STUDY OF THE OUTRIGGER STRUCTURAL SYSTEM IN HIGH RISE BUILDINGS

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Abstract:
The paper represents the brief concept of Outrigger Structural System and their types , advantage and disadvantages of outrigger structural system for tall buildings. As the height of the building increases, the stiffness of the building reduces. The Outrigger and Belt trussed system is the one of the lateral load resisting systems that can provide significant drift control for tall 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. The main objective of this paper is to study, the performance of outrigger structural system in high-rise RC Building subjected to seismic load and Wind Load. Also, paper presents an elaborate comparison of the lateral load resisting systems and also compares the virtual system with the conventional outrigger system. The paper also helps to get idea about outrigger structural system in existing high rise RC building worldwide.

Keywords -*Lateral loads resisting buildings, conventional outrigger, virtual outrigger, seismic load, wind load, lateral displacement, and storey drift.*

I. INTRODUCTION:

1.1 General

Since time immemorial the human pursuit to reach the sky has been hysterical. In ancient times, tall monumental structures like pyramids, cathedrals or temples - built to honor the Sky Gods -were considered a way to reach the stars and heaven in the after-life. Today, every sky-scraper defines a country's economic strength and technological advancement. The skyline fashioned by the tall buildings reflects a city's economic prosperity and adds to the aesthetic appeal of the city's structural bounty. Sky-scrapers today, are built as symbols of power, wealth and prestige.

In the early twentieth century, tall buildings were designed as commercial spaces in response to the urgent need for the office units to be positioned as closely as possible to one another. Architects' creative approaches in their designs for tall buildings, rapid urbanization, shortage and high cost of urban land, desire to prevent disorderly urban expansion, effort to create a skyline concept, and trends for a cultural identity and for prestige have driven the increase in the height of buildings. In the past, the forms used in design of tall buildings were restricted, but currently freedom in the design of tall buildings, along with a contemporary widening of the form spectrum design has enabled various structural configurations and profiles. Tall buildings today, designed with the aid of advanced computer technologies, are built with exceedingly daring architectural and structural designs that were almost never found in their predecessors. The key factors enabling the construction of tall buildings are developments and innovations in: materials, construction techniques, operating systems, structural systems and analysis.

No doubt man has reached the apogee in construction of sky-scrapers; but as the height of building increases, it's vulnerability to lateral loads increases. Wind and earthquake induced lateral loads may cause excessive building sway resulting in damage to non-structural elements, breaking of windows, shortening of fatigue life, malfunction of elevators and other mechanical equipment damage. In substantial cases, wind or seismic loads may even cause failure of structural system. Hence, in tall buildings it is essential to assure structural safety and standards of occupancy comfort (serviceability), both forming a critical component of tall buildings' design.

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.

1.1.1 Lateral Loads affecting tall buildings

Tall buildings, because of their extraordinary height, show greater sensitivity to wind and earthquake induced lateral loads as compared to low-rise building. Determining these lateral loads in the design of tall buildings is essential since they have a major influence on the structural stability and serviceability of the building.

Estimation of the lateral loads on a tall building is a major task. Earthquake loads increase according to the building weight; whereas wind loads increase according to the building height. For this reason, wind loads, while they are generally an unimportant issue in the design of structural systems for low- and mid-rise buildings, play a decisive role in that of tall buildings, and can even be a cause of large lateral drift (sway) that is more critical than that from earthquake loads. Consequently, the occupancy comfort takes prominence in the design of structural systems in tall buildings, and it is necessary to limit the building sway.

Wind Loads:

Wind loads were initially ignored in the design of skyscrapers as the weight of the construction materials and the structural systems used in the early skyscrapers made vertical loads more critical than lateral loads. But over time, as the strength to weight ratio of construction materials and the ratio of floor area to structural weight in structural systems increased and the total weight and rigidity of structures decreased, consideration of wind loads became important. Wind speed and pressure increases parabolically with respect to height, and therefore wind loads affecting tall buildings become important as the height of the building increases. In general, structural design begins to be controlled by wind loads in buildings of more than 40 storeys.

Today, due to the advancements in structural systems and high-strength materials, tall buildings have increased in their height to weight ratio but on the other hand reduced in stiffness compared with their precursors, and so have become greatly affected by wind. With the reduced stiffness, the sensitivity to lateral drift, and hence the sway under wind loads, increases. The sway, which cannot be observed outside the building or at the lower floors, can cause discomfort to occupants at the higher floors of a building. Architectural, structural, and mechanical design approaches are used to control lateral drift in tall buildings.

Earthquake Loads:

Earthquakes are the propagation of energy released as seismic waves in the earth when the earth's crust cracks, or when sudden slippage occurs along the cracks as a result of the movement of the earth's tectonic plates relative to one another. With the cracking of the earth's crust, faults develop. Over time, an accumulation of stress in the faults results in sudden slippage and the release of energy. The propagation of waves of energy, formed as a result of seismic movement in the earth's crust, acts upon the building foundations and becomes the earthquake load of the building. In determining earthquake loads, the characteristics of the structure and records of previous earthquakes have great importance. Compared with wind loads, earthquake loads are more intense but of shorter duration.

The general principle in earthquake-resistant design is to protect life without a collapse of the structure, even if there is damage to structural and non-structural elements of the building. Earthquake codes aim to ensure: the avoidance of damage to structural and non-structural elements of the building during earthquakes of low intensity; the limitation and reparability of the damage that may occur to structural and non-structural elements during earthquakes of medium intensity; the avoidance of the collapse of structural elements where there is limited and permanent damage, and the protection of life during earthquakes of high intensity.

1.1.2.Structural Concept of Tall Buildings

The key idea in conceptualizing the structural system for a narrow tall building is to think of it as a beam cantilevering from the earth. The laterally directed force generated, either due to wind blowing against the building or due to the inertia forces induced by ground shaking, tends to both snap it (shear), and push it over (bending).

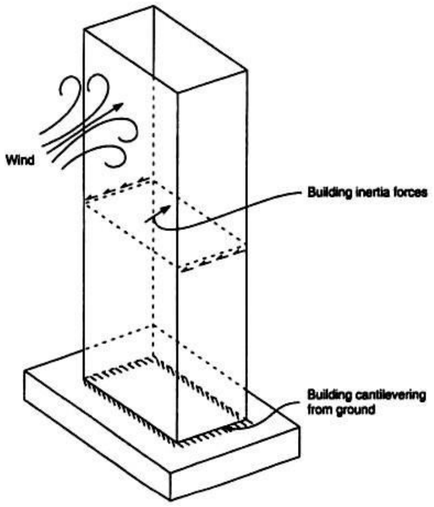

Figure 1.1: Structural concept of tall building

Therefore, the building must have a system to resist shear as well as bending. In resisting shear forces, the building must not break by shearing off, and must not strain beyond the limit of elastic recovery. Similarly, the system resisting the bending must satisfy three needs: The building must not overturn from the combined forces of gravity and lateral loads due to wind or seismic effects; it must not break by premature failure of columns either by crushing or by excessive tensile forces: its bending deflection should not exceed the limit of elastic recovery. In addition, a building in seismically active regions must be able to resist realistic earthquake forces without losing its vertical load carrying capacity.

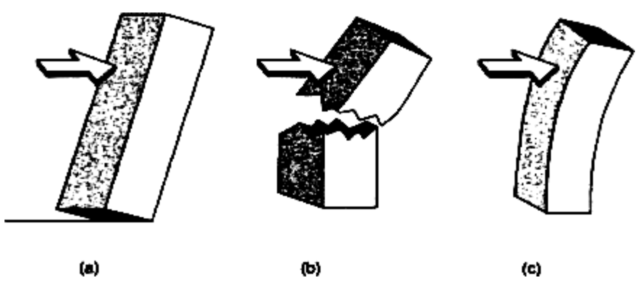

Figure 1.2: Bending resistance of building for (a) overturning (b) tension failure/compression & (c) bending deflection

In the structure's resistance to bending and shear, a tug-of-war ensues that sets the building in motion, thus creating a third engineering problem; motion perception or vibration. If the building sways too much, human comfort is sacrificed, or more importantly, non-structural elements (glass fascia) may break resulting in expensive damage to the building contents and causing danger to the pedestrians.

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 Introduction:

Tall buildings have become an integral part of the human society. Sensitivity to laterals loads is a critical element in the design of tall buildings. An essential criterion for the design of tall buildings is the lateral drift at the top of the structure. Also, the acceleration caused due to wind or seismic load is an important factor as it actually brings about the feel of drift to human perception.

The core-wall system has been very efficiently used as lateral load resisting system. But, as the height of the building increases, the impact of the lateral loads also increases and the stiffness provided by the core is not adequate enough to keep the drift in acceptable limits. For such tall structures outrigger are introduced.

Although outriggers have been used for approximately four decades, their existence as a structural member has a much longer history. Outriggers have been used in the ship industry for many years to resist wind. The slender mast with spreaders works in similar way to that of a core – outrigger system. As a comparison, the core can be related to the mast, the outriggers are like the spreaders and the exterior columns are like the shrouds or stays.

The outrigger and belt truss system is a lateral load resisting system in which the external columns are tied to the central core wall with very stiff outriggers and belt truss at one or more than one levels. The belt trusses are tied to the peripheral column of building while the outriggers engage them with main or central shear wall. The outrigger and belt truss system is commonly used to effectively control the excessive drift due to lateral l oad, so that, during small or medium lateral load due to either wind or earthquake load, the risk of structural and non-structural damage can be minimized. For high-rise buildings, particularly in seismic active zone or wind load dominant, this system can be chosen as an appropriate structure.

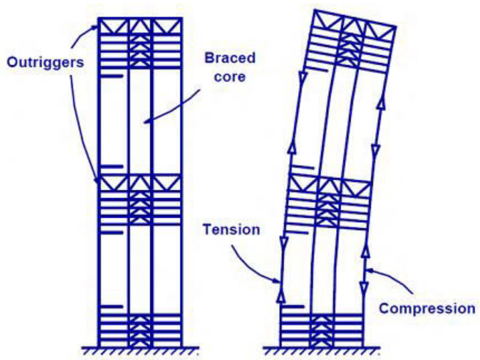


Figure 3.1: Outrigger structural system

(Source – Google slideshare by Akshay Revekar& Durgesh Pippal, MITS Gwalior)

3.2 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.

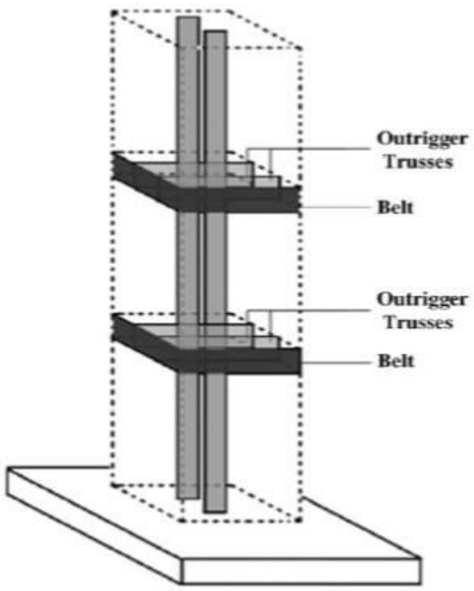


Figure 3.2: Multi - level belt truss and outrigger

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.

3.3 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.

3.4 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

3.4.1 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.

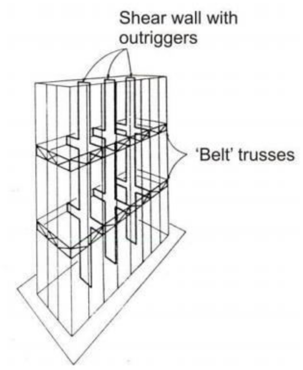


Figure 3.3.1: Conventional Outrigger

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.

3.4.2 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.

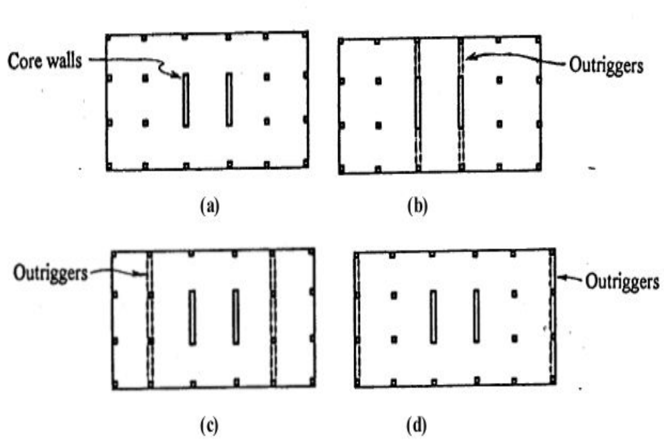


Figure 3.3.2: (a) Typical Floor Plan (b) Conventional Outrigger Plan (c) Offset Outrigger Plan (d) Alternative Offset Outrigger Plan

3.4.3 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.

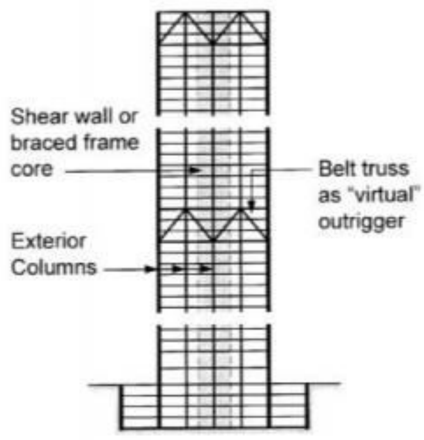


Figure 3.3.3: Virtual Outrigger

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.

3.5 Existing buildings with Outriggers:

Technological advancements and continuous research have metamorphically made reaching the stars a reality. Buildings with heights as high as 800 m have been conveniently built. But at such heights, resisting lateral loads is a challenge; which is vigilantly tackled by engineers by careful selection of suitable lateral load resisting system. A number of noted buildings around the world have outriggered frame structural system which has proven to effectively resist lateral loads and provide structural serviceability. In order to carry out research in any forte, it is imperative that real life examples and practical implications are studied.

A number of tall buildings around the world have been constructed successfully using the principles of outrigger structural system. Greater resistance to lateral loads and wider flexibility has enabled the popularity of this structural system. The above table lists buildings in various parts of the world - with different designs and architectural configurations – which use outrigger structural system. These buildings have gained fame as those of the iconic structural marvels of the century. These buildings prominently use the conventional type of outrigger system: direct connection between central core and peripheral columns using outrigger beams or trusses.

Figure 3.3.3: Burj Khalifa

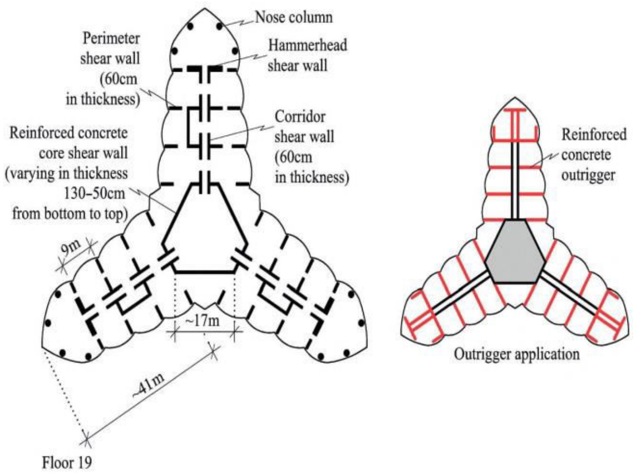


Figure 3.4: Burj Khalifa plan and

structural axonometric section

The structural system of Burj Khalifa is composed of a hexagonal central core (buttressed by wing shear walls) and outriggers. The hexagonal core consists of reinforced concrete shear walls with thickness varying between 130 cm at the bottom to 50 cm at the top through the height of the building. Each wing has hammerhead ended corridor shear walls (extending from central core), perimeter shear walls at the sides and circular nose columns at the tip. Outriggers connect the core with the perimeter shear walls and nose columns through buttresses (wing shear walls). Multi-storey outrigger shear walls at the mechanical floors at 5 levels increase the strength of the buttressed core against lateral loads and thus the structural system is an outriggered frame system.

[2] Taipei 101

Taipei 101 of Taipei, Taiwan is an office building with 101 storeys and is 508 m tall. It is a composite building with and outriggered frame. The Taipei 101 gained the title of "the world's tallest building" in 2004. The design of the building is inspired by the form of a bamboo with ground floor of 63.5 x 63.5 m square cross-section, then a 25–storey pyramid form on the top of which are 8 modules consisting of 8–storey truncated pyramids. The top of the building has a 12- storey truncated pyramid.

Figure 3.5: Taipei 101

The Taipei 101 is an example of a building with setbacks and an aerodynamic building top. The design of the structural system is such as that it can efficiently resist wind speed up to 43.3 m/s. The 8 perimeter columns and 16 core columns, all composite, consist of box-section steel filled with high strength concrete (70 MPa). At the ground floor the perimeter columns have dimensions 2.4 x 3 m. The perimeter and core columns are connected by outriggers, 1 or 2 storeys deep, at 10 levels along the height of the building.

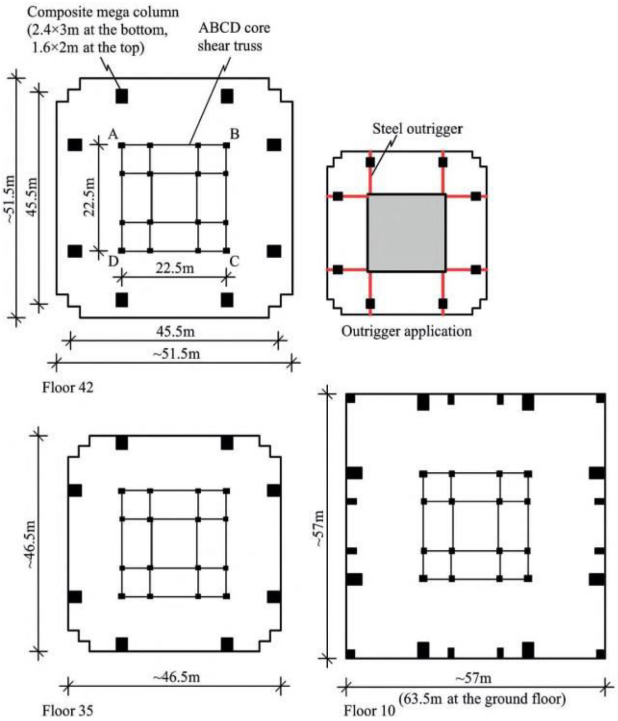


Figure 3.6.Taipei 101 schematic sections and plans

[3] Petronas Twin Towers

The 88-storey, 452 m high Petronas Twin Towers in Kuala Lumpur, Malaysia gained the title of "the world's tallest building" in 1998. They are reinforced concrete buildings with and outriggered frame system. The 8-pointed star formed from overlapping squares and 8 semi-circles provided the inspiration for the design for the design of the Petronas Twin Towers. Both the towers have identical cylindrical shape of diameter 46.3 m and floor-to-floor height of 4 m.

The diameter of the 16 perimeter columns varies from 240 cm at the bottom to 120 cm at the top. The columns are spaced approximately at 9 m centres. Reinforced concrete cores of the two towers, beginning with square cross-sections of 22.9 x 22.9 m at the base, decrease in size towards the top of the building in steps, ending with rectangular cross-section of 18.9 x 22 m. The reinforced concrete cores have inner walls of thickness 35 cm and outer walls varying in thickness from 75 to 35 cm from bottom to top.

Figure 3.9: Petronas Twin Towers

For additional stiffness, reinforced concrete core shear walls and perimeter columns are connected to each other by 2-storey-deep outriggers at the 38th floor (floors 38-40: almost mid-height of the building), which is xa mechanical equipment floor.

Figure 3.7: Petronas Twin Towers

For additional stiffness, reinforced concrete core shear walls and perimeter columns are connected to each other by 2-storey-deep outriggers at the 38th floor (floors 38-40: almost mid-height of the building), which is xa mechanical equipment floor.

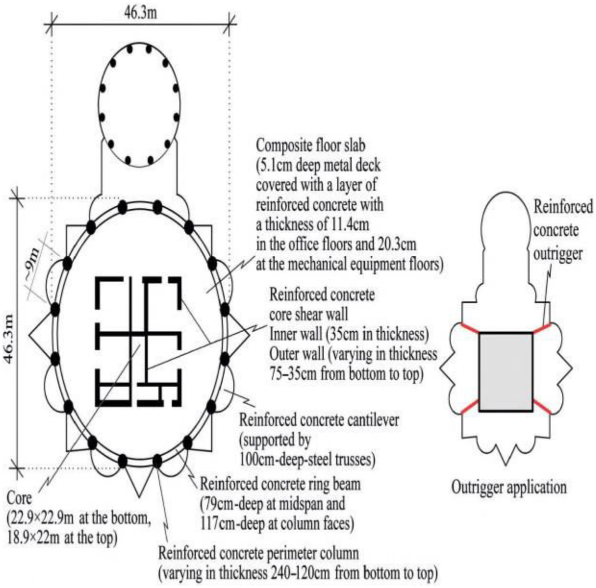


Figure 3.8: Petronas Twin Towers plan and structural axonometric section

[4] New York Times Tower

The 52-storey, 319 m high New York Times in New York, USA is a steel building with an outriggered frame system. The building was designed to assure adequate natural lighting resulting the building with

Figure 3.9: New York Times Tower

inner glazed façade and an outer transparent screen layer composed of closely spaced horizontal ceramic rods mounted outboard of the façade.

The structural core is centrally located braced core with 27.8 x 19.8 m dimension which remains the same throughout the height of the building. The tower has 30 columns made of built-up box sections with dimensions of 76 x 76 cm. Two-storey-deep outriggers are located at the mid-height and top mechanical floors of the building. The lateral stiffness of the outriggered frame system is improved by 2-storey-high pretension X-braces.

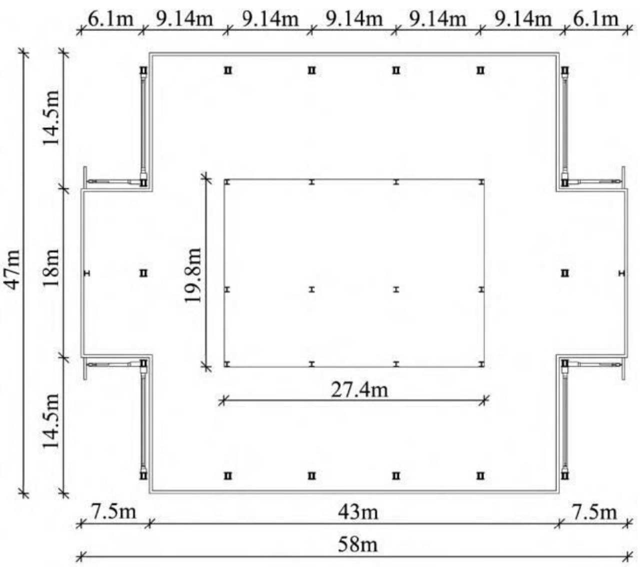


Figure 3.10: New York Times Tower plan

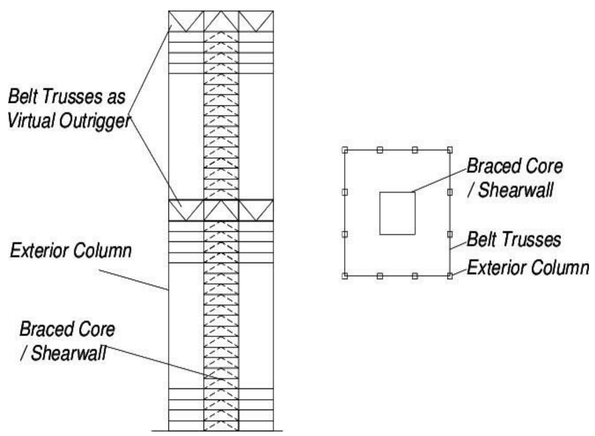
Virtual Outriggers in Tall Buildings

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 3.11: Belt truss as Virtual Outrigger



3.6.1 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.

3.6.1.1 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.

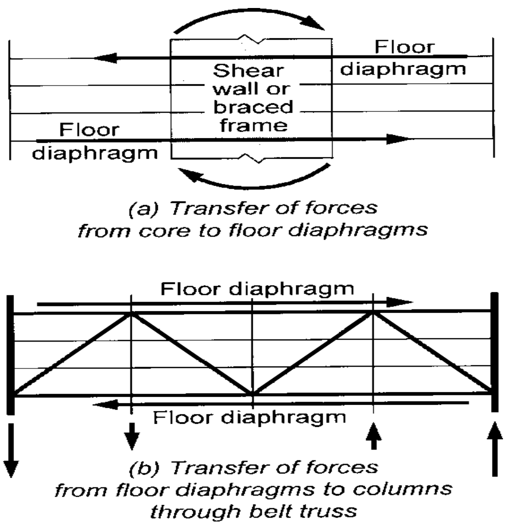


Figure 3.12: Working of Belt truss as Virtual Outrigger

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.

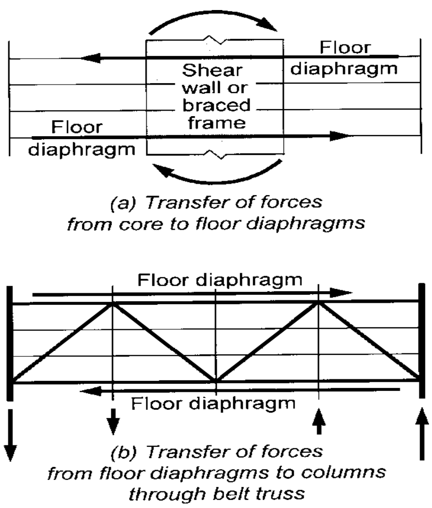
3.6.1.2 Basements as Virtual Outrigger

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 3.13: 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.

3.6.2 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.

3.7 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.ADVANTAGES AND DISAVDANTAGES

Advantages of Outrigger systems:

1. The outrigger systems may be formed in any combination of steel, concrete, or composite construction.

2. Core overturning moments and their associated induced deformation can be reduced through the "reverse" moment applied to the core at each outrigger intersection. This moment is created by the force couple at the exterior columns to which the outrigger connect. It can potentially increase the effective depth of the structural system from the core only toalmost the complete building.

3. Significant reduction and possibly the complete elimination of uplift and net tension forces throughout the column and the foundation systems.

4. The exterior column spacing is not driven by structural considerations and can easily mesh with aesthetic and functional considerations.

5. Exterior framing can consist of "simple" beam and column framing without the need for rigid-frame-type connections, resulting in economies.

6. For rectangular buildings, outriggers can engage the middle columns on the long faces of the building under the application of wind loads in the more critical direction. In core-alone and tubular systems, these columns which carry significant gravity load are either not incorporated or underutilized. In some cases, outrigger systems can efficiently incorporate almost every gravity column into lateral load resisting system, leading to significant economies.

Disadvantages of outrigger systems.

The most significant drawback with use of outrigger systems is their potential interference with occupancy and rentable space.

This obstacle can be minimized or in some cases eliminate by incorporation of any of the following approaches:

1. Locating outrigger in mechanical and interstitial levels

2. Locating outriggers in the natural sloping lines of the building profile

3. Incorporating multilevel single diagonal outriggers to minimize the member's interference on any single level.

4. Skewing and offsetting outriggers in order to mesh with the functional layout of the floor space.

5. Another potential drawback is the impact the outrigger installation can have on the erection process. As a typical building erection proceeds, the repetitive nature of the structural framing and the reduction in member sizes generally result in alearning curve which can speed the process along.

V. CONCLUSION

No doubt man has reached the apogee in construction of sky-scrapers; but as the height of building increases, it's vulnerability to lateral loads increases. Different structural systems have proved to be suitable at different locations and for different architectural and aesthetic requirements. Outrigger structural system has evolved since late 20th century to give the world modern marvels. Conventional outrigger system is no doubt a very efficient and reliable model of structural system, but the scope of improvement cannot be denied. Virtual outrigger presents a unique solution to the needs of structural stability as well as commercial utility and economic viability of a building. When designed proportionately and with more research, the virtual outrigger system can also be employed skyscrapers with no wastage of space and easier connections. The possibilities in achieving optimisation in terms of material as well as construction techniques for the virtual outrigger system are numerous.

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