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ANALYSIS OF OUTRIGGER STRUCTURAL SYSTEM FOR HIGH-RISE BUILDING SUBJECTED TO EARTHQUAKE LOADS

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ABSTRACT

Designing a high rise building has its challenges. Different structural systems have been developed to control the lateral displacement of high rise buildings. One of these systems is called the outrigger which decreases both the horizontal movement of the structure and the moment on the foundation of the structure. However the location of the outriggers has an immense influence on the efficiency of the structure. Outrigger optimization is a significant challenge. The objective of this thesis is to give a better understanding of outrigger locations and its efficiency of each outrigger when several outriggers are used in the structure and the behavior of outriggers. Tall building development has been rapidly increasing worldwide introducing new challenges that need to be met through engineering judgment. In modern tall buildings, lateral loads induced by wind or earthquake are often resisted by a system of coupled shear walls. But when the building increases in height, the stiffness of the structure becomes more important and introduction of outrigger beams between the shear walls and external columns is often used to provide sufficient lateral stiffness to the structure.

The outrigger structural system is commonly used to control the excessive drift due to lateral load, so that, during small or medium lateral load due to either wind or earthquake load, the risk of structural and nonstructural damage can be minimized. For high-rise buildings, particularly in seismic active zone or wind load dominant. In this study two structural systems were considered, moment resisting frame system (bare frame) and outrigger structural system (with four configurations). A 40 story high rise building is modeled and performed analysis in ETABS 2017 software for all models and the results were compared in terms of lateral displacement, story drift and base shear.

KEYWORDS: Outriggers, High Rise Buildings, Earthquake Load, Wind Load, Outrigger Location, Base Shear, Story Drift, ETABS.

INTRODUCTION

Civil engineers strive to build higher buildings. However, some constraints keep them from building infinitely tall buildings. One of these restrictions is that the lateral displacement of the building limits the height of the building. Structural engineers have come up with innovative designs throughout history to decrease the lateral movement of tall buildings. One of these innovative designs is the bracing system. However as the building height exceed 30-40 stories this method becomes too expensive. Therefore engineers have developed other designs. One example is the belt truss system, also known as the core-outrigger system. In this method the structural engineers use a "hat" or "cap" truss to tie the core to the exterior columns (Figure 1.1). This method is mostly used against wind loading. One of the main advantages of the outrigger system is that it puts a limit on the lateral displacement of the building. In addition it will decrease the overturning moment of the building which will also decrease the cost of its columns and its foundation. Therefore this system is definitely an efficient way of material use. A structure with outriggers will have 30 to 40 percent less overturning moment in the core compared to a free cantilever in addition to having less drift.

This structural system includes a core in the middle of the building (braced frames or shear walls) with horizontal trusses cantilevered from the central core. One can see there are different types of outrigger systems. They can have a concrete core or a truss core. The other components of the outrigger system are also varied. They can be trusses, mega bracings or girders (the forces are carried by the moment connections to the core). The core is used to resist horizontal shear and the outriggers are used to transfer the vertical shear to the exterior columns. With proper placing of the outriggers, the flexural capacity of the building increases but the shear capacity remains the same, since the core mainly has to carry the shear. The outriggers can be on one or both sides of our structure. The exterior columns will cause a moment in the opposite direction of the moment in the core which is induced by the external loading. This results in a smaller moment in the core at the base than a free cantilever.

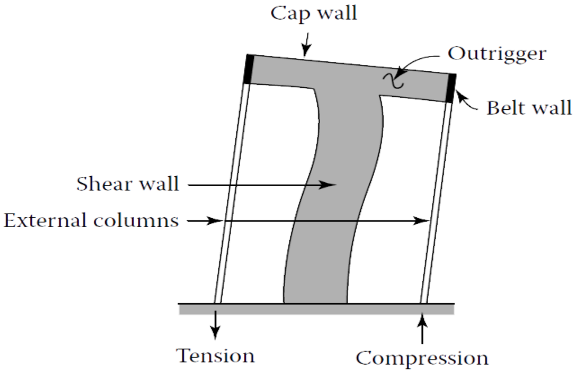
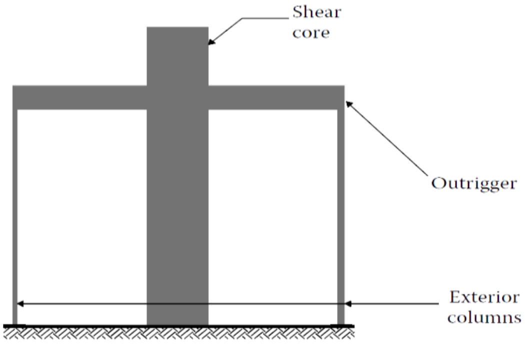


Fig. cap wall system



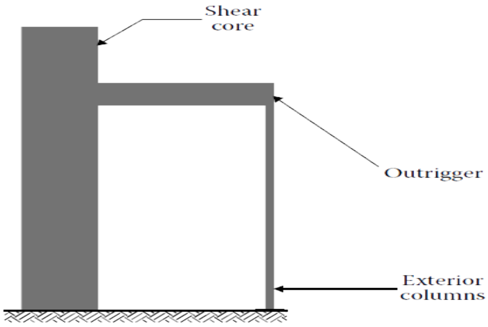


Fig. outriggers at both ends of core and outrigger with an offset core

OUTRIGGER EXISTENCE

Recently many tall buildings incorporate a core in the middle of the structure to accommodate elevators. This requires the core to tolerate horizontal loading applied on the structure. This is inefficient after exceeding a certain amount of stories. The resistance that the core system provides to the overturning component of the drift decreases approximately with the cube of the height, showing that as the height of the structure increases the core system becomes more inefficient. Also the core structure alone can generate excessive uplift causing the foundation cost to exceed economic amounts. For example because of uplift the foundation has to be a mat or rock anchors instead of simple foundation alternatives. Another aspect of interest to architects is that they want space between the core and the exterior columns for free rentable space. These two reasons added up and made the structural engineers to create the outrigger solution which incorporates the exterior columns in the lateral structural system.

OUTRIGGER PERFORMANCE

The outrigger acts like a rotational spring on top of the structure (the main purpose of an outrigger is to reduce the rotation of the core). By creating a resisting moment it decreases the moment in the core and the lateral movement of the core. The amount of reduction in the drift is a function of the building's property. The magnitude of this reduction is dependent on

- The flexural rigidity of the core
- The flexural rigidity of the outriggers
- The location of the outriggers up the height of the core
- The axial force of the columns about the centroid of the core

EXAMPLES OF OUTRIGGER SYSTEM

The First Wisconsin Center

The First Wisconsin Center is shown in the figure below. The building is 42 stories and 1.3 million square feet (120,770 meter square). The height of the building is 601 ft. (183 m). The building is used as a bank and an office space. It has three belt trusses which are located at the bottom, middle and top of the building. The belt truss located at the bottom of the structure acts as a transfer truss but the belt trusses located at the top and the middle of the structure act as outriggers. The mechanical equipment is located at the outrigger floor. This system was selected by the engineers and architects to create a light-open-frame type structure on the exterior with columns six meters apart along the perimeter. The frame is continuous with belt trusses which are expressed architecturally on the exterior. Engineers reported a 30% increase in overall lateral stiffness through the utilization of the outrigger and belt trusses. The architectural design was done by the Chicago office of Skidmore, Owings & Merrill.

One Houston Center

This building is located in Houston Texas. It has 48-strories. The total height of the building is 681 ft. (207.5 m). It has a 2-story outrigger between the 3 3rd story and 3 5 the story. Because of the facade the outriggers cannot be seen, however a picture of the K-braced outrigger is shown in figure 1.5. The use of outriggers has enabled the engineers to decrease the drift to - where H is the total 460 height of the structure

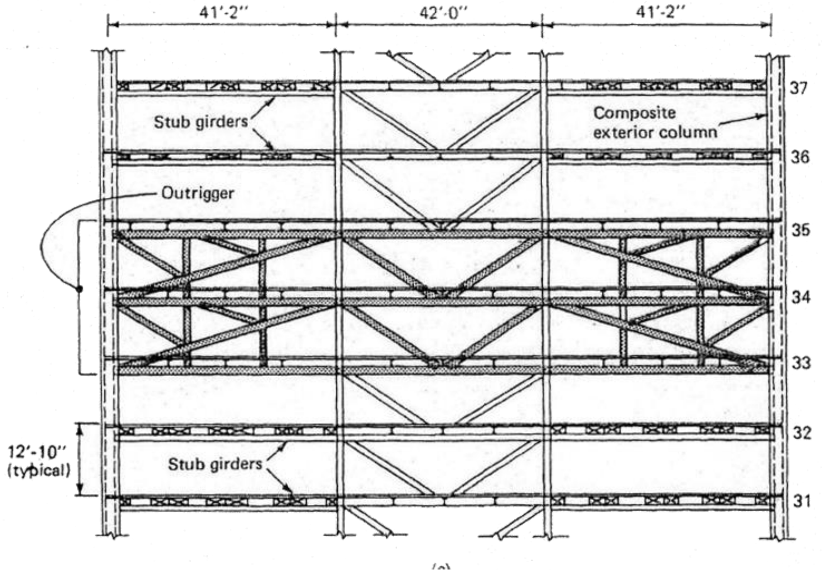


Fig. Schematic elevation view of the One Houston Center

STRUCTURAL CONCEPT OF TALL BUILDING

Although shape plays a major part in how the building acts under wind and seismic loads, few engineers are given the opportunity (and rightly so, otherwise all of our buildings would be prismatic and either square or round) to influence the shape of the building. Instead, their role is limited to optimizing the structure for the specific form that the architect and the owners provide the core idea in conceptualizing the structural system for a narrow tall building is to think of it as a cantilevering column from the earth (see Fig. A). The laterally directed force produced, either by wind blowing against the structure or by the inertia forces caused by floor shaking, tends to snap it (shear) and push it over (bending). The structure must, therefore, have a system for both shear resistance and bending. The building must not break by shearing off in resisting shear forces (see Fig. B), and generally must not strain beyond the elastic recovery limit. Similarly, the system that resists bending must satisfy three requirements (see Fig. C). is

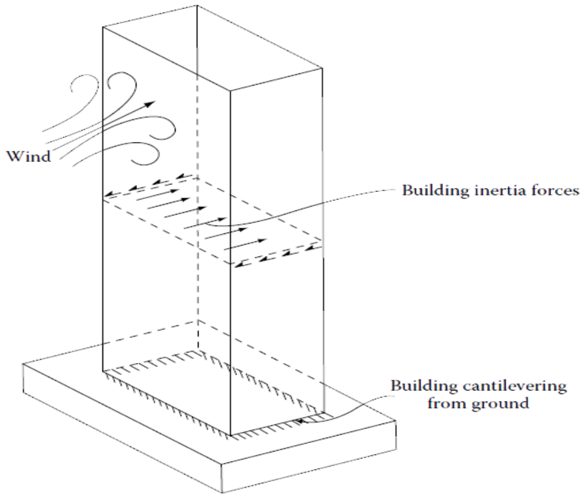
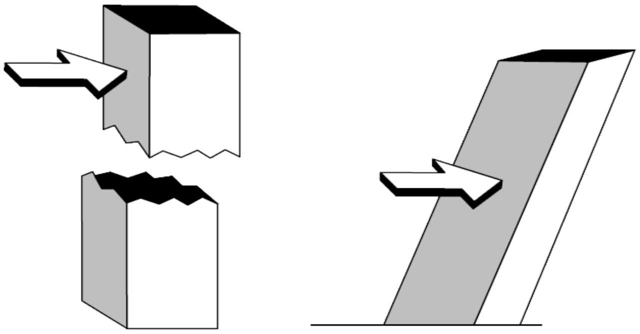


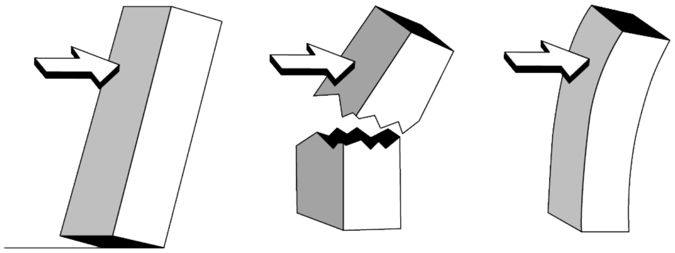
Fig. A. structural concept of tall building

The building must not overturn the combined forces of gravity and lateral loads due to wind or seismic impacts; it must not break through early column failure either by crushing or excessive tensile forces; and its bending deflection, in particular, should not exceed the elastic recovery limit.



(a) (b)

Fig. B. building shear resistance: (a) building must not break and (b) building must not have excessive shear deflection .



(a) (b) (c)

Fig. C. Bending resistance of building: (a) building must not overturn, (b) columns must not fail in tension or compression, and (c) bending deflection must not be excessive.

In addition, a building in seismically active areas must be able to withstand the forces of the earthquake without losing its vertical load carrying capacity. A tug-of-way sets the building in motion in the resistance of the structure to bending and shear, thus generating a third engineering issue: movement perception or vibration. If the building drifts and accelerates quite so much, human comfort is sacrificed, or more importantly, non-structural components can break, leading in costly deformation to the building contents and endangering the pedestrians. An ideal structural system to withstand the impacts of bending, shear, and excessive vibration is a system with vertical continuity ideally situated at the far end of the building's geometric middle. A concrete chimney is perhaps an ideal, if not an inspirational engineering model for a rational super-tall structural form. The search for the best solution is to translate the optimal shape of the chimney into a more practical skeletal structure.

OUTRIGGER STRUCTURAL SYSTEM

The core may be considered as a single-redundant cantilever with the rotation restrained at the top by the stretching and shortening of windward and leeward columns. The resultant of these forces is equivalent to a restoring couple opposing the rotation of the core. Therefore, the cap wall may be conceptualized as a restraining spring located at the top of the shear core. Its rotational stiffness may be defined as the restoring couple due to a unit rotation of the core at the top.shape plays a major part in how the building acts under wind. Since the equivalent spring stiffness is calculated for unit rotation of the core (i.e., $\theta = 1$), the axial deformation of the equivalent columns is equal to $1 \times d/2 = d/2$ units.
The corresponding axial load is given by

$$P = \frac{AEd}{2L}$$

Where,
P is the axial load in the column
A is the area of column
E is the modulus of elasticity
d is the distance between the exterior columns (d/2 from the center of core to exterior columns)
L is the height of the building

DEFLECTION CALCULATION:

Outrigger wall at the top

The rotation compatibility condition at $z = L$ (see Figure D) can be written as $\boldsymbol{\theta_w - \theta_S = \theta_L}$

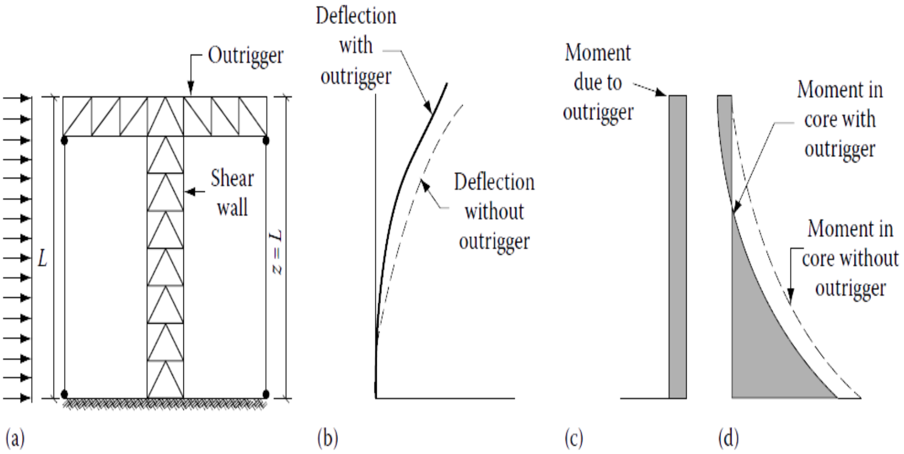


Fig. D. Outrigger located at top, z = L

θ_w is the rotation of the cantilever at $z = L$ due to a uniform lateral load W (rad)
θ_S is the rotation due to spring restraint located at $z = L$ (rad). The negative sign for θ_S in Equation indicates that the rotation of the cantilever due to the spring stiffness is in a direction opposite to the rotation due to the external load
θ_L is the final rotation of the cantilever at $z = L$ (rad)
For a cantilever with uniform moment of inertia I and modulus of elasticity E subjected to uniform horizontal load W

$$\theta_w = \frac{wL^3}{6EI}$$

Outrigger Wall at Quarter-Height from the Top

The general expression for lateral deflection *y*, at distance *x* measured from the top for a cantilever subjected to a uniform lateral load (see Figure 3.2) is given by

$$y = \frac{W}{24EI}(x^4 - 4L^3x + 3L^4)$$

Note that *x* is measured from the top and is equal to (L - z).
Differentiating the Equation above, with respect to *x*, the general expression for the slope of the cantilever is given by

$$\boldsymbol{\frac{dy}{dx} = \frac{W}{6EI}(x^3 - L^3)}$$

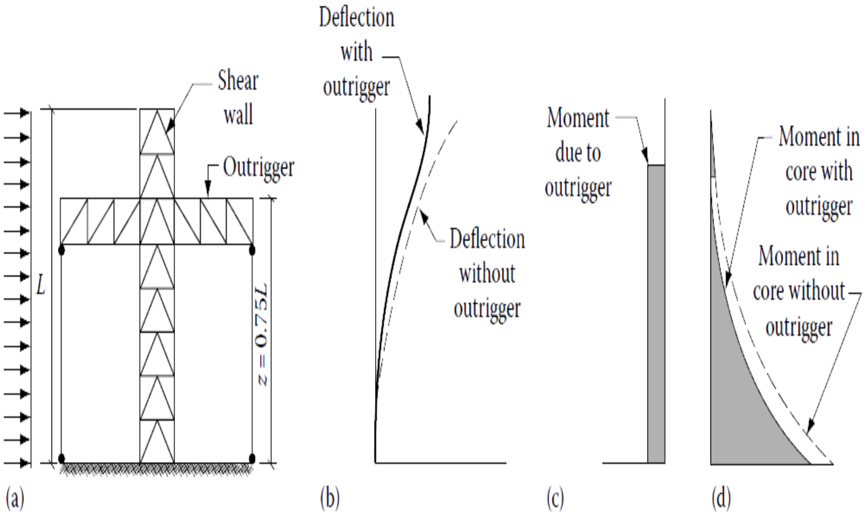


Fig.E. Outrigger at quarter-height from top, z = 0.75L

Outrigger wall at mid height

The rotation at z = L/2 due to external load W (see Figure F) can be shown to be equal to $7WL^3/48EI$, resulting in the rotation compatibility equation

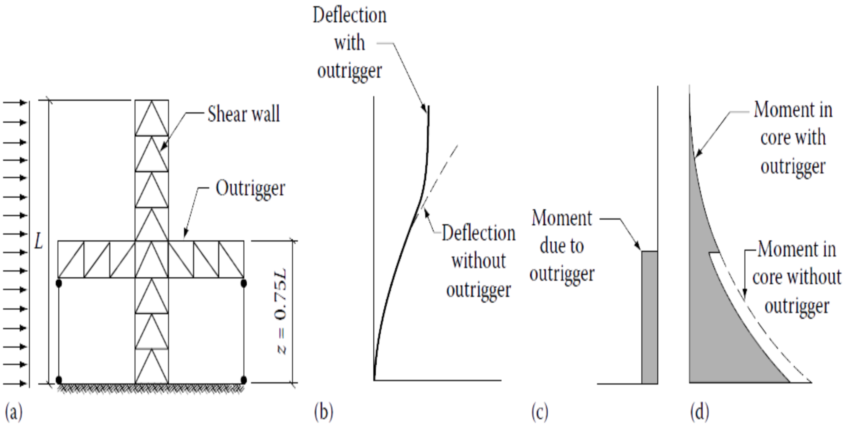


Fig. F. Outrigger at mid height z=0.5L

Location Of Outrigger

Location of Single Outrigger

The preceding analysis has indicated that the beneficial action of outrigger is a function of two distinct characteristics: (1) the stiffness of the equivalent spring; and (2) the magnitude of the rotation of the cantilever at the spring location due to lateral loads. The spring stiffness, which is a function of column length below the outrigger location, varies inversely as the distance of the outrigger from the base. For example, the stiffness is at a minimum when the outrigger is located at the top and a maximum when at the bottom. On the other hand, the rotation, 0, of the free cantilever subjected to a uniformly distributed horizontal load varies parabolically with a maximum value at the top to zero at the bottom. Therefore, from the point of view of spring stiffness, it is desirable to locate the outrigger at the bottom, whereas from consideration of its rotation, the converse is true. It must therefore be obvious that the optimum location is somewhere in between. To search for the optimum location of a single outrigger, we start with the following assumptions:

1. The building is prismatic and vertically is uniform; that is, the perimeter columns have a constant area and the core has a constant moment of inertia for the full height.
2. The outrigger and the belt walls/truss are flexurally rigid.
3. The lateral resistance is provided only by the bending resistance of the core and the tie- down action of the exterior columns.
4. The core is rigidly fixed at the base.
5. The rotation of the core due to its shear deformation is negligible.
6. The lateral load is constant for the full height.
7. The exterior columns are pin-connected at the base.

Consider a 40 storey high rise building as shown in Figure 3.5, which shows schematics of a single outrigger located at a distance x from the building top. To evaluate the optimum location, first the restoring moment M_x of the outrigger located at x is evaluated. Next, an algebraic equation for the deflection of the core at the top due to M_x is derived. Differentiating this equation and equating a zero results in a third-degree polynomial, the solution of which yields the outrigger optimum location corresponding to the minimum deflection of the building at top due to external load. The details are as follows.

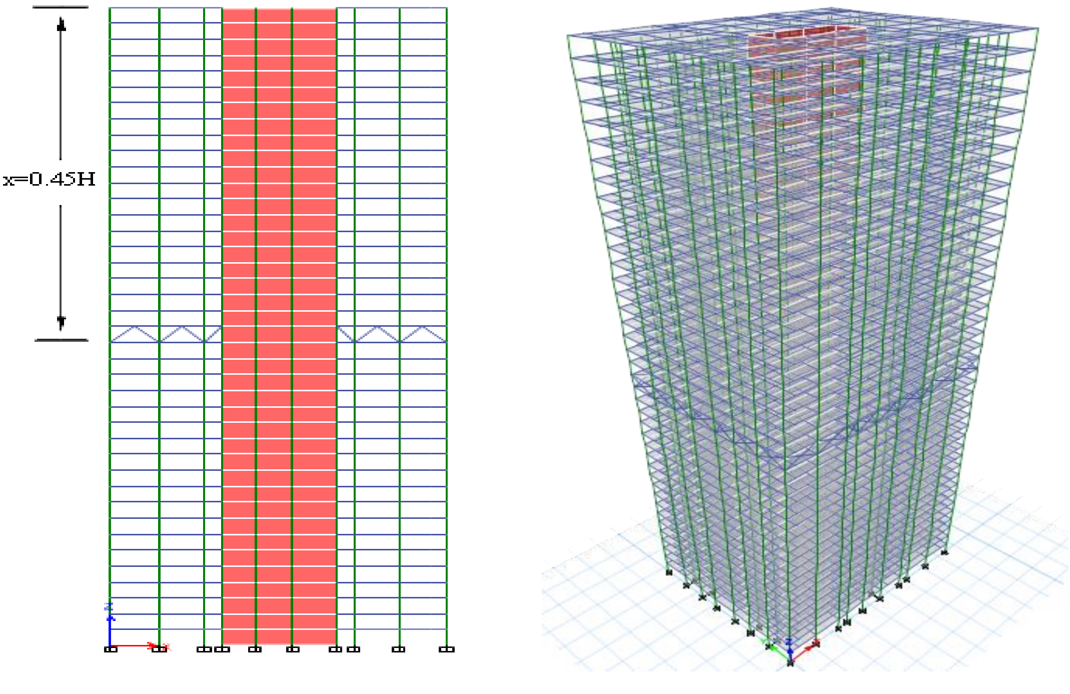


Fig.G. Outrigger at distance x from top

Location of Multiple Outriggers

Based on conceptual study presented thus for, the following recommendations are made for optimum locations for outriggers. As stated previously the primary purpose to minimize the lateral drift

- The optimum location for a single outrigger is, perhaps unexpectedly, not at the top. The reduction in the drift with the outriggers located at top is about 50%, as compared to a maximum of 75% achievable by placing it at approximately mid height. However, since other architectural requirements take precedence in a structural layout, the benefits of placing a truss at the top are still worth pursuing.

- A two-outrigger structure appears to offer more options in the placements of outriggers. Reductions in building deflections close to the optimum results may be achieved with outriggers placed at levels entirely different from the optimum locations. Thus, the engineer and architect have some leeway in choosing the outrigger locations. However, as a rule of thumb, the optimum location for a two-outrigger structure is at one-third and two-third heights. And for a three outrigger system, they should be at the one-quarter, one-half, and three-quarter heights, and so on. Therefore, for the optimum performance on an outrigger structure, the outriggers should be placed at (l/n + 1), (2/n + 1), (3/n + 1), (4/n + 1)…. (n/n + 1) height locations.For example, in a 40-story building with four outriggers (i.e., $n = 4$), the optimum locations are at the 8th, 16th, 24th, and 32nd levels. A summary of the recommendations is shown in Figure H.

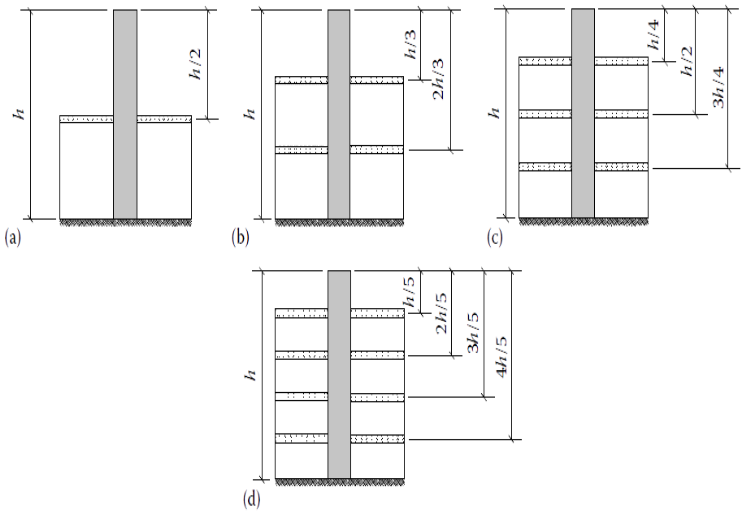


Fig. H. Optimum location of outriggers, (a) single outrigger, (b) two outriggers, (c) three outriggers, and (d) four outriggers.

STRUCTURAL PLANNING

Plan: Preliminary design sections were considered in the RCC 40 storied high rise building for the analysis as an initial trial. Some of the sections were changed due to over stress in the members after performing the design check. Columns from basement to third story are changed from 700mmx700mm to 800mmx800mm, and beams which are framing into the shear core columns are changed from 300mmx700mm to 500mmx800mm and 500mmx900mm are shown in Fig. I

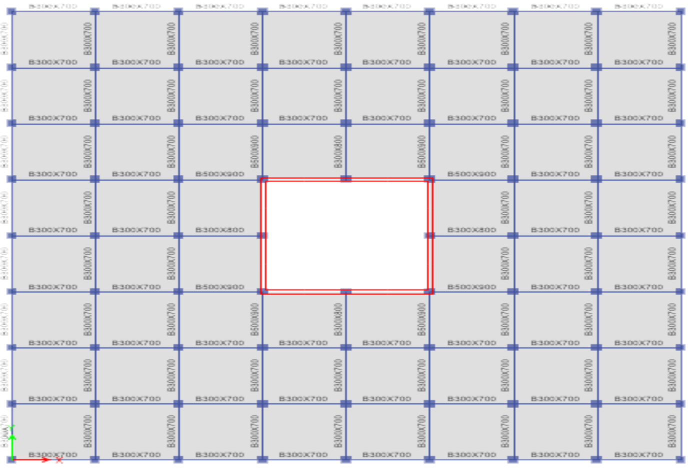


Fig. I. plan layout of beams

Bare Frame: The MRF structural configuration consists of Shear walls placed around building services such as elevators and stair cores instead of RCC beams. This type of system can be considered as a spatial system capable of transmitting lateral loads in both directions. The advantage is that, being spatial structures, they are able to resist shear forces and bending moments in two directions and also torsion particularly. The shape of the core is typically dictated by the elevator and stair requirements and can vary from a single rectangular core. A 3D view and elevation of grid 4 are shown in figure J

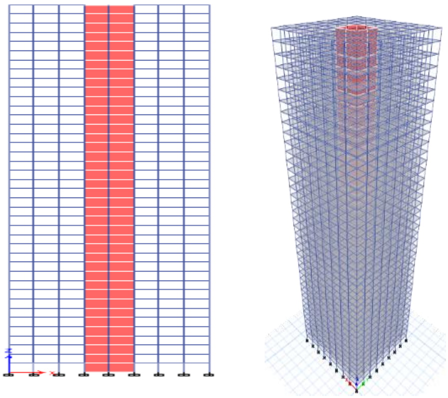


Fig. J elevation of grid 4 and 3D view of moment resisting frame with shear core

Single Outrigger Structural System model:

The structural configuration of this model is similar to that of the Moment resisting frame (bare frame), the only change is the addition of outriggers and perimeter belt truss at 20th storey. The outrigger arms extends from the shear core to perimeter columns in horizontal grids 4 & 6 and vertical grids D & F. A 3D view and elevation of grid 4 are shown in figure K

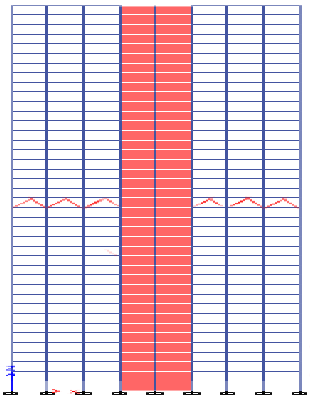


Fig. K . Elevation of grid 4 and 3D view of single outrigger system model

Two Outrigger Structural System Model:

The structural configuration of this model is similar to that of the Moment resisting frame (bare frame) the only change is the addition of outriggers and perimeter belt truss at 14th and 27th stories. For both stories the outrigger arms extends from the shear core to perimeter columns in horizontal grids 4 & 6 and vertical grids D & F. A 3D view and elevation of grid 4 are shown in figure L

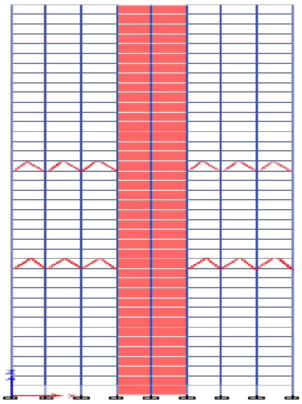


Fig. L. Elevation of grid 4 and 3D view of two outrigger system model

Three Outrigger Structural System Model:

The structural configuration of this model is similar to that of the Moment resisting frame (bare frame) the only change is the addition of outriggers and perimeter belt truss at 10th, 20th and 30th stories. For three stories the outrigger arms extends from the shear core to perimeter columns in horizontal grids 4 & 6 and vertical grids D & F. A 3D view and elevation of grid 4 are shown in figure M

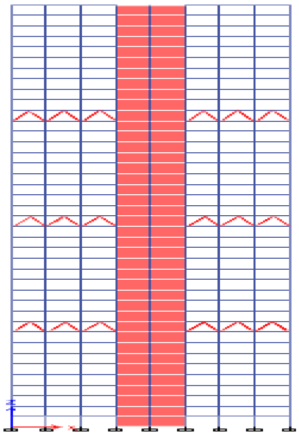


Fig. M. Elevation of grid 4 and 3D view of three outrigger system model

Four Outrigger Structural System Model:

The structural configuration of this model is similar to that of the Moment resisting frame (bare frame) the only change is the addition of outriggers and perimeter belt truss at 8th, 16th, 24th and 32nd stories. For four stories the outrigger arms extends from the shear core to perimeter columns in horizontal grids 4 & 6 and vertical grids D & F. A 3D view and elevation of grid 4 are shown in figure N

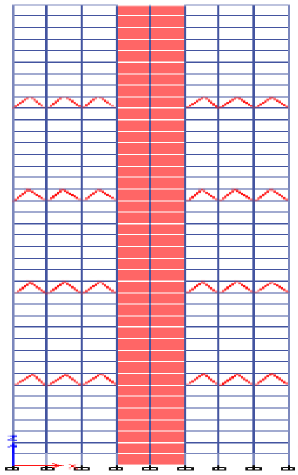


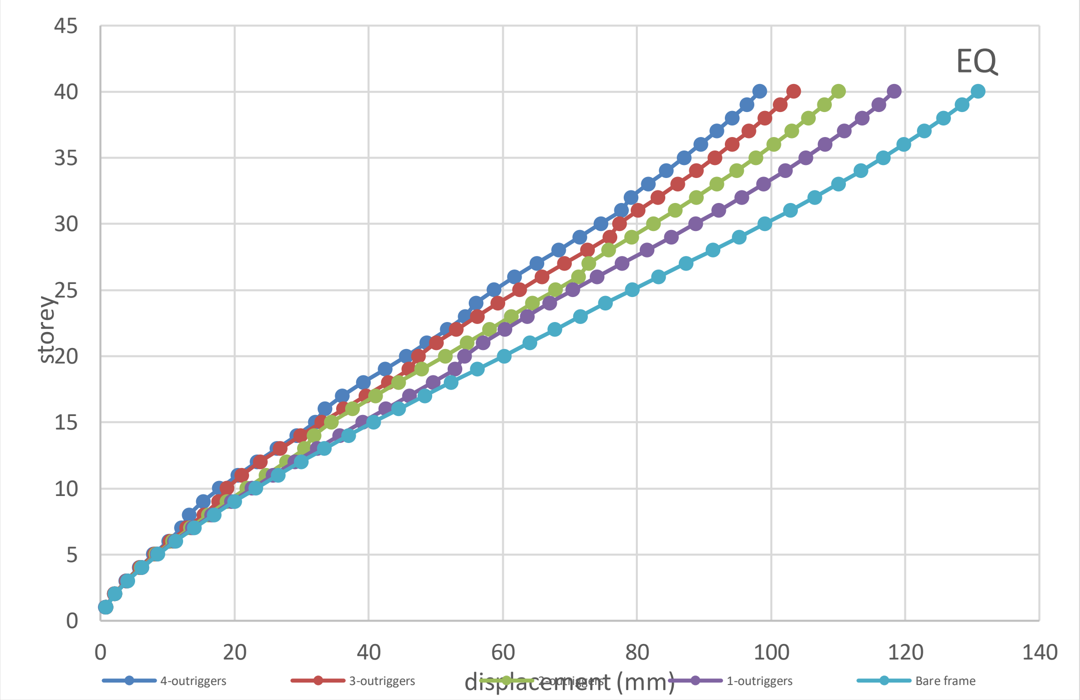
Fig. N. Elevation of grid 4 and 3D view of four outrigger system model

RESULTS AND DISCUSSIONS:

Lateral Displacement: Story displacement is the absolute value of displacement of the storey under the action of lateral forces. Based on the method of analysis considered, lateral load calculations are made by the software itself. The total displacements obtained from the analysis and the values are presented for 40 stories in tables 5.1 for static earthquake loads in X and Y since, the plan is symmetric in both directions results displayed for one direction only. From the comparison of lateral displacement between bare frame and four outrigger models the bare frame holds the maximum top story displacement among the five models. A 55% top storey displacement reduction is observed in the comparison between bare frame and single outrigger model, 58% with two outrigger model, 61% with three outrigger model and 63% with four outrigger model under the action of static earthquake loads in both direction. The four outrigger model shows the best performance in top story displacement than other structural configuration models.

Table: Story displacement under static earth quake loads for all models

EQ					
Displacement (mm)					
Story	bare frame	1 outrigger	2 outrigger	3 outrigger	4 outrigger
Story40	130.8	118.29	109.98	103.33	98.27
Story39	128.4	116.05	107.89	101.32	96.34
Story38	125.67	113.51	105.52	99.05	94.16
Story37	122.79	110.83	103.01	96.65	91.86
Story36	119.79	108.02	100.39	94.15	89.46
Story35	116.65	105.1	97.65	91.54	86.97
Story34	113.39	102.04	94.8	88.83	84.37
Story33	109.99	98.87	91.84	86.03	81.61
Story32	106.46	95.58	88.78	83.13	79.07
Story31	102.82	92.18	85.63	80.08	77.67
Story30	99.07	88.68	82.42	77.35	74.57
Story29	95.22	85.1	79.14	75.88	71.41
Story28	91.29	81.45	75.78	72.55	68.24
Story27	87.28	77.76	72.81	69.16	65.02
Story26	83.2	74.03	71.26	65.77	61.74
Story25	79.23	70.43	67.83	62.47	58.66
Story24	75.3	66.92	64.4	59.22	55.96
Story23	71.53	63.58	61.18	56.13	54.35
Story22	67.74	60.25	57.94	53.02	51.65
Story21	63.95	57.05	54.67	50.04	48.65
Story20	60.17	54.27	51.37	47.4	45.61
Story19	56.16	52.84	47.85	45.99	42.37
Story18	52.21	49.57	44.39	42.9	39.14
Story17	48.3	46	40.96	39.52	36.04
Story16	44.44	42.49	37.57	36.22	33.4
Story15	40.65	39.04	34.4	32.99	32.04
Story14	36.95	35.63	31.77	29.83	29.25
Story13	33.36	32.28	30.39	26.76	26.25
Story12	29.86	28.98	27.7	23.76	23.32
Story11	26.45	25.74	24.7	21.07	20.47
Story10	23.15	22.59	21.75	18.81	17.72
Story9	19.96	19.53	18.87	17.6	15.25
Story8	16.88	16.55	16.05	15.38	13.17
Story7	13.94	13.69	13.34	12.86	12.07
Story6	11.15	10.98	10.73	10.37	10.1
Story5	8.55	8.44	8.27	8.02	7.86
Story4	6.16	6.09	5.99	5.83	5.71
Story3	4	3.97	3.91	3.82	3.75
Story2	2.13	2.12	2.1	2.07	2.05
Story1	0.75	0.74	0.74	0.74	0.73



Graph: comparison of story displacement under static earthquake loads for all models

CONCLUSIONS

This study assessed the overall behaviour of outrigger braced building under lateral loads from which the following conclusions can be drawn based on the results

- Outrigger braced tall building is considered as one of the most popular and efficient tall building design because they are easier to build, save on costs, and provide massive lateral stiffness.
- The optimum location for a one-outrigger structure is at mid height, two-outrigger structure is at one-third and two-third heights, for a three outrigger system, they are found to be at the one-quarter, one-half, and three-quarter heights and for four-outrigger structure is at one-fifth, two-fifth, three-fifth and four-fifth heights.
- With the implementation of outrigger systems, factors such as base shear, displacement and story drift of the structure during an earthquake are lowered, hence reducing the size of structural elements, results in an economic construction
- Numerical study was conducted on a 40 storied RCC high rise building for five models out of which one structures is moment resisting frame system (bare frame) and the other four models are with outrigger configuration such as one-outrigger structure, two- outrigger structure, three-outrigger structure and four-outrigger structure. It is observed that the four-outrigger structure shows superior performance among the other structures in terms of story drift and displacement, since it is confirmed to the safety limits described in IS 1893 (Part I): 2002

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