# OPTIMUM LOCATION OF VIRTUAL OUTRIGGER STRUCTURAL SYSTEM IN HIGH RISE BUILDINGS

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***Abstract:***

*This paper represents the outrigger structural system with importance of virtual outrigger structural system for high rise buildings. Thus, to improve the performance of the building under seismic loading, this system can prove to be very effective. The paper tries to establish advantages of virtual system over others. In this paper design and study of virtual outrigger system for 50,60 and 70 storey high rise building with different outrigger system like one outrigger system, double outrigger system and three outrigger system for more details. The paper also gives the results for lateral displacement ,base reaction ,storey drift and overturing momemntfor wind and seismic load.*

**Keywords -*Lateral loads resisting buildings, conventional outrigger, virtual outrigger, seismic load, wind load, lateral displacement, and storey drift,base reaction, overturning moment***

## I. INTRODUCTION:

### 1.1.1 Introduction to Tall Buildings

The definition or perception of 'tall building' varies from person to person as it varies with region and locality. A 10 storey building of 40 m height in New York might not be considered as a tall building, since the average height of buildings in the city of New York is 140 m. But a 5 storey building in a country -side might appear to be a tall building. "Skyscrapers", "high-rise buildings" or "tall buildings" are complex to define and distinguish only from a dimensional point of view because height is a relative matter that changes according to place and time. There is no general standard on the height or number of storeys above which buildings should be classified as tall buildings or skyscrapers which can be accepted uniformly across the globe.

According to the CTBUH (Council on Tall Buildings and Urban Habitat), the architectural/structural height of a building is measured from the open-air pedestrian entrance to

the top of the building, ignoring antennae and flagpoles. With this reference;

- Buildings of 14 storeys or 50 meters height and above are considered as 'tall buildings'
- Buildings of 200 meters height and above are considered as 'super-tall buildings', and
- Buildings of 300 meters height and above are considered as 'mega-tall buildings'.

The tall buildings have had a fascinating history – from the Pyramids of Egypt of the $14^{th}$ century to the sky scrapers we see today – tall buildings have undergone a massive transformation in terms of design, shape, configuration and construction techniques and materials. Of course the skills, knowledge and vision of architects and engineers cannot be negated in any of the generations.

Tall buildings are definitely a need in today's urbanized world; but as the vertical dimension of the building increases, so does a number of challenges for architects as well as structural Engineers.Increased heights means increased vertical as well as lateral loads. Any viable structure should base efficient design, structural stability, occupational serviceability and mate material economy as the principles for construction.

**1.1.2 Structural Systems for Tall Buildings**

In the early twentieth century, buildings were designed to mainly resist vertical loads. But with the increasing heights, consideration of the impact of lateral loads on the structural stability and serviceability of the building became imperative. Wind and earthquake induced lateral loads are primary loads which pose more threat in high rise buildings than in small or medium height buildings. As a result, for structural engineers, providing the strength to resist lateral loads in tall buildings, whether wind or earthquake induced, has become an essential input in the design of new structural systems.

As the height of buildings increases, the choice of structural system decreases. While the choice of structural system in low-rise buildings is considerable, the alternatives in choice of a structural system become restricted by limitations imposed by the height of buildings. Therefore, especially in tall building s, architectural and structural design should be considered together.

Tall buildings can be designed using the following structural systems:

- Rigid frame systems
- Flat plate/slab systems
- Core systems
- Shear wall systems
- Shear-frame systems
- Mega column (mega frame) systems
- Mega core systems
- Outriggered frame systems
- Tube systems

## II.LITERATURE REVIEWS

**2.1 Introduction**

The need for Tall building constructions has been astonishingly increasing worldwide to accommodate the rapidly growing population, to facilitate trade and commerce and as a mark of social status and power of a region. New advancements have made possible the erection of tall buildings with light-weight components and faster modes of construction. The design of tall structure is usually governed by the lateral loads imposed on the structure – namely wind load and earthquake load. As building gets taller, the structural engineers have been increasingly challenged to achieve structural safety under lateral wind load. Also, at seismically active zone, earthquake safety is a major concern. The outrigger structural system has been in use since past few decades and has proven to be satisfying the structural requisites of tall building in terms of safety, serviceability as well as economy.

Successful projects have been built with the outrigger concept. A lot of research has been done in the typologies, materials and placing of outriggers. Also, many researchers have studied and analyzed the optimum location of outrigger beams and belt truss in structural system depending upon the number of outriggers and the height of the building. This chapter aims at summarizing the various investigations by the researchers and their deductions in the scope of positioning of the outrigger. The objective of the literature review is to be accustomed with the current trends in optimum location of outriggers in tall buildings. In 1991, Smith and Coull, by made a hypothetical assumption. that the outriggers are flexurally rigid, and devised for the optimum performance of an n-outrigger structure, that the outriggers should be placed at 1/(n+1), 2/(n+1), up to the n/(n+1) height locations, i.e. for a one -outrigger structure at approximately half-height, for a two-outrigger structure at approximately one-third and two-thirds heights, for a three-outrigger structure at approximately one-quarter, one-half and three-quarter heights, and so on. Andrew J. Horton later commented that these findings also hold true for the subsequently discussed offset, alternative offset and virtual outrigger systems under similar simplifying assumptions.

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**Andrew J. Horton**, in his research paper titled 'Virtual Outriggers in Tall Buildings' gave an elaborated overview of Outriggers: Conventional, Offset and Alternative offset. Mr. Nair later coined the term 'Virtual outrigger' for alternative offset outriggers. Horton's paper explains the evolution of Conventional outriggers as well as offset and virtual outriggers and also how they have been successfully used in world's iconic buildings. The paper also gives comparison of the three systems of outriggers – Conventional, Offset and Virtual Outriggers – and gives suitable real life examples for each. The paper concludes that virtual outriggers can be used with same efficiency as conventional outriggers when efficiently proportioned perimeter belt truss and floor diaphragms are used.

**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 system. The two ways of using virtual outrigger: belt truss as virtual outrigger and use of basement walls as virtual outrigger are explained. The paper also gives example of Plaza Rakyat Tower (under-construction) in Kuala Lumpur, Malaysia which has two virtual outriggers and a conventional outrigger at top storey - to resist lateral loads. The paper then compares the lateral displacement caused due to wind load for a 75 – storied model building using design loads in accordance with the City of Chicago Building Code and using GTSTRUDL computer program. The following results are obtained:

- Lateral displacement in case of no outrigger : 108.5 inch (2.75 m)
- Lateral displacement in case of conventional outrigger : 25.3 inch (0.64 m)
- Lateral displacement in case of belt truss as virtual outrigger : 37.1 inch (0.94 m)
- Lateral displacement in case of belt truss as virtual outrigger : 31.0 inch (0.78 m) with 10 fold increase in floor diaphragm stiffness
- Lateral displacement in case of belt truss as virtual outrigger : 26 inch (0.66 m) with 10 fold increase in floor diaphragm and belt truss stiffness

The paper proposes the use of virtual outriggers over conventional outriggers owing to the wide range of advantages and convenience offered by the former.

**Po Seng Kian and Frits Torang Siahaan (2001)** presented a paper on the use of outrigger and belt truss system in high rise concrete buildings of 40 storey and 60 storey subjected to wind and earthquake loads. The basic wind speed of 32 m/s was used and calculations done on the basis of CP3 – British Standard and the earthquake load was obtained using Indonesian response spectra zone 4. The GT-Strudl package program was used to analyze wind load and ETABS software selected to perform static and dynamic analysis of earthquake loads. Results were obtained for both the models by locations outriggers at different locations. The paper concluded that the use of outrigger and belt-truss system in high rise buildings increased the stiffness and made the structural form efficient under lateral loads.

**J. R. Wu and Q. S. Li (2003)** presented designs of multi-outriggers in tall buildings and also gave an elaborate description for understanding of the structural performance of outrigger -braced frame-core structures. The paper studies the influences of outriggers and other structural element stiffness on the base moment in core, top drift and fundamental vibration period. A non -linear optimum design procedure for reducing the base moment in the core is presented based on penalty function method. The paper presents numerical equations for analysis multi-outrigger systems subjected to uniformly distributed load and horizontal triangular loads and determining optimum core dimensions. Variation in optimum location for outrigger braced structure subjected to uniform and triangular load is determined.

**Z. Bayati, et al (2008)** gave light on the use of 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 in Tehran's Vanak Park (Iran). The paper compares the deflection of buildings with no outrigger, one outrigger and two outriggers and determines the equation for optimum location in outrigger structure using maximum deflection equations. Also the model with outrigger is analyzed and results for lateral displacement obtained. The results show that using optimized multi-outriggers system can effectively reduce the seismic response of a building and can also decrease structural elements' size and foundation dimensions.

**N. Herath, et al (2009)** reviewed the behavior of outrigger beams in high rise buildings under the influence of seismic loads. A 50 storey building was modelled and STRAND 7 finite element package was used to identify the behavior of structure with three different peak ground acceleration to peak ground frequency

ratios using response spectrum analysis under earthquake loads. Lateral displacement and drift index for one and two outrigger systems were studied and it was concluded that the behavior of a structure varies from earthquake to earthquake. Also, the location of the outrigger beam has a critical influence on the lateral behavior of the structure. The optimum outrigger location determined at 0.44-0.48 times the height of the building.

**S. Fawzia, et al (2011)** studied the effects of cyclonic winds on 28, 42 and 47 storey buildings of L – shaped layout. Wind loads were assigned as per the Australian code. Three dimensional modelling was done using STRAND 7 finite element based software. The software validated and results obtained for deflection minimization with respect to variation of frequency of vibration. The results show that the plan dimensions have vital impact on structural heights. Increase in height with same plan dimensions, leads to reduction in lateral rigidity. To achieve required stiffness, additional bracing system like outriggers and belt truss can be used.

**Kiran Kamath, et al (2012)** studied the static and dynamic behavior of a 40 storey building

without outrigger and with outrigger placed at varying locations. The behavior of various

alternative 3D models is analyzed using ETABS software for reinforced concrete structure with

relative flexural rigidity varying from 0.25 to 2. Variation in lateral displacement, shear force and bending moment for wind loads, static earthquake loads and dynamic earthquake loads based on past records are studied and results drawn and compared for reduction in drift, peak acceleration and optimum outrigger location. The outrigger is most efficient for a relative height of 0.5 the height of the building.

**P.M.B. Raj Kiran Nanduri, et al (2013)** studied the optimum position of outrigger system for

high-rise reinforced concrete buildings under wind and eart hquake loadings. A 30 storey building of rectangular shape with floor to floor height 3 m was modelled using ETABS and the behavior of outrigger, outrigger location and outrigger efficiency was analyzed. The parameters examined were effect of drift, axial column forces and moment on the building by varying outrigger location for wind and seismic loads. The impact of outrigger on building stiffness and optimum outrigger location was determined. Optimum location of single outrigger was suggested to be at 0.5 times the height of the building.

**Srinivas Suresh Kogilgeri and Beryl Shanthapriya (2015)** studied the variation in stiffness of high rise building by varying outrigger depth in ETABS v2013 software. A 40 storey model of 30 x 30 m cross section is assumed to be located in Bangalore. The outrigger depth was reduced to 2/3rd and 1/3rd the typical storey height and the height of belt truss remained that of the storey height. Static and dynamic behaviour of the outrigger structural system was analyzed. The key parameters considered are lateral deflection and storey drift. Results showed that performance of outrigger with depth of full storey height and decreased depth shows minor difference in resistance to lateral loads.

**Akshay Khanorkar, et al (2016)** studied the effect of outrigger and belt truss system in tall

building for controlling deflections due to lateral loads. The paper presents various techniques and methods used to investigate use of outrigger and belt truss system in tall buildings. The effect of concrete strength and reinforcement arrangement is also taken into consideration. Parameters like lateral displacement, storey drift, base shear, core moment and optimum outrigger location are also reviewed. It is concluded that outrigger and belt truss is active and cost effective structural system which is one of the most developing structural systems for lateral load resistance.

**Ajinkya Prashant Gadkari and N. G. Gore (2016)** gave a review of the behaviour of outrigger structural system in high rise building. The paper explains the evolution of outrigger, its types, advantages, working and types of virtual outrigger. The paper summarizes work of researches in the forte of lateral load resisting system using outriggers and also gave a possible scope of study.

**Prajyot A Kakde and Ravindra Desai (2017)** used a 70 storey 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. Percentage reduction in drift was analyzed.

**Anupam S. Hirapure, et al (2017)** analyzed a G+15 model of a building for drift and lateral displacement with and without outrigger. The analysis was done in STAADPRO software. The outrigger used was either a deep beam or an I – section. Also, outrigger location was varied to study the variation in stiffness. The paper concluded that deep beam and I- beam gave varied results for efficiency in case of lateral drift and storey diaplacement.

**Sathyamurthy K and Kavitha A. S. (2017)** analyzed a G+40 storey building with outriggers in high seismic zone IV using Response Spectrum in ETABS software. The building was varied with double diagonal bracing and chevron bracing along with varying positioning of outrigger location. The parameters considered were time period, storey drift and base shear.

**Nishit Shah & Prof N. G. Gore (2018)** presented a comparative study on the working of conventional and virtual outriggers. The paper analyses two models of G+40 and G+50 buildings using Response Spectrum method and Time History method. Results are obtained for time period, storey displacement and storey drift. Comparative advantages of virtual outriggers are proved with data.

**2.2 Summary of Literature Review**

Outrigger systems are widely used to provide efficient lateral load resistance in tall slender contemporary buildings. Outriggers are rigid horizontal structures connecting a building core or spine to distant columns. They improve stiffness against overturning by developing a tension – compression couple in perimeter columns when a central core tries to tilt, generating restoring moment acting on the core at the outrigger level. Outrigger system behavior is simple in principle, but analysis, design, detailing and construction of a complete core-and-outrigger system is complex in practice: being indeterminate, distribution of forces between the core and the outrigger system depends on the relative stiffness of the elements, differential strains between elements and other factors.The use of outrigger and belt truss system in high-rise buildings increases the stiffness of the structure by 20-30% and makes the structural form efficient under lateral load. Steel outrigger and belt truss system is found to be efficient as compared to concrete outrigger and belt truss system.

When the criterion considered for placing the outrigger system is lateral displacement, then the optimum position of the outrigger is at mid-height for both static and dynamic behaviour of the structure. The location of the outrigger beam has a critical influence on the lateral behaviour of the structure under earthquake load and the optimum outrigger locations of the buildings have to be carefully selected in the building design. The optimum outrigger location of a high rise building under the action of earthquake load is between 0.44-0.48 times the height of the building (from the bottom), which is consistent with the optimal location associated with wind loading.

**2.3 Gaps in Literature**

- Researchers have studied the working and placing of Outrigger beams and trusses for conventional outrigger system but there is lack of data on optimum location of Virtual outrigger system.
- Virtual outriggers are recommended for square or rectangular sections but no research exists on other plans.
- Till now majority of the studies have been performed on the steel structures and there is a lack of research on slender concrete structure.
- No building exists with using virtual outrigger concept in spite of the theory.

## III.OUTRIGGER STRUCTURAL SYSTEM

### 3.1 Outrigger System in Buildings:

Outriggered frame systems have been developed by adding outriggers to shear-frame systems with core (core-frame systems) so as to couple the core with the perimeter (exterior) columns. The outriggers are structural elements connecting the core to the perimeter columns at one or more levels throughout the height of the building so as to stiffen the structure.

An outrigger consists of a horizontal shear truss or shear wall (or deep beam). This structural element is a horizontal extension of the core shear truss/wall to the perimeter columns in the form of a knee. To make them sufficiently effective, outriggers are at least one storey deep, and have a high flexural and shear rigidity (adequately stiff in flexure and shear).

Because the outriggers affect the interior space, they are generally located at the mechanical equipment floors in order not to hinder the use of normal floors. The outriggers, which are connected rigidly to the core and by hinges to the perimeter columns, increase the effective flexural depth and so the flexural stiffness of the system in the direction of bending under lateral loads by enabling the core to receive support from the perimeter columns. The outrigger supports the core shear truss/wall against bending, creating axial tension and compression on the perimeter columns. In this way, the cantilever tube behavior of the system is ensured, and the stiffness of the shear-frame system is increased, while reducing the lateral drift of the building to a significant degree.

In addition to those columns located at the ends of the outriggers, it is usual to also mobilize other peripheral columns to assist in restraining the rotation of outriggers. This is achieved by tying the exterior columns with a one- or two-story deep wall or trusses commonly referred to as a “belt wall” or “belt truss” around the building.

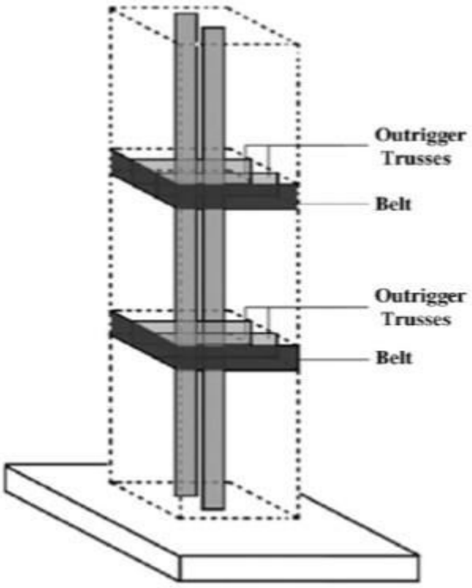



**Figure 3.1: Multi - level belt truss and outrigger**

Belts are used not only in the above mentioned conventional outrigger systems, but also used in the “virtual” outrigger systems. Virtual outrigger concept takes advantage of floor diaphragms to eliminate direct connection of core and perimeter columns by outriggers. A virtual outrigger consists of belt, and floor slabs engaged by belt. In this manner, the problem associated with the space occupied by the conventional outriggers is avoided. Efficiency of the virtual outriggers depends on the rigidity of the belt and floor slabs at belt levels.

The factors affecting the effectiveness of outrigger system are as follows:

- The stiffness and location of outrigger truss system.
- The stiffness and location of the belt truss system.
- Geometry of the tall building.
- Stiffness of the central core.
- Floor-to-floor height of the tall building.

### 3.2 Working Principle of Outriggers

The basic structural response of the system is quite simple. Because outrigger acts as a stiff arm engaging outer columns, when central core tries to tilt its rotation at outrigger level, a tension compression couple is induced in outer columns and acts in a direction opposite to that moment. The result is the type of restoring moment acting on the core at that level. As a result, the effective depth of the structure for resisting bending is increased when the core bend as a vertical cantilever, by the development of tension in the windward columns, and by compression in the leeward.

Outriggers are rigid horizontal structures i.e. truss or beam which connect core wall and outer column of building to improve building strength and overturning stiffness. Outrigger system is one type of structural system which is formed from a cantilever shaped horizontal member connected to structures inner core and outer columns. Through the connection, the moment arm of the core will be increased which lead to higher lateral stiffness of the system. Central core in building acts as cantilever, outriggers are provided to reduce overturning moment in core and to transfer moment from core to outer column by connecting the core and column.

Wall frame outrigger trusses is one of the most efficient and economical structures in tall building, at outer end they connected to the foundation through exterior columns. When the structure is subjected to horizontal loading, the wall and outrigger trusses will rotate, causing compression in the downwind column and tension in column on the upwind side, these axial forces will resist the rotation in the wall.

When the structure is subjected to lateral forces, outrigger and columns resist the rotation of the core and thus significantly reduce the lateral deflection and base moment, which would have arisen in a free core. Outrigger structural systems not only proficient in controlling the top displacements but also play substantial role in reducing the inter storey drifts.

**3.3 Types of Outrigger:**

On the basis of connectivity to the core there are two types of outrigger truss:

- Conventional Outrigger system
- Offset Outrigger system
- Virtual Outrigger system

**3.3.1 Conventional Outrigger system:**

In the conventional outrigger system, the outrigger trusses or girders are connected directly to shear walls or braced frames at the core and to columns located outboard of the core.

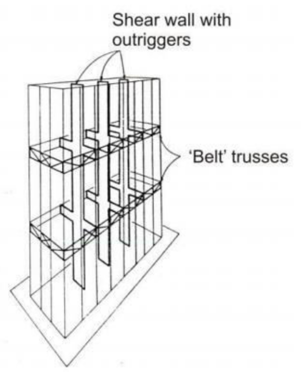



**Figure 3.2.1: Conventional Outrigger**

Generally but not necessarily, the columns are at the outer edges of the building. The number of outriggers over the height of the building can vary from one to three or more. The outrigger trusses, which are connected to the core and to columns outboard o f the core, restrain rotation of the core and convert part of the moment in the core into a vertical couple at the columns.

Shortening and elongation of the columns and deformation of the trusses will allow some rotation of the core at the outrigger. In most designs, the rotation is small enough that the core undergoes reverse curvature below the outrigger.

**3.3.2 Offset Outrigger system:**

Stafford Smith et al (1996) proposed that the outriggers can be located elsewhere than in the planes of the core walls, while retaining all the advantages and mitigating some of the disadvantages of the conventional outrigger system. They are proposed to move, or offset the outrigger arms horizontally within the floor plan, away from the central core.

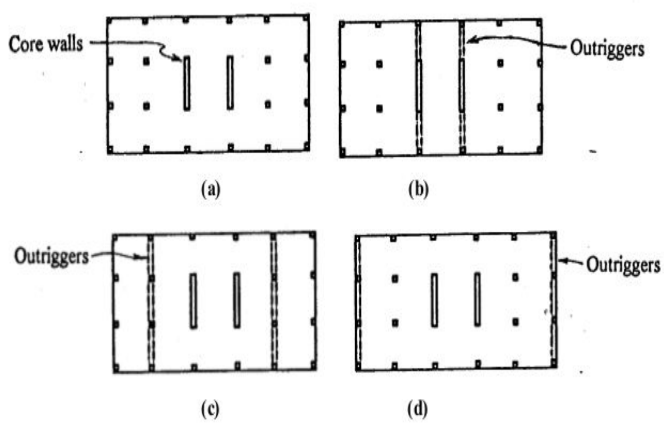



**Figure 3.2.2: (a) Typical Floor Plan (b) Conventional Outrigger Plan (c) Offset Outrigger Plan (d) Alternative Offset Outrigger Plan**

**3.3.3 Virtual Outrigger:**

In the conventional outrigger system, the outrigger trusses connected directly to the core and to outboard columns convert moment in the core into a vertical couple in the peripheral columns. In the "virtual" outrigger concept, the same transfer of overturning moment from the core to elements outboard of the core (peripheral columns) is achieved, but without a direct connection between the peripheral columns and the core in the form of deep outrigger beams/trusses. The elimination of a direct connection between the peripheral columns and the core avoids many of the problems associated with the use of outriggers.

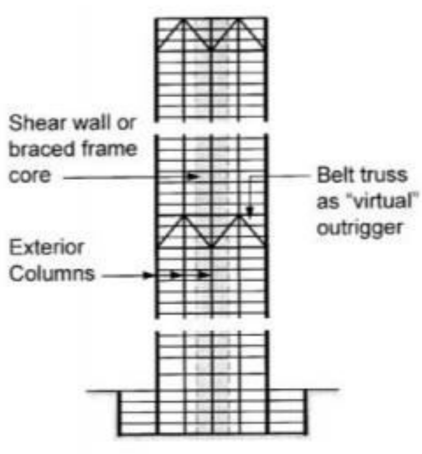



**Figure 3.2.3: Virtual Outrigger**

The basic concept behind the virtual outrigger concept is the use floor diaphragms. These are typically very stiff and strong in their own plane and transfer moment in the form of a horizontal couple from the core to trusses or walls that are not connected directly to the core. The trusses or walls then convert the horizontal couples into vertical couples in columns or other structural elements outboard of the core. Belt trusses and basement walls are well suited to us e as virtual outriggers.

**Virtual Outriggers in Tall Buildings**

For an aspect ratio exceeding 8 or so the structural premium to control drift and resist overturning is large enough to consider introducing outriggers to alleviate dependence on the core for overturning resistance and maximize useful space between the core and exterior columns. When direct or conventional outrigger walls or trusses are not acceptable for the building due to space limitations or a column layout which is not aligned with the core walls, an indirect 'virtual' outrigger or belt truss system may be used. In an indirect or virtual outrigger belt truss design,

Virtual outrigger provides lateral stability to the building by no direct connection between the core and the peripheral columns. The load is transferred to peripheral columns via floor diaphragms which are stiffer in their plane. The concept of virtual outrigger presents a reasonably unique solution to the problems posed by conventional outrigger system.

**Andrew J. Horton** defined virtual outrigger concept as being where belt truss or belt walls are provided, full depth, continuously, around the perimeter of an outrigger level – in a square or appropriately proportioned rectangular plan building – and act, together with the top and bottom structural diaphragm of the outrigger level to transfer substantially the same magnitude of overturning moment from the core to the perimeter columns – engaging axially all of the perimeter columns – as could realistically be achieved via the use of conventional outriggers.

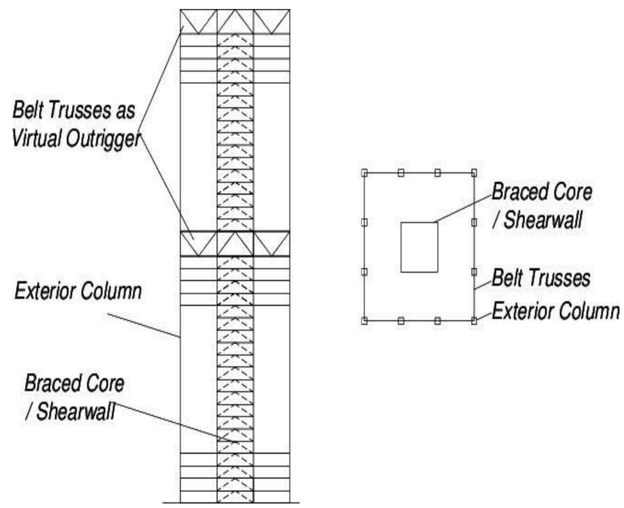


**Figure 3.3: Belt truss as Virtual Outrigger**

### 3.4 Working of Virtual Outriggers

Virtual outriggers have similar function to that of a conventional outrigger but the method employed varies. The working of virtual outriggers is explained in the following texts.

#### 3.4.1 Belt Trusses as Virtual Outriggers

The way in which overturning moment in the core is converted into a vertical couple at the exterior columns is shown in Figure 4.2. 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 (Figure 4.2(a)). The horizontal couple, transferred through the two floors to the truss chords, is converted by the truss into vertical forces at the exterior columns.

The forces and moments in all components can be determined by three-dimensional elastic analysis of the lateral load-resisting system, which includes the core, the trusses, the exterior columns, and the floors that connect the core to the trusses. The in-plane stiffness of the floors at the top and bottom of each outrigger should be represented accurately in the analysis (such as through the use of planar finite elements). These floors should not be regarded as infinitely stiff diaphragms. When the core is a steel braced frame, the transfer of horizontal forces between the core and the floors can be achieved through shear studs on the horizontal frame members.

When the core is a concrete shear wall, forces may be transferred through the concrete-to-concrete connection, with reinforcing steel extending through the connection. The transfer of horizontal forces between the floor diaphragms and the chords of the belt trusses can be achieved through shear studs on the chords. The floor slabs that transfer horizontal forces from the core to the belt trusses will be subjected to in-plane shear (in addition to the usual vertical dead and live load effects) and should be proportioned and reinforced appropriately. In many applications, it will be necessary to use thicker-than-normal slabs.

#### 3.4.2 Basements as Virtual Outrigger

The basement of a tall building can serve as a virtual outrigger, to create a base with a greater effective width for resisting overturning. This can reduce lateral load-induced forces in foundation elements and eliminate uplift. Since basement walls are typically of ample strength and stiffness to be effective as outriggers, there may be little additional cost involved in applying this concept.

The principle is the 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.

The final vertical reactions at the ends of the basement can be supplied by friction or adhesion of soil against the wall surfaces or by conventional foundation elements under the walls. The effectiveness of the basement as an outrigger is likely to be greatest when the core has a “soft” support, such as footings on soil or long caissons subject to elastic length changes. A “hard” support, such as footings directly on rock, may result in most of the moment in the core going down directly into the core foundation, not into the outrigger system. The forces and moments in the various components can be determined by three-dimensional analysis. It is important that the stiffness of the core foundation be modeled with reasonable accuracy (not as rigid supports). The in-plane stiffness of the floors that connect the core to the basement walls should also be modeled accurately; the floors should not be idealized as perfectly rigid diaphragms.

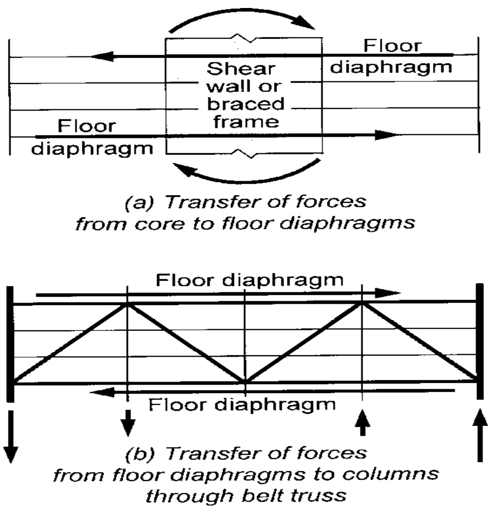



**Figure 3.4: Working of Basements as Virtual Outrigger**

The major advantage offered by virtual outrigger or belt wall/truss system is that it is unaffected by differential inelastic vertical deformations between core and perimeter columns. Thus, no vertical load transfer occurs between the core wall and perimeter columns.

### 3.5 Diaphragm floors:

Understanding diaphragm behaviour is essential for any outrigger system. If a belt wall or virtual outrigger system is used, a stiff and strong floor diaphragm is required at the top and bottom chord of each belt wall in order to transfer the core bending moment, in the form of floor shear and axial forces, to the belt wall and eventually to the columns. Indeed, the floors at belt walls of an indirect outrigger system are significantly thicker, or specially trussed, to provide that stiffness and strength. However the effect must not be exaggerated: a simple rigid diaphragm modelling assumption cannot be used. Improperly modelled diaphragms will result in misleading behaviours and load paths, and incorrect member design forces, for both indirect 'virtual' outrigger/belt truss system and direct/conventional outrigger systems.

### 3.6 Conventional outrigger vs Virtual outrigger

Conventional outriggers offer the following advantages for resisting a structural system against wind and earthquake induced lateral loads:

- **Deformation Reduction:** In a building with a central core braced frame or shear walls, an outrigger system engages perimeter columns to efficiency reduce building deformations from overturning moments and the resulting lateral displacements at upper floors. A tall building structure which incorporates an outrigger system can experience a reduction in core overturning moment up to 40% compared to a free cantilever. Also, a significant reduction in drift, depending on the relative rigidities of the core and the outrigger system.
- **Efficiency:** For systems with belt trusses that engage all perimeter columns, columns already sized for gravity load may be

calculated of resisting outrigger forces with minimal changes in size or reinforcement, as different load factors apply to design combinations with and without lateral loads. In the event that additional overall flexural stiffness is required, the greater lever arm at outrigger columns makes additional material more effective than in the core. Outriggers may also permit optimization of the overall building system using techniques such as the unit load method to identify the best locations for additional material.

- **Foundation:** A separate but related advantage is force reduction at core foundations. Outrigger systems help to effectively distribute overturning loads on foundations.

In-spite of the given advantages, conventional outriggers also present a few major constraints which are a major setback in construction and aesthetic appeal of the structure:

- The space occupied by the outrigger trusses (especially the diagonals) causes constraints on the utility of the floors at which the outriggers are located. Even in mechanical equipment floors, the presence of outriggers can be a major problem.
- Architectural and functional reasons may limit placement of large outrigger columns, where they could most conveniently be engaged by outrigger trusses extending out from the core.
- The connections of the outrigger trusses to the core can be very complicated, especially in the case when a concrete shear wall core is used.
- In most instances, the core and the outrigger columns will not shorten equally under gravity – causing differential shortening. The outrigger trusses, which need to be very stiff to be effective as outriggers, can be severely stressed as they try to restrain the differential shortening between the core and the outrigger columns. Expensive and elaborate measures are required to prevent this anomaly.

- Virtual outriggers offer many benefits over conventional outriggers and problems associated with conventional outrigger system:
- No trusses in the space between the building core and the building exterior.
- Complications caused by differential shortening of the core and the outrigger columns are avoided.
- Fewer constraints on the location of exterior columns. The need to locate exterior columns where they can be directly engaged by outrigger trusses extending from core is eliminated.
- Strenuous connections of the outrigger trusses to the core are eliminated.
- All the exterior columns participate in resisting overturning moment.
- Exterior framing consists of simple beam and column framing without the need for rigid-frame-type connection, thus reducing the overall cost.

- One of the major advantage of the indirect or virtual outrigger or belt wall system is that it is not affected by differential inelastic vertical deformations between core and perimeter, so no vertical load transfer occurs between the core wall and perimeter columns. However, a belt truss can experience vertical load transfer forces if it tries to equalize axial strains that differ between adjacent perimeter columns.

- Owing to the considerable set of easier solutions offered by Virtual outriggers, research to facilitate more and more development in the field becomes imperative.

## IV.PROBLEM CONFIGURATION AND MODELLING

### 4.1 Introduction:

The literature for the Outrigger structural system gives an outline of the advances and research made in the field of Outrigger structural system. In spite Outrigger being a reasonably old structural system, most of the work has been done in the forte of Conventional outrigger system. There is a dearth of information on the concept of Virtual outriggers.

The buildings made till date have also used the concept of Conventional outrigger beams or trusses in the construction. After scrutinizing in the available information, data and statistics, the problems or gaps in the literature associated to Outrigger system, the project aims at analyzing and designing a model of a tall building using the concept of Virtual Outrigger structural system and also determining the optimum location and number of virtual outrigger systems suitable for a structural system.

### 4.2 Methodology

1. Considering a high rise commercial structure (floor-to-floor height 4 m) of three different heights (50, 60 and 70 storey).

2. Designing the structures in accordance with the Indian Codes of Practice.3. Using :

   IS: 456 (2000) for RCC design:

   IS: 875: Part III (2015) for Wind analysis:

   IS: 1893: Part I (2016) for Seismic analysis

4. Virtual outriggers located at suitable heights for one, two and three outrigger system.

5. Obtaining post-processing results for lateral displacement, storey drift, top storey acceleration, base shear and overturning moment.

6. Analyzing and comparing of the results are obtained for structure without outrigger and with outrigger level(s).

7. Observing the results and selecting of most suitable outrigger(s) position in accordance with different base criteria.

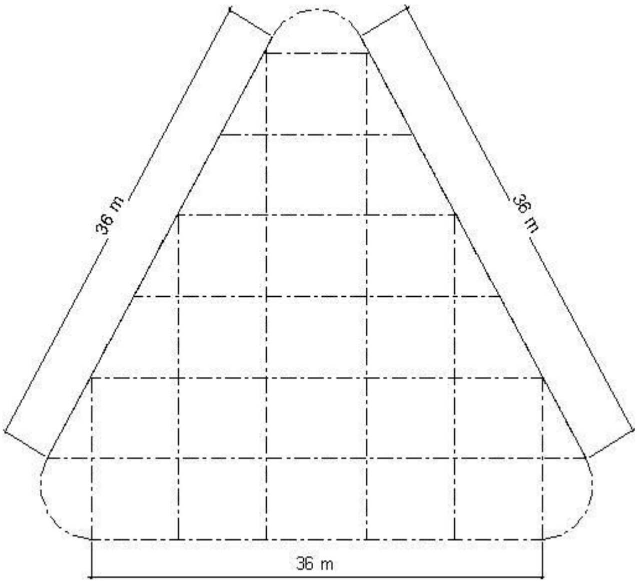
8. Conclusion based on results obtained.

### 4.3Model Configuration

The selection of model configuration is most important in the context of Outrigger structural system since model configuration greatly affects the performance of the structure. Almost every research conducted in the past on outrigger structure involves square or rectangular models. But, in reality there is a high possibility of selecting varied shapes owing to architectural suitability, structural stability and aesthetic appeal.

#### 4.3.1. Floor plan

In this thesis, a triangular model is selected for project model designing and analysis. The triangular shape is selected so as to assume factors (majorly in terms of wind effects) which can be more critical than the standard square or rectangular sections. The details of the floor plan are given below:




**4.1: Triangular plan with curved edges**

*(Modelled in Revit)*

The plan was modeled in Revit software and then exported to ETABS 2016 for three dimensional modeling and then later designed and analyzed for various parameters. Peripheral mega – columns were designed suitably in circular cross-section for easier belt-truss connections and located as per the design requirement. Interior columns are mostly square in cross-section as they are easily fabricated. The plan view in ETABS 2016 is as given below:

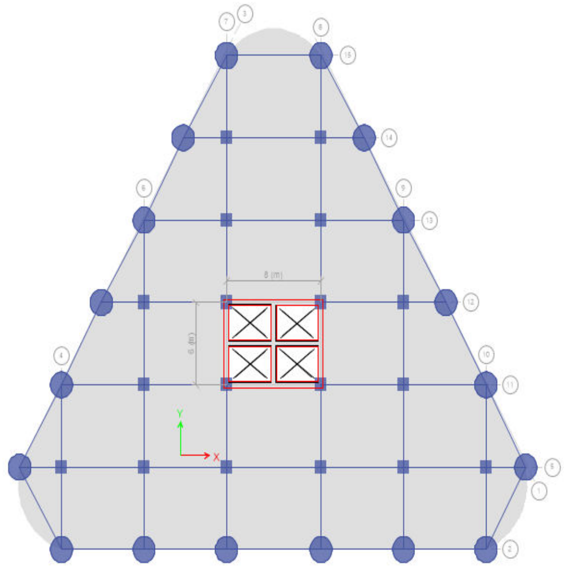


**Figure 4.2: Triangular plan with curved edges and placement of perimeter columns**

*(Exported in ETABS 2016)*

The building is assumed to be a commercial building and as per Indian Standards, the floor to floor height is taken to be 4m. After the plan and column placement were confirmed, slab was created as per the design requirement and the grid drawn for 70 – storey structure. The grid and 3 dimensional views are as below:

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**Figure 4.3: 3 – Dimensional view with slabs, columns & beams (70 storey)**

*(Modelled in ETABS 2016)*

**4.3.2 Structural configuration of model:**

For current research the following models are studied: Models with three different heights of 200 meters (**50 storeys),** 240 meters (**60 storeys**) and 280 meters (**70 storeys**). The floor plan of the model structure is **Triangular** with curved edges. The edges are curved at the edges to minimize the critical impact of wind at apex and to reduce wastage of space at corners. Also, aesthetically, the curved apexes are more appealing.

**4.3.3 Load Combinations:**

As per IS 1893 the load combinations for limit state design of reinforced concrete structures are:

1. 1.5 (DL + IL)

2. 1.2 (DL + IL + EL)

3. 1.5 (DL + EL)

4. 0.9 DL + 1.5EL

Where, DL : Dead load
IL : Imposed load
EL : Earthquake load

As per the IS code, the lateral load which is greater is taken for design purposes. Either earthquake load or wind load, whichever is greater, will be used.

**4.4 Design considerations:**

- For any structure to be viable it has to be checked for safety and serviceability. The following checks are verified as per IS 456 (part 20) to ensure stability of the structure:
- Overturning: The stability of a structure as a whole against overturning shall be ensured so that the restoring moment shall not be less than the sum of 1.2 times the maximum overturning moment due to the characteristic dead load and 1.4 times the maximum overturning moment due to the characteristic imposed loads. In case where dead load provides the restoring moment, only 0.9 times the characteristic dead load shall be considered.
- Sliding: The structure shall have a factor against sliding of not less than 1.4 under the most adverse combination of the applied characteristic forces. In this case on 0.9 times

the characteristic dead load shall be taken into account.

- Probable Variation in Dead Load: To ensure stability at all times, account shall be taken of probable variation in dead load during construction, repair or other temporary measures. Wind and seismic loading shall be treated as imposed loading.
- Lateral Sway: Under transient wind load the lateral sway at the top should not exceed H/500, where H is the total height of the building.

**4.5 Virtual Outrigger storey configuration:**

Virtual outrigger is basically a storey wherein moment is transferred from the core to peripheral columns using floor diaphragms. The peripheral columns which are connected by a belt truss or belt walls then can equally transmit the moment to the foundation thus reducing the impact of lateral loads.

Thickness of Floor diaphragms : 200mm

Grade of concrete : M50

Reinforcement : Fe550

Size of perimeter beams : 0.8 x 1 m

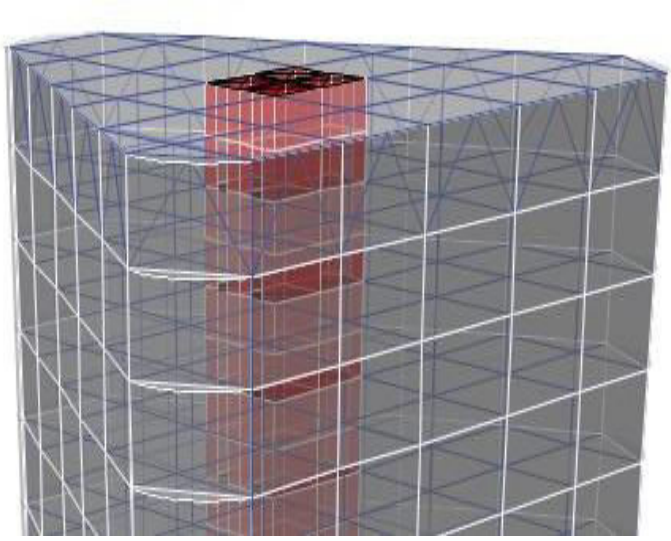

**Figure 4.4: 3-D model for Virtual Outrigger storey with belt truss at Top storey**

The peripheral columns are connected by a belt truss of steel. The truss is so designed as to ensure proper load transfer. The grades of concrete and reinforcement are taken as per the design requirements of the structural models and also with reference to research papers.

**Table 4.1: Preliminary structural data for design**

| | | | | | |
|---|---|---|---|---|---|
| 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 | | | | |

## V. ANALYSIS OF OPTIMUM LOCATION FOR VIRTUAL OUTRIGGER

### 5.1 Single Outrigger System

In a single outrigger system, the probable locations for locating a floor with virtual outrigger are as follows:

1. Virtual Outrigger @ top
2. Virtual Outrigger @ 3/4th height
3. Virtual Outrigger @ 2/3rd height
4. Virtual Outrigger @ mid-height
5. Virtual Outrigger @ 1/3rd height
6. Virtual Outrigger @ 1/4th height

A lot of researchers have argued that in case of single outrigger system, when the outrigger is placed below the mid-height of the structure, the benefits are not economical and hence we will study only 4 cases i.e. top height, 3/4th height, 2/3rd height and mid-height, for the assumed parameters which determine safety, stability and serviceability.

### 5.2 Two - Outrigger System

To ensure stability for higher buildings and resist the lateral loads, single outrigger system may not be sufficient in case the wind loads are critical and the structure lies in an earthquake prone area. According to Hi Sun Choi, Thorton Tomasetti & Leonard Joseph, for a conventional two outrigger system, 1/3rd and 2/3rd height is ideal to start with. If one of the outriggers must be at top, the second one can be located at 20% to 60% of the building height. These references are for conventional system. For ensuring these standards in case of virtual outrigger system as well, the following heights are considered:

1. Virtual outrigger at top and 3/4th height
2. Virtual outrigger at top and 2/3rd height
3. Virtual outrigger at top and mid-height
4. Virtual outrigger at 3/4th and mid-height
5. Virtual outrigger at 3/4th and 1/4th height
6. Virtual outrigger at 2/3rd and mid-height
7. Virtual outrigger at 2/3rd and 1/3rd height

### 5.3 Three Outriggers System:

According to Hi Sun Choi, Thorton Tomasetti and Leonard Joseph, if there are three outriggers, ¼, ½ and ¾ height points are good to start design. Taking this as a guideline, the following models are made for three outrigger system:

1. Virtual outrigger at top, 3-4th and mid height
2. Virtual outrigger at 3-4th, mid and 1-4th height
3. Virtual outrigger at 2-3rd, mid and 1-3rd height

## VI. RESULTS FOR OPTIMUM LOACTION VIRTUAL OUTRIGGER

The optimum location of the virtual outrigger can be determined by checking for the safety parameters and various factors as mentioned earlier, by locating the outrigger at different levels. Models of 50, 60 and 70 storey were analyzed for factors like lateral displacement, storey drift, top storey accelerations, base reactions and maximum overturning moment. These structures were modelled for one, two and three outrigger system wherein the location of the outrigger was varied to understand the impact of the change in location on the stability factors. The following results were obtained for the optimum location of Virtual outrigger in tall buildings.

### 6.1. Single Outrigger system

The single Outrigger system was analyzed by locating Virtual Outriggers at top [1a], 3-4$^{th}$ [1b], 2-3$^{rd}$ [1c] and mid [1d] height. The results obtained for various parameters are as follows:

- **Lateral displacement:** Least values of lateral displacement are obtained for all the models when the Virtual Outrigger storey is located at **mid – height i.e. case '1d'**. Also, average values for average lateral displacement are least when the virtual outrigger is located at mid-height. But as the height of the structure increases, the influence of wind load increases and thus we can see that for 70 storey model least values of average lateral displacement for wind loads occur when the virtual outrigger is located at **2-3$^{rd}$ height i.e. case '1c'.**
- **Storey drift:** The data clearly states that least values of average storey drift occur when the Virtual outrigger is located at **mid height**. The data also shows that maximum storey drift is also least in the case when the outrigger is located at mid height.
- **Top storey acceleration:** No clear pattern can be seen to draw inferences. But, as the height of the structure increases there is a shift for optimum location of outrigger from top to mid-height.
- **Base reactions:** For **seismic response in X direction**, optimum location of outrigger is at **top height**. However, for **seismic response in Y direction** the optimum location is at **2-3$^{rd}$ height.**
- **Maximum overturning moment:** No clear inferences can be drawn.

### 6.2. Two Outrigger system

The results obtained in this case are as follows:

- **Lateral displacement:** For lower heights (i.e. 50 & 60 storeys), least values of lateral displacement were found for case **'2e' (i.e. virtual outrigger located at 3-4$^{th}$ and 1-4$^{th}$ height) for seismic forces**. In the same models, **for wind loads, case '2g' (i.e. Virtual outrigger at 2-3$^{rd}$ and 1-3$^{rd}$ height)** gave optimum results. However, as the height increases optimum results are obtained when the outriggers are located at **2-3$^{rd}$ and 1-3$^{rd}$ the height of the structure i.e. case '2g'**.
- **Storey drift:** A varied pattern of drift is observed in this case. This variation is peculiar because of the shape of the building. Least values of storey drift are obtained for **seismic as well as wind loads in X direction for case '2g' i.e. outriggers located at 2-3$^{rd}$ and 1- 3$^{rd}$ height** of the building. However, **for wind and seismic forces in Y direction, optimum location is case '2e' i.e. virtual outriggers located at 3-4$^{th}$ and 1-4$^{th}$ height** of the building.
- **Top storey acceleration**: Least acceleration values are obtained for case '2f' i.e. outriggers located at **2-3$^{rd}$ and mid height**.
- **Base reactions**: No clear inferences can be drawn.

- **Maximum overturning moment**: Optimum location is at case '2e'i.e. 3-4th and 1-4th height of the structure.

### 6.3.Three Outriggers system

The results obtained are as follows:

- **Lateral displacement**: The data gives a very clear indication that optimum location in case of 3 virtual outriggers system is for case **'3b' i.e. Virtual outriggers located at 3- 4th, mid and 1-4th height.**
- **Storey drift**: Least values of storey drift are obtained for case '3b' i.e. virtual outriggers located at 3-4th, mid and 1-4th height of the structure. However, for 70 storey model, in case of wind loads the optimum results are obtained for case '3c' i.e. virtual outrigger located at 2-3rd, mid and 1-3rd height.
- **Top storey acceleration**: No clear inferences can be drawn.
- **Base reactions**: Least values occur at **case '3a' i.e. Virtual outriggers at top, 3-4th and mid height.**
- **Maximum overturning moment**: Optimum location at case '3b' i.e. Virtual outriggers at 3-4th, mid and 1-4th height of the structure.

## VII.CONCLUSION AND SCOPE OF WORK

### 7.1.Introduction

Virtual Outrigger system is an improvised version to remove the deficits of the conventional outrigger system with added advantages. A systematic analysis on various parameters would clearly give a better insight on the possible practical and advantageous use of the structural system.

### 7.2.Conclusion

The following conclusion can be drawn by the results obtained from the analysis of one, two and three outrigger systems by locating outriggers at various heights based on the parameters of analysis like the lateral displacement, storey drift, storey accelerations and overturning moment.

- For one outrigger system, locating virtual outrigger at mid-height gives optimum results.
- In case of two-outrigger system, placing virtual outriggers at 2-3rd and 1-3rd heights gives optimum results.
- For three-outrigger system optimum results are obtained when virtual outriggers are located at 3-4th, mid and 1-4h height of the building.
- The optimum location of outrigger varies for lateral displacement and storey drift with wind and seismic loads with respect to x and y direction and also with the height.

The most important consideration here is the design and usage of the building along with the technical capability. Architects and engineers need an absolute coordinated effort to optimize the location of the outrigger storey depending on the requirement of the structure as well as feasibility. Overall, virtual outrigger presents an innovative benefit over conventional outrigger and can be successfully and economically used in the decades to come.

**7.3.Scope for Future Work**

Virtual outriggers undoubtedly present an added advantage over the conventional types. The paper presents the possible optimum locations for one, two and three outrigger systems based on parameters like lateral displacement, storey drift, top storey acceleration, base reaction and maximum overturning moment. This research in the forte of virtual outriggers can be taken further and has the scope as listed below:

- Impact of change in stiffness of floor diaphragm on stability of the structure.
- Comparison of structural stability and economy as the number of outrigger levels are increased.
- Comparison of working of steel and RC belt truss for virtual outriggers.
- Comparison of change in effect of wind and seismic forces on virtual outrigger as the height of the structure increases.

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