrigger is between 0.5 times its height.

Lame (2008) reported the results of the study carried out on optimization of outrigger structures. The results show that outriggers are with no doubt an efficient structural system against lateral loading and wind in specific. In general, they reduce the drift of the structure and reduce the moment in the core. Bayati et al. (2008) analysed and shows the results of the study carried out on optimized use of the outrigger system to stiffen the coupled shear walls in tall buildings. From the results it is concluded that the position of the outrigger considerably affected the behaviour and horizontal deflection of the structure. Though an outrigger is very effective on horizontal deflection, the effect of the outrigger on shear is minimal, when an internal beam is used in the structure.

Haghollahi et al. (2012) analysed Optimization of outrigger locations in steel tall buildings subjected to earthquake loads. Lee and Tovar (2014) studied Outrigger placement in tall buildings using topology optimization. Nouri and Ashtari (2015) conducted Weight and topology optimization of outrigger-braced tall steel structures subjected to the wind loading using GA. Das and Tesfamariam (2020) studied optimization of SMA based damped outrigger structure under uncertainty.

Bayati et al. (2008) explained the results of the study carried out on optimized use of multi-outriggers system to stiffen tall buildings. Based on the results the basements used as outriggers generate a wider effective base to resist overturning. The effectiveness of belt truss system as virtual outriggers had been validated by an example. It is clear from the example that the outrigger theory had worked as it is meant. For the same outrigger column sizes and locations, virtual outriggers are found to be less effective than conventional outriggers because of the reduced stiffness due to the indirect force transfer mechanism. Nawar merza, Ashna zangana Reported the results of the study carried out on sizing optimization of structural systems of tall buildings. The results showed that the core structure with single outrigger is more effective structural system in comparison to the shear wall-braced structure. The result also showed that a key factor is the structure's slenderness, meaning the geometry of the building.

Optimization of damped outrigger systems subject to stochastic excitation is studied by Fang et al. (2019). Bayati et al. (2008) reported optimized use of multi-outriggers system to stiffen tall buildings. Analysis of outrigger numbers and locations in outrigger braced structures using a multi objective genetic algorithm is conducted by Chen and Zhang (2018). Case study on the field application of parametric design technique for optimization of outrigger system High-rise Building Structures is conducted by Kim et al. (2012).

2. STRUCTURAL MODELLING

2.1. Structural Information

The structural data given below are kept common for all the models of the three MODEL sets. • The buildings are essentially R.C.C. framed structures with Beam, slabs and columns.

- The columns are connected with each other with a network of beams and slabs, with the slabs acting as in-plane semi rigid diaphragms for each of the floors. • Floor to floor height of 3m except for the floor level of outrigger is adopted.
- The foundations are assumed to be fixed with no degrees of freedom.
- At the level of outriggers, the floor heights are 1.8m as outrigger is 1.8m deep is adopted.
- Outriggers are positioned of at 1/3rd height from top and bottom of the building, wherever positioned.
- Materials:
  - Concrete: M30 grade (for all beams, slabs and shear walls), M35 grade (for all columns)
  - Steel: Fe-500, and Fe-415
- Member sizes:
  - Beams: 230 X 450 mm, 300 X 600 mm.
  - Columns: 300X750mm, 450 X 700mm, 600X600mm.
  - Slabs: 150 mm thick.
  - Shear walls: 300 mm thick, 5 m long. 300 mm thick, 1.25/1.75/2.3 m long.

2.2. Loading Parameters

All other dead load including self-weight of various materials & finished items relevant to the design work and shall be considered as per IS: 875 (Part-1). Live load is considered as per IS: 875 (Part-2).

- Floor loads – 4 kN/sq.m
- Over Head Tank – 15 kN/sq.m
- Lift Machine Room – 20 kN/sq.m
- Terrace – 1.5 kN/sq.m Gust factor is calculated as per IS 875 part-3.

2.3. Stability Checks

The following lateral stability checks are performed for every model as per IS-1893: 2016 and IS-16700.

1. The deflection of any horizontal member shall not exceed Length/350 (or) 20 mm, whichever is less.
2. The first two modes of the structure should be in translation and not rotation.
3. The fundamental time period of a structure is preferred to be less than 0.1xN (N = no. of levels).
4. The maximum inter storey drift shall not exceed 0.004.
5. Modal mass participation ratio – shall be greater than 65% in the first two modes.
6. Minimum Base Shear – 0.7% of seismic weight of building, for seismic zone - 2.
7. The maximum lateral displacement or sway against earthquake shall not exceed H/250.
8. The maximum lateral displacement or sway against wind shall not exceed H/500.
9. The ratio of maximum to average lateral displacement shall not exceed 1.2.
10. Stiffness of the floor less than 70% of stiffness of storey above, so that the storey above is not a soft storey.

2.4. Model Details

Three sets of models each for G+10, G+20, G+30 are modeled, namely model 1, model 2, and model 3 for a plan dimension of 20 x 15 m.

2.4.1. Model set 1 (G+10 models)

Model 1:

Model 1 is an ordinary moment resisting frame (OMRF) system with lift core walls symmetrically placed facing each other at the mid portion of the building model. A spacing of 2.5 m for the periphery columns along Y - axis and 5 m centre to centre for interior and along other direction is assigned. The central two columns are of dimension 600x600 mm, rest all are of 300x750 mm dimension. The periphery beams along Y-axis are of size 230x600 mm, the central beam along Y-axis in the middle of the structure connecting square columns is of size 300x450 mm, the beams connecting within the core wall are modeled as spandrel of size 300x600 mm. all the shear walls are modeled and labeled as piers with lengths of 2.5m along Y-axis and 1.67m along X-axis. All the slabs are assigned the property of semi rigid diaphragms. The plan of G+10 model with OMRF are shown in the Figure 1a Model 2:

Model 2 is a special moment resisting frame (SMRF) system with lift core walls symmetrically placed facing each other at the mid portion of the building and structural wall system. The spacing for all the columns from centre to centre is 5 m. The central two columns are of dimension 600x600 mm, rest all are of 300x750 mm dimension. The periphery beams are of size 300x600 mm, the central beams along Y-axis in the middle of the structure connecting square columns is of size 230x450 mm. All the shear walls are modeled and labeled as piers with lengths of 5m along Y-axis and 1.67m along X-axis for the core walls and 1.25m for the corner structural walls. All the slabs are assigned the property of semi rigid diaphragms. The plan of G+10 model with SMRF are shown in the Figure 1b.

Model 3:

Model 3 is a special moment resisting frame (SMRF) along with outrigger system with lift core walls symmetrically placed facing each other at the mid portion of the building. The outriggers are positioned in between storey 8 and 9 and the outrigger is modeled as a spandrel beam of breadth 300mm and depth 1.8m. Horizontally, within the storey level the outrigger is positioned as shown in fig. 5. The spacing for all the columns from centre to centre is 5 m. The central two columns are of dimension 600x600 mm, rest all are of 300x750 mm dimension. The periphery beams are of size 300x600 mm, the central beams along Y-axis in the middle of the structure connecting square columns is of size 230x450 mm. All the shear walls are modeled and labeled as piers with lengths of 5m along Y-axis and 1.67m along X-axis for the core walls and 1m for the corner structural walls. All the slabs are assigned the property of semi rigid diaphragms. The plan of G+10 model with SMRF are shown in the Figure 1c.

2.4.2. G+20 Floor system

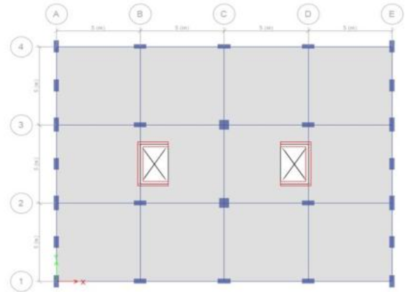
From the discussions of G+10 models, it is clearly observed that the fundamental time period for model-1 with OMRF is exceeding the permissible value given in IS 1893: 2016 and that of the other two models is within the permissible limits and moreover the building skeleton looks clumsy with many columns spaced closely to each other. This spacing of the columns may further decrease as the height of the building increases in order to maintain the stiffness and stability of the building. It is for this reason the option of OMRF system had been ruled out in G+20 and G+30 models and they are modeled with SMRF systems with and without outriggers.

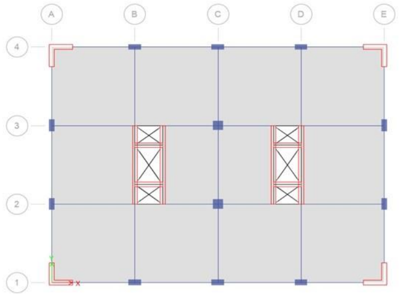
Model 1 :

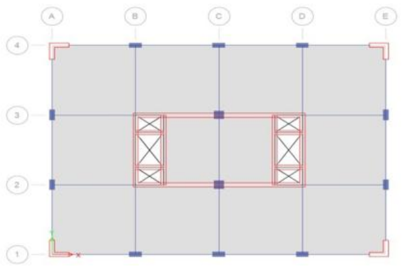
Model 1 is a special moment resisting frame (SMRF) system with lift core walls symmetrically placed facing each other at the mid portion of the building and structural walls at the corners of the building without outriggers. The dimensions of all the structural elements hereafter for every model of the model sets are kept the same as that of model-3 of G+10 models except for structural walls. The dimension of the structural wall at the corners is of length 1.75 m. Figure 1e shows the terrace level plan for G+20 model without outrigger system.

Model 2:

Model 2 is a special moment resisting frame (SMRF) system with lift core walls symmetrically placed facing each other at the mid portion of the building and structural wall system at all the corners plus outriggers. The length of structural shear walls at the corners is 1.25m. Figure 1g shows the plan at the level of outrigger for G+20 model with outrigger system. Two outriggers are placed in this model at the height 1/3rd from top and bottom of the model, i.e. in between storey 7-8 and 15-16 . The width of the outrigger is 300 mm and height is 1.8 m. the

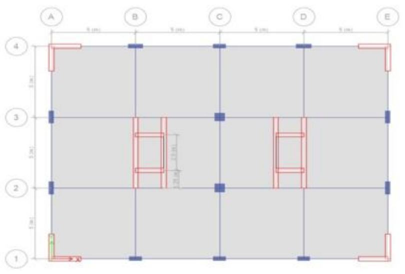


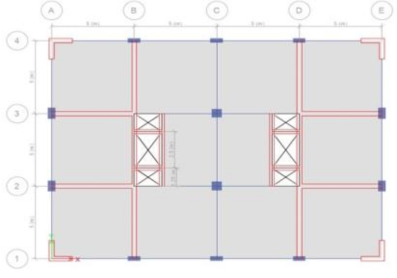


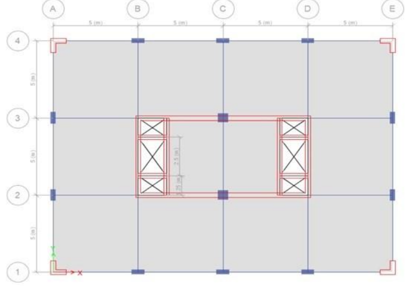


(c) G+10 model with SMRF + structural wall system + outrigger

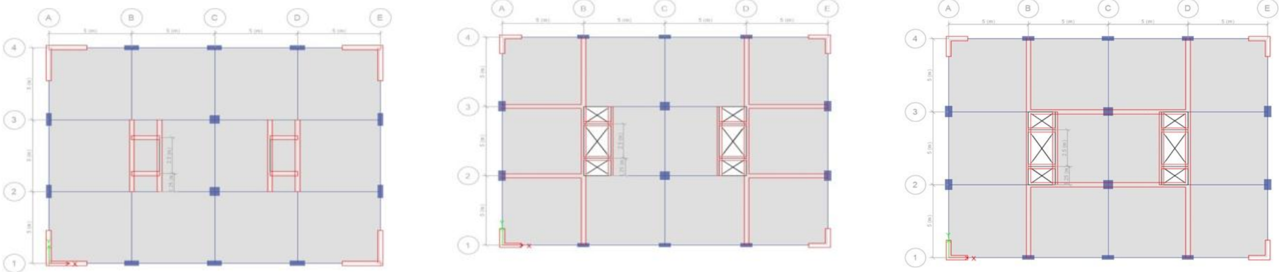
(a) G+10 model with OMRF(b) G+10 model with SMRF + structural wall system







(d) G+20 model with SMRF (e) G+20 model with SMRF + structural wall system
\+ (f) G+20 model with SMRF + structural wall
system + outriggers outrigger



(h) G+30 model with SMRF + structural wall system +(i) G+30 model with SMRF + structural wall system +
(g) G+30 model with SMRF
outriggers outrigger

Figure 1: Plan of all Models

outriggers are modeled and labeled as spandrel.

Model 3:

Model 3 is a special moment resisting frame (SMRF) system with lift core walls symmetrically placed facing each other at the mid portion of the building, structural wall system and outriggers. This model is similar to that of model 2 of G+20 model set except for the position of the outriggers within the level and eliminating the outriggers along Y-axis. The length of structural walls is further reduced to 0.75m from 1.25m as in model 2 of G+20 set.

2.4.3. G+30 models

Model 1:

Model 1 is a special moment resisting frame (SMRF) system with lift core walls symmetrically placed facing each other at the mid portion of the building and structural walls at the corners of the building without outriggers. The dimension of the structural wall at the corners is of length 2.3 m. This length of the structural walls at the corners of the model is adopted to satisfy the lateral stability of the structure, results for which will be discussed in chapter 4. Figure 1g shows the terrace level plan for G+30 model without outrigger system.

Model 2:

Model 2 is a special moment resisting frame (SMRF) system with lift core walls symmetrically placed facing each other at the mid portion of the building and structural wall system at all the corners plus outriggers. The length of structural shear walls at the corners is 1.2m. Figure 1h shows the plan at the level of outrigger for G+30 model with outrigger system. Two outriggers are placed in this model at the height 1/3rd from top and bottom of the model, i.e. in between storey 11-12 and 2122. The width of the outrigger is 300 mm and height is 1.8 m.the outriggers are modeled and labeled as spandrel.

Model 3

Model 3 is a special moment resisting frame (SMRF) system with lift core walls symmetrically placed facing each other at the mid portion of the building and structural wall system at all the corners plus outriggers. The length of structural shear walls at the corners is 1.2m. Figure 1i shows the plan at the level of outrigger for G+30 model with outrigger system with modified position of outrigger. Two outriggers are placed in this model at the height 1/3rd from top and bottom of the model, i.e. in between storey 11-12 and 21-22 . The width of the outrigger is 300 mm and height is 1.8 m. the outriggers are modeled and labeled as spandrel.

3. RESULTS AND DISCUSSION

3.1. Maximum deflection of horizontal member.

Figure 2a shows the short term, long term and total maximum horizontal deflection of G+10 Building models. The maximum deflection of all the models is less than the allowable maximum value of L/350 or 20 mm whichever is less. Figure 2b shows the short term, long term and total maximum horizontal deflection of G+20 Building models. The maximum deflection of all the models is less than the allowable maximum value of L/350 or 20 mm whichever is less. Model 1 has more deflection compared to Model 2 and 3.

Figure 2c shows the short term, long term and total maximum horizontal deflection of G+30 Building models. The maximum deflection of all the models is less than the allowable maximum value of L/350 or 20 mm whichever is less. Similar to G+20 building Model 1 performed poorly than Model 2 and 3.

3.2. Fundamental Time Period, and Modal Mass Participation Ratios

3.2.1. G+10 Building

For Model 1, Modal participation ratios in the first three modes along X and Y direction are 78.21% and 75.92% respectively and is greater than the permissible limit if 65% as per table -6 of IS – 1893: 2016. The time period of the first mode is 1.505 seconds and the permissible value is 0.1 x N (N= no. of floor levels) = 0.1 x 12 which is 1.2 seconds. Thus, it is clear that the structure with ordinary moment resisting frame has a greater time period than the permissible limit.

For Model 2, and 3 the modal participation ratios in the first three modes are greater than the permissible limit 65% The time period of the first mode is 1.081 seconds for Model 2 and 0.971 for Model 3 and the permissible value is 1.2 seconds, thus it is within the permissible limit and the structure with SMRF has improved stiffness when compared to OMRF

3.2.2. G+20 Building

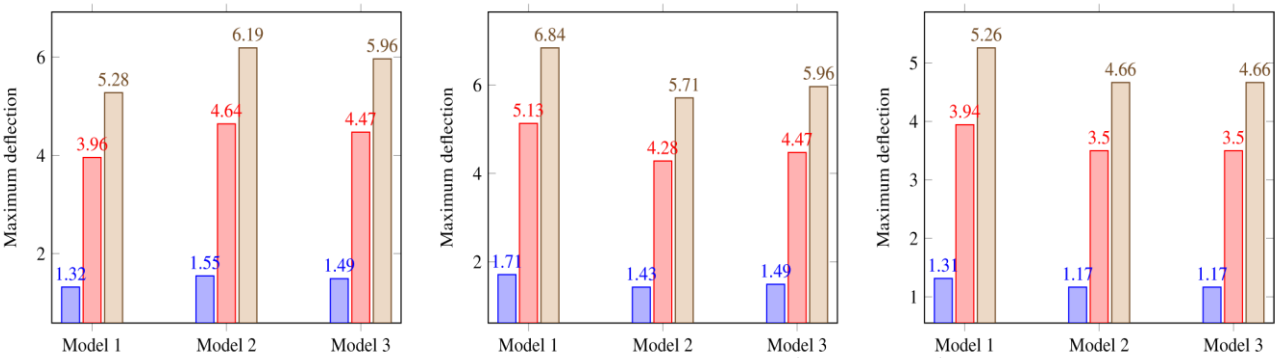
The modal participation ratios for all three models are greater than the permissible limit if 65%. The time period of the first mode is 2.206 seconds and the permissible value is 0.1*N (N= no. of floor levels) = 0.1*22 which is 2.2 seconds. The time period for structure with SMRF is slightly greater than the permissible limit. The time period of the first mode for Model 2 is 1.982 seconds and Model 3 is 2.003 which is less than the allowable limit 2.2 seconds.

3.2.3. G+30 Building

The modal participation ratios for all three models are greater than the permissible limit if 65%. The time period of the first mode is 3.186 seconds and the permissible value is 0.1*N (N= no. of floor levels) = 0.1*22 which is 3.2 seconds. The time period for structure with SMRF is within the permissible limit. The time period of the first mode is 3.293 seconds for both Model 2 and 3, thus it is within the permissible limit and the structure with SMRF + outrigger has improved stiffness when compared to SMRF.

3.3. Stability Checks

Table 1 shows all the stability parameters of all Models. All models pass the stability checks.



(a) Horizontal deflection of G+10 Building(b) Horizontal deflection of G+20 Building (c) Horizontal deflection of G+30 Building

Figure 2: Maximum Deflection of all Models

(a) Comparison of quantity of concrete for G+10 (b) Comparison of quantity of concrete for G+20 (c) Comparison of quantity of concrete for G+30

Table 1: Stability parameters for all Models

Criteria	G+10			G+20			G+30		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
Maximum lateral displacement or sway against earthquake									
Observed (in mm)	42.788	14.81	11.61	30.033	25.23	23.42	42.03	45.06	45.06
Allowable (in mm)	144	144	139.2	264	254.4	254.4	384	374.4	374.4
Maximum lateral displacement or sway against wind									

Observed (in mm)	33.65	17.188	11.626	71.44	56.12	52.61	164.55	176.63	160.63
Allowable (in mm)	72	72	69.6	132	127.2	127.2	192	187.2	187.2
Inter storey drift:									
Observed	0.0016	0.0005	0.000489	0.0006	0.000528	0.000505	0.002	0.0025	0.002447
Allowable	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004

3.4. Quantity of Concrete

Figure 3a shows the graph comparing the total quantity of concrete in terms of self-weight of the members (beams, columns, shear walls, slabs) of the framed structure for G+10 Models. The quantity of concrete required for models 2 and 3 is greater than that of model 1 and are proven to be uneconomical in terms of cost of concrete.

Figure 3b shows the same for G+20 Models. The quantity of concrete required for models 3 is much less than that of model 1 and 2 and is proven to be economical in terms of cost of concrete.

Figure 3c shows the same for G+30 Models. The quantity of concrete required for models 2 and 3 is much less than that of model 1 and is proven to be economical in terms of cost of concrete. Also from the above discussions for model set 3, modified outrigger position has shown improved values for parameters like drift, minimal lateral displacement, reduced time period, etc., and had an improved performance when compared to the other two models of the same set.

4. CONCLUSION

From the above discussions, it can be concluded that

1. Introduction of outriggers in high-rise buildings had shown a remarkable improvement in various structural parameters.
2. Outriggers are found to be economical for buildings of height greater than 50m.
3. As the height of the structure increases, wind plays a governing role as compared to earthquake in terms of lateral stability, horizontal displacement, storey drifts,
4. Optimal location and positioning of outrigger system had shown a decrease in natural time period of the structure.
5. Rearranging the outriggers within the optimal level of the structure can still improve the stiffness criteria of the building structure.
6. Well positioned outrigger system had brought down the self-weight of concrete of the whole structure, reducing the quantity of concrete in the construction of the building.

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