

Outrigger Structural System – A Review and Comparison of the Structural System

Prof. N. G. Gore, Miss Purva Mhatre
Assistant Professor, Post Graduate Student

Mahatma Gandhi Mission's College of Engineering and Technology, Navi Mumbai, India

Abstract

The paper presents a brief understanding of the concept of outrigger system and explains its structural composition and advantages. The paper explains the different types of outrigger – conventional, offset and virtual. It tries to establish advantages of virtual system over others. Although theoretically conceptualized, the structural system has potential to suit the requirements and demands of a structurally and economically viable tall building. The paper presents an elaborate comparison of the lateral load resisting systems and also compares the virtual system with the conventional outrigger system.

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

I. INTRODUCTION

The never ending human quest to reach the sky has developed far more from its historical advancements. Continuous research in the field of materials, construction technology and development of analysis soft-wares and operating systems has facilitated the construction of the modern marvels of the 21st century. These tall buildings have come to define human dominance and have essentially become a symbol of status and social & economic well-being of a country.

Though fancy on the outward, high-rise buildings are a result of pioneering architecture, calculated engineering and sheer hard-work. As the height of building increases, it is subjected to the action of lateral (horizontal) loads – seismic forces and wind forces. Intensity of seismic forces varies with the location of the building. Wind forces increase parabolically with the height of the building. Seismic forces are more intense in comparison to wind forces, but are shorter in duration. Apart from the vertical loads (dead and imposed loads), tall buildings are essentially designed to resist the lateral loads acting on these buildings.

II. STRUCTURAL SYSTEMS FOR TALL BUILDINGS

In the modern era, tall buildings are designed majorly using the following structural systems:

- **Interior system:** When the major part of lateral load resisting system is located within the interior

of the building, it is known as interior structural system. A brief comparison of various interior structural systems is shown in the table below:

TABLE 1: INTERIOR STRUCTURAL SYSTEM

Structural System	Material/Configuration	Efficient height
Rigid frames	Concrete	20
Braced hinged frames	Steel shear trusses + Steel hinged frames	10
Shear wall/Hinged frames	Concrete shear wall + Steel hinged frame	35
Shear truss frame	Concrete shear wall + Steel rigid frame	60
	Concrete shear wall + Concrete rigid frame	70
Outrigger system	Shear core + Belt truss + Steel/Concrete composite columns	150

- **Exterior system:** If the major part of the lateral load resisting system is located at the building perimeter, it is called exterior structural system. The table below compares different types of exterior systems:

TABLE 2: EXTERIOR STRUCTURAL SYSTEM

Structural System	Material/Configuration	Efficient storey limit	
Tube	Framed tube	Concrete	60
	Braced tube	Concrete	100
	Bundled tube	Concrete	110
	Tube in tube	Ext. frame tube + Int. core tube	80
Diagrid	Concrete	60	
Super frames	Concrete	100	

From the given tables it can be concluded that, outrigger systems provide the possibility of higher number of floors with structurally stable configuration. Outrigger system has been successfully used in a number of iconic buildings since the late 20th century, including the world's tallest building - proving its prevalence over other structural system.

III. OUTRIGGER STRUCTURAL SYSTEM

The outrigger structural system is a lateral load resisting system in which the external peripheral columns are tied to the central core with very stiff outriggers and belt truss at or more levels. The belt trusses are tied to the peripheral columns of the building while the outriggers engage them with main or central shear wall. This structural system is commonly used as one of the structural systems to efficiently control excessive drift due to lateral load, so that during small or medium lateral load due to either wind or earthquake, the risk of structural and non-structural damage is minimized. The structural response of an outrigger system is based on tension-compression couple induced in the outer columns. The outrigger acts as a stiff arm engaging outer columns and central core. The lateral load when induced in the central core is transferred to peripheral columns via outriggers and the overturning moment reduced.

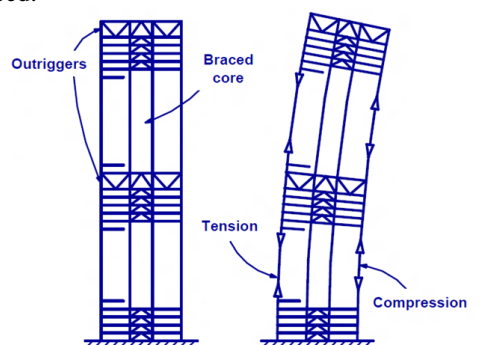


Fig 1: Structural response of Outrigger

For high-rise buildings, particularly in seismically active zone or wind dominant regions, outrigger system is chosen to be appropriate structural system. Outrigger structural system is broadly classified into the following:

- **Conventional outrigger system:** In this system, the outrigger trusses or girders are connected directly to shear walls or braced frames at the core and to the columns located at the periphery of the structure.
- **Offset outrigger system:** In offset outrigger system, the outriggers are 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.
- **Virtual outrigger system:** In virtual outrigger system the transfer of overturning moment from core to peripheral columns is achieved without a direct connection between the peripheral columns and the core. This is achieved using floor diaphragms which transfer overturning moment in the form of a horizontal couple from core to the outboard. A belt truss connecting the peripheral is also added.

IV. LITERATURE REVIEW

The concept of outrigger system is drawn from the use of a contraposing float rigging beyond the side of a boat to improve the vessel’s stability against wind in the sea. This simple mechanism sophisticated modern researchers’ minds to develop outrigger structural system. Successful projects have been built with the outrigger concept. A lot of research has been done in understanding outrigger typologies, material use, placing and connections and efficient positioning of outriggers.

Andrew J. Horton in ‘Virtual Outriggers in Tall Buildings’ has given an elaborate overview of conventional, offset and alternative offset outriggers. His paper concludes that virtual outriggers can be used with the same efficiency as conventional outriggers when efficiently proportioned perimeter belt truss and floor diaphragms are used.

Smith and Coull made a hypothetical assumption that the outriggers are flexurally rigid and devised for the optimum – the outriggers should be placed at $1/(n+1)$, $2/(n+1)$, up to the $n/(n+1)$ height locations, i.e. for one-outrigger structure at approximately half-height, for two-outrigger structure at one-third and two-third height, for three-outrigger structure at one-quarter, one-half and three-quarter heights, and so on.

R Shankar Nair explained the advantages of virtual outrigger system over the conventional type and explained the ways of using virtual outrigger system. The paper compared lateral displacement of 75 - storey model subjected to wind load for different structural designs. The results obtained are as follows:

TABLE 3: COMPARISON FOR LATERAL DISPLACEMENT

Structural System	Lateral displacement
No outrigger	108.5 inch
Conventional Outrigger	25.3 inch
Belt truss as virtual Outrigger	37.1 inch
Belt truss as virtual Outrigger: 10 fold increase in floor diaphragm stiffness	31.0 inch
Belt truss as virtual Outrigger: 10 fold increase in floor diaphragm stiffness, 10 fold increase in floor belt truss stiffness	26 inch

Po Seng Kian and Frits Torang Siahaan studied the use of outrigger and belt truss system in high-rise concrete buildings of 40 and 60 storeys subjected to wind and seismic load. The paper concluded that the use of outrigger and belt-truss system in high rise buildings increases the stiffness and made structural form efficient under lateral loads.

J. R. Wu and Q. S. Li presented designs of multi-outriggers in tall buildings and also gave an elaborate description of the structural performance of outrigger-braced frame-core structures. The paper presents

numerical equations for analysis of multi-outrigger systems subjected to uniformly distributed load, horizontal load and triangular load.

Z. Bayati gave light on the use of optimum number of outrigger systems in a building using a 80 storey model and investigating on drift reduction. The results imply that optimized use of multi-outrigger system effectively reduces the seismic response of a building.

N. Herath reviewed the behaviour of outrigger beams in high rise buildings under the influence of seismic loads. The optimum outrigger location is determined at 0.44-0.48 times the height of the building.

S. Fawzia, et al studied the effects of cyclonic winds on 28, 42 and 47 storey buildings of L-shaped layout. The results show that the plan dimensions have vital impact on structural heights. Also, increase in height with same plan dimensions leads to reduction in lateral rigidity.

Hi Sun Choi and Leonard Joseph outlined a detailed approach for design considerations in outrigger system. It gives design guidelines for conventional and virtual outrigger system. It explains factors like structural aspects, load transfer paths, optimum location of outrigger, diaphragm floors, stiffness reduction, differential shortening of columns and thermal impact.

V. EXISTING TALL BUILDINGS WITH OUTRIGGER

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 are a challenge; which are vigilantly tackled by engineers by careful selection of suitable lateral load resisting system. A number of noted buildings around the world have outrigger frame structural system which has proven efficiency to effectively resist lateral loads and provide structural serviceability. Existing buildings have made use of conventional outrigger system as well as offset outrigger system. The table below lists few of the popular tall-buildings round the globe using outrigger system:

TABLE 4: SKYSCRAPERS WITH CONVENTIONAL OUTRIGGER SYSTEM

Building	City	Details	#
Burj Khalifa	Dubai	828 m 160 floors	5
Taipei 101	Taipei	509 m 101 floors	11
Shanghai Worlds Financial Centre	Shanghai	492 m 101 floors	8
International	Hong	483 m	4

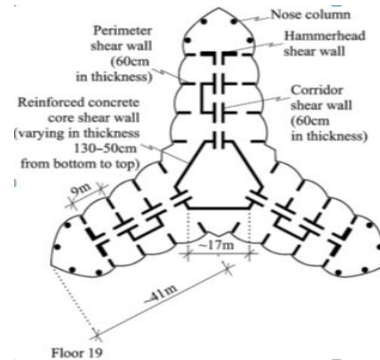
Commerce Centre	Kong	118 floors	
Petronas Twin Towers	Kuala Lumpur	452 m 88 floors	1
Nanjing Greenland Financial Centre	Nanjing	450 m 89 floors	3
Trump International Hotel & Tower	Chicago	423 m 96 floors	3

#: Number of Outrigger levels in the building

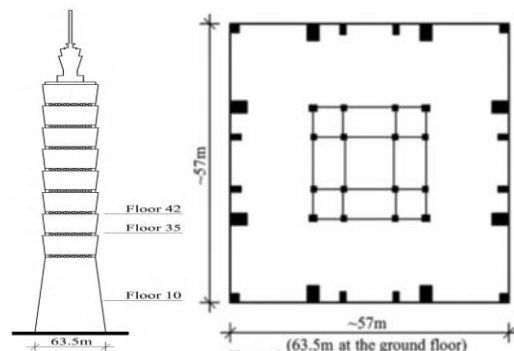
The 163 storey and 828 m tall **Burj Khalifa** is a ‘Y’ shaped building constructed in 2010 in Dubai, UAE.



The world’s tallest building is a reinforced concrete structure using high strength concrete of 60-80 MPa throughout the height of the building. The central hexagonal core is buttressed by wing shear walls with each wing having outriggers connecting shear walls to external columns.

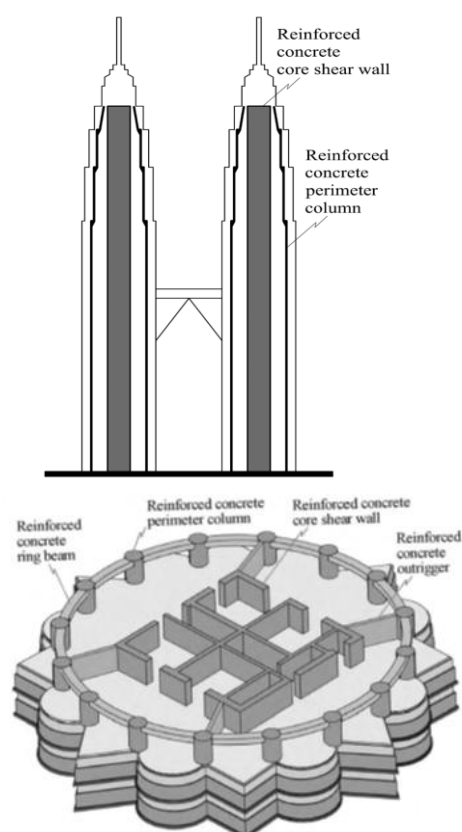


Taipei 101 is an office building with 101 storeys and is 508 m tall.



A composite building with a 63.5 x 63.5 m square cross section at the base, the building has 8 modules of truncated pyramid. High strength concrete of 70 MPa is used and the structure has 8 perimeter mega columns and 16 core columns – all composite.

Constructed in 1998, the **Petronas Towers** is a 452-m tall, 88- storey building reinforced concrete building in the shape of an 8-pointed star. Both towers of the building have identical shape and are connected at 38th floor by a two-storey deep outrigger.



The diameter of 16 perimeter columns varies from 240 cm at the bottom to 120 cm at the top. The reinforced concrete cores of both the buildings are sized 22.9 x 22.9 m

Although successfully used, the conventional outrigger system has its own disadvantages. Also, in contrast to the wealth of information and real life examples of conventional outriggers, there is a relative dearth in the exploration in the field of virtual and offset outrigger. Very few buildings have been made using these structural systems. They are:

TABLE 4: SKYSCRAPERS WITH OUTRIGGER SYSTEM

Building	Details	Outrigger information
Dubai Tower, Doha	438 m 90 floors	1 Conventional; 2 Alternative offset
Plaza Rakyat Office Tower, Malaysia	382 m 79 floors	1 Conventional; 2 Virtual

Aston Apartments Residential Tower, Sydney	90 m 30 floors	1 Alternative Offset
--	-------------------	----------------------

The only skyscraper with a virtual outrigger system is Plaza Rakyat in Kuala Lumpur. The construction of the 382 m tall-building started in 1990s but is still pending.

VI. VIRTUAL OUTRIGGER SYSTEM

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.

The main feature of virtual outriggers is the use of **diaphragm floors**. Understanding the behaviour of floor diaphragms is important for efficient functioning of a structure with virtual outrigger as lateral load resisting system. Diaphragm floor is a stiff & strong floor placed at the top and bottom of the virtual outrigger storey, at the periphery of which belt wall or belt truss is used to connect external columns. The diaphragm transfers the overturning moment from the core to external columns and the belt truss/wall distributes it equally throughout.

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

- **Belt trusses as virtual outriggers:** The overturning moment in the core is converted into a vertical couple at the exterior columns. The 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. The horizontal couple, transferred through the two floors to the truss chords, is then converted by the truss into vertical forces at the exterior columns.
- **Basement as virtual outriggers:** The basement of a tall building can serve as a virtual outrigger by creating a base with 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 as outriggers, there may be little additional cost involved in applying this concept.

VII. CONVENTIONAL VS. VIRTUAL OUTRIGGER

Conventional outriggers hold their popularity owing to the considerable advantages of deformation reduction and structural efficiency put forth by them.

But in spite of these advantages, conventional outrigger has the following drawbacks:

- The space occupied by the outrigger trusses causes constraints on utility floors at which outriggers are located. Even in mechanical equipment floors, the presence of outriggers can be a major problem.
- Architectural and functional reasons limit the placement of large outrigger columns.
- 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 be shorted equally under gravity – causing differential shortening.

These disadvantages of conventional outriggers present a number of challenges for the architects, engineers as well as users. Virtual outriggers present a polished solution to the problems presented by the conventional type. Benefits of virtual outriggers over conventional outriggers are as follows:

- No trusses in the space between the building core and building exterior.
- Complications caused by differential shortening of the core and the outrigger columns are avoided.
- Fewer constraints on the location of exterior columns.
- Strenuous connections of the outrigger trusses to the core are eliminated.
- All 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.
- 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.

VIII. CONCLUSION

High-rise buildings are the essence of modernisation and structural systems define their existence. 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 in 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.

IX. FUTURE SCOPE

Virtual outrigger system is a widely known topic but it lacks sufficient research. Analysis can be done to determine optimum depth of floor diaphragms, economic number of virtual outrigger storeys in a given height of building, material usage and optimum positioning of virtual outrigger in a given height of a building.

REFERENCES

- [1] R Shankar Nair, Belt Trusses and Basements as Virtual Outriggers for Tall Buildings, *Engineering Journal*, Fourth Quarter, Page 140-146, 1998.
- [2] PoSeng Kian & Frits Torang Siahaan, The Use of Outrigger and Belt Truss System for High-rise Concrete Structures, *Dimensi Teknik Sipil*, Volume: 0.33, Number: 01, Page 36-41, March 2001.
- [3] J R Wu & Q S Li, Structural Performance of Multi-Outrigger-Braced Tall Buildings, *The Structural Design of Tall and Special Buildings*, Published online by Wiley InterScience, page 155-176, 2003.
- [4] Z Bayati, M Mahdikhani & A Rahaei, Optimized use of Multi-Outrigger System to Stiffen Tall Buildings, *The 14th World Conference on Earthquake Engineering*, October 12-17, 2008, Beijing, China.
- [5] N Herath, N Haritos, T Ngo & P Mendis, Behaviour of Outrigger Beams in High rise Buildings under Earthquake Loads, *Australian Earthquake Society Conference*, 2009.
- [6] S. Fawzia, A Nasir & T. Fatima, Study of Effectiveness of Outrigger System for High-Rise Buildings under Earthquake Loads, *International Journal of Civil Environmental, Structural, Construction and Architectural*, Volume: 05, Number: 12, Page 789-797, 2011.
- [7] Hi Sun Choi & Leonard Joseph, Outrigger System Design Considerations, *International Journal of High-rise Buildings*, Volume: 01, Number: 03, Page 237-246, September 2012.