EFFECTIVENESS OF VARIOUS OUTRIGGER SYSTEMS UNDER DIFFERENT STRUCTURAL MATERIALS FOR A REINFORCED CONCRETE HIGH RISE BUILDING SUBJECTED TO WIND LOADS

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Dissertaion submitted in partial fulfillment of the requirements for the degree Master of Science in Civil Engineering

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Declaration

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Abstract

The structural efficiency of tall buildings significantly relies on the lateral stiffness of building and its resistance capacity against lateral loads. However, when the structure becomes taller and slender, the building responses under wind loads become more pivotal as it reduces structural stiffness of building. Therefore outrigger and belt truss structural systems that connect through the central core system and the most exterior columns in building are often introduced in high rise structures to provide adequate lateral stiffness in order to control the wind deflection and drift criteria in acceptable limits. Most research works are limited to building with outrigger systems of concrete material, consisting of simple square and rectangular shaped building plan layouts having vertical regularity. Only few studies were based on a single model under different patterns of outrigger structural systems to identify the optimum outrigger structural system when outrigger arrangements are varied. This study aims to bring a broader understanding of both conventional outrigger & virtual outrigger systems by identifying the most efficient lateral load resisting outrigger system for a reinforced concrete high rise building under different outrigger structural materials of concrete, steel and composite by comparing the performance for three different outrigger arrangements; only outriggers, only belt truss and combination of both outrigger and belt truss when subjected to wind loads while their positions remain constant for all the three cases. The structural performance was evaluated based on building frequency, wind induced lateral displacement at top storey and inter storey drift ratio and results demonstrate that addition of outriggers and belt trusses of different structural materials have significantly enhanced the structural performance of building against wind action and the best form of outrigger structural arrangement is varied based on each structure material.

Keywords: Outriggers, Reinforced Concrete Building, Wind Load, Lateral Displacement, Inter Storey Drift

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List of Abbreviations

Abbreviation	Description
CTBUH	Council on Tall Building and Urban Habitat
UAE	United Arab Emirates
USA	United States of America
RC	Reinforced Concrete
3D	3 Dimensional
MEP	Mechanical, Electrical & Plumbing

List of Appendices

1. INTRODUCTION

1.1 Research Background

Tall structures have enchanted mankind from the inception of civilization, originally for defense purposes and then subsequently for aesthetic concerns. In ancient times, tall monumental structures like pyramids, cathedrals and temples were built to honor the Gods and it was 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 and they are built to showcase the power, wealth and prestige of a country.

Recent advances in creative design approaches of architects, rapid urbanization and lack of urban lands, excessive cost and necessity of prevention of disorder urban expansion have resulted in increasing the height of buildings and trend in erection of tall building structures. In early days, very few structural forms were used in the design of tall buildings. However, currently due to the rapid technological advancements in modern science like innovations in material technology, developments in construction techniques and operating systems it enables various structural configurations and profiles to be used for tall buildings.

Currently due to the rapid pace of developments in high strength materials, the weight of the buildings have decreased considerably while enhancing the slenderness and flexibility of structure. Eventually, the buildings become more critical under wind and earthquake induced lateral loads as it reduces structural stiffness of building.

By accommodating a very effective and efficient core-wall structural system into a tall building, drift and displacement parameters due to lateral loads can be reduced remarkably. Nevertheless in tall buildings as the structure height increases, the standalone core wall structural system can barely provide the sufficient structural stiffness to control the drift and displacement criteria within the acceptable limits. Therefore, in such cases, outrigger structural systems are introduced into tall buildings where deep and stiff elements are connected through the central core wall system and the most exterior columns of the building, reducing the sway of the building.

However, the comparison of structural performance of both conventional and virtual outrigger systems to resist lateral loads in tall buildings has been widely investigated and those studies have extensively done for various outrigger typologies and to determine the optimum number and positions of outriggers to be used in different heights of buildings. On the other hand those studies are mostly limited to concrete outriggers only. Hence, this research is focused on identifying the most efficient lateral load resisting outrigger system under different outrigger structural materials of concrete, steel and composite by comparing the performance for three different outrigger arrangements; only outriggers, only belt truss and combination of both outrigger and belt truss for a reinforced concrete high rise building.

1.2 Objectives

The structural performance and efficiency of outrigger systems used in tall buildings to resist lateral loadings depend on different forms of structural outrigger configurations, the number of outrigger levels provided in building, relative locations of outrigger/outriggers along its height of building, outrigger plan layout, outrigger truss depths, primary structural materials used etc.

In this framework, the specific objectives of the present dissertation are briefly summarized below:

- Investigate the effectiveness of conventional outrigger and virtual outrigger systems on the structural performance of a reinforced concrete multi-outrigger level circular shape high-rise structure when subjected to static wind loads

- Evaluate the best outrigger structure type; only outrigger, only belt truss & combination of both outrigger and belt truss systems for above reinforced concrete building under each category of different structural materials; concrete, steel & composite

1.3 Scope of Research

The foremost objective of present study is to explore the effectiveness of conventional and virtual outrigger systems on the structural performance of a reinforced concrete high-rise structure subjected to static wind loads and evaluating the best outrigger structure type under each category of different structural materials used for outrigger bracings and belt trusses through a modeling program.

This analysis program consists of two parts. The first part consists of identifying the effectiveness of using conventional and virtual outrigger systems on the structural performance of a reinforced concrete high-rise building when sustained to static wind loads by evaluating the performance of different outrigger arrangements of only outrigger, only belt truss & combination of both outrigger belt truss, compared to the structure without outriggers in terms of different response parameters of natural frequency, maximum wind induced lateral displacement and inter storey drift.

The latter part consists of evaluating the best outrigger structure arrangement for above reinforced concrete building under each category of different structural materials used for outrigger bracings and belt trusses; concrete, steel & composite by comparing the results of above performance characteristics.

1.4 Research Significance

In the modern world both conventional outriggers and virtual outriggers have been used as efficient lateral loads resisting mechanisms in tall buildings. In conventional outrigger concept, the trusses are directly tied in between the central core and mega columns which are occupied at the perimeter of the building and it is proven to be one of the well-structured systems in resisting lateral loads. However, there are several problems associated with conventional outrigger systems due to the reduction of usable floor area with the arrangement of outriggers. Therefore majority of the drawbacks related to conventional outriggers can be overcome by using offset outriggers or virtual outriggers in tall buildings. Majority of research have been investigated the structural performance of both conventional and virtual outrigger systems to withstand against lateral forces imposed in tall buildings. The studies have abundantly done for various outrigger typologies, to determine the optimum number and positions of outriggers to be used in different heights and various shapes of buildings in each system.

This study aims to bring a broader understanding of both conventional outrigger & virtual outrigger systems by identifying the most efficient lateral load resisting outrigger system for a reinforced concrete high rise building under different outrigger structural materials of concrete, steel and composite by comparing the performance for three different outrigger arrangements; only outriggers, only belt truss and combination of both outrigger and belt truss, while their positions remain constant for all the three cases.

Most of the previous studies were based on square and rectangular shaped buildings considering simple grids and plans. The present study is to be performed on a circular shaped building having vertical irregularity along its height which represents the actual building topology in modern structures. Only few researches were based on a single model with distinct forms of outrigger arrangements to identify the most efficient outrigger structural system. Therefore this study extends towards analyzing the behavior of a reinforced concrete high rise building, for different types of outrigger arrangements under different structural materials to identify the most efficient outrigger structural system and the optimum primary structural materials to be used in each system when subjected to wind loading.

1.5 Arrangement of the Dissertation

In this dissertation, contents have been organized in five chapters and brief outline of the content in each chapter is presented below.

The first chapter presents an introduction to the research, the overall objectives and the significance of research. In addition to that, the overall framework of the research program is also presented in this chapter.

The second chapter presents a detail review of the literature review conducted throughout the research program and it covers the development of tall building structures and outrigger structural systems.

The third chapter aims to present the methodology of analytical program of research project.

The fourth chapter is focused on the results and the discussion and fifth chapter concludes the findings and recommendations of the research project.

2. LITERATURE REVIEW

2.1 Introduction

The structural design of tall buildings is exceptionally influenced by the magnitude and intensity of lateral loads imposed on that structure. Taller the building, the achievement of structural safety under lateral loads has become a challenge for the structural engineers. The outrigger structural system has been in use since the past few decades and has proven to be satisfying the structural requisites of tall buildings in terms of safety, serviceability and economically (Po Seng Kian, 2001). A large number of projects have been built successfully with outrigger structural concepts all over the world (Choi and Joseph, 2012). Different types of typologies, materials and placing of outriggers have been considered in plenty of studies conducted till date. Simultaneously they have studied the optimum location for outrigger systems for a high rise building depending upon the number of outrigger levels to be used and height of building (Nanduri, Suresh and Hussain, 2013) & (Gawate and Bhusari, 2015). This chapter explains a concise summary of literature review for outrigger structural systems and its performance in tall buildings.

2.2 Tall Buildings

The construction of tall buildings scenario satisfies the demand of rapid growing population in current developing cities to a greater extent. The rapid advancements in modern concrete technology, structural forms and systems, structural analysis software and construction techniques during the twentieth century made it possible to construct more tall buildings globally. For a high rise structure, the building's height plays a vital role during the design, construction and operation phases in the life of the structure when compared to a common building. From a scientific perspective, interpretation of structural behaviour of a tall building has become a barrier for the structural designers.

The definition or perception of 'tall building' varies from person to person as it varies with region and locality. A 10-storey building in New York might not be considered as a tall building, since the average height of buildings in the city of New York is higher. However, 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 from each other only from a dimensional perspective, as the height of the structure is a relative parameter which changes according to the place and time. There is no general standard which can be accepted uniformly across the globe to be used to classify the buildings as tall buildings or skyscrapers. However CTBUH gives some measures to define tall buildings (Choi *et al.*, 2012).

- 50 m or above height buildings are considered as ‘tall buildings’
- 200 m or above height buildings are considered as ‘super-tall buildings’
- 300 m or above height buildings are considered as ‘mega-tall buildings’

The tall buildings had a fascinating history from the Pyramids of Egypt of the 14th century to the modern sky scrapers, where tall buildings have undergone a massive transformation in terms of design, shape, configurations, construction techniques and materials.

In ancient times apartment buildings in Ancient Rome reached around 10 floors. During the classical period most of the high-rise towers were built in many cities by the affluent for defense and for their social status. Prior to the 19th century, structures of more than 6 storeys were rare across the world because reaching to a higher elevation was too difficult at that time. However, with the never ending thirst for reaching the heights and immediate need to optimize the utilization of urban and commercial spaces, engineers invented elevators; facilitating vertical movements within the buildings of any height.
The earliest steel skyscraper, Home Insurance Building was built in Chicago, Illinois. After the construction of Home Insurance Building, the never ending race to the sky was joined in by World Building, Manhattan Life Insurance Building, Park Row Building, Woolworth Building and Empire State Building in New York, followed by Petronas Twin Towers in Kuala Lumpur and Burj Khalifa in Dubai.

When the tall structures are subjected to extreme lateral loads such as wind and earthquake loads, they require special structural arrangements for their structural stability and hence the structural design is generally controlled by those lateral loads imposed on them. As the building becomes taller and slender, it's vulnerability to lateral loads also increases and top storey deflection and drift criteria become more notable parameters. Wind and earthquake induced lateral loads may cause excessive building sway, resulting in severe damage to non-structural elements of the building and façade and may cause malfunctioning of elevators and other mechanical equipment while creating disturbances for occupants comfort and building functions. Hence, in tall buildings it is essential to assure structural safety and standards of occupancy comfort during buildings' design stage.

2.3 Structural Systems for Tall Buildings

Few decades ago in structural designing, only the gravity loads were assumed to be carried by structural members. However, currently due to the rapid pace of developments in structural engineering with respect to high strength materials, the weight of the building has decreased considerably while enhancing the slenderness of structure. Eventually, as the structural slenderness and flexibility improves, the buildings become more critical under wind and earthquake induced lateral loads. Therefore the building's height is one of the predominant factors in identifying the most appropriate structural system for a building in resisting lateral loads.

From a structural engineer's perspective, the finalization of the best and most appropriate structural form for a high rise building may mainly consider the criteria of selection of most efficient arrangement for major structural elements to resist the different gravity and horizontal loading combinations. In practice not only the above consideration, but there are several other key parameters which will strongly affect the choice of the best structural form for a particular high rise structure. The internal planning, structural material and method of construction, external architectural appearance and perspectives, operation of services, nature and extent of horizontal loading applied on structure and the height and aspect ratio of building are some of the crucial factors which need to take into consideration when deciding the most appropriate structural form for a building (Smith and Coull, 1991). When the structure is taller and slender, it is necessary to select the most appropriate structural form for building for its structural stability. Sitapara and Gore have discussed various types of lateral load resisting structural systems employed in high-rise structures to resist lateral forces (Sitapara and Gore, 2016). Out of those, the outrigger structural system has scientifically proven to be the most effective method to be accompanied for high-rises.

The various structural forms available are:

- Rigid frame structural system

  A typical rigid frame structure comprises series of column-beam moment resisting frames and bending resistance of columns, beams along with rigid joints tend to provide the required resistance against horizontal loading imposed on building.

- Wall-frame structural system

  In wall-frame structural system resistance of building against lateral loads is controlled by the interaction between shear walls and rigid frame and this interaction can be effective and economical up to 50 storeys.

- Braced frame structural system

  Integration of bracing is extremely efficient mode in resisting horizontal forces induced in a frame structure. A braced structure comprises series of columns and beams frames predominantly to carry gravity loads and diagonal bracing members which are connected to the primary moment resisting frame to form a vertical cantilever truss to cater horizontal forces applied on the building.

- Outrigger structural system

  In outrigger structures main core is connected to the exterior columns in the moment resisting frame structure by very stiff horizontal beams or girders called outriggers. This arrangement enhances the overall effective depth of the structure and eventually improves the flexural stiffness of building against lateral loads.

- Tubular structural system

  The tube structural systems are considered as hollow cylinders which are widely used in super-tall structures in the different structural forms of framed-tube, bundled-tube, braced-tube and composite-tube systems to resist lateral forces induced on structure.

2.4 Outrigger Structural System

The structural efficiency of a tall building mostly relies on lateral structural stiffness and its resistance capacity against lateral loads. By accommodating a very effective and efficient core-wall structural system into a tall building, drift and displacement parameters due to lateral loads can be reduced remarkably. Nevertheless in tall buildings as the structure height increases, the standalone core wall structural system can barely provide the sufficient structural stiffness to control the drift and displacement criteria within the acceptable limits. Therefore, in such cases, outrigger structural systems are introduced into tall buildings (Po Seng Kian, 2001). They are deep and stiff elements that connect through the central core wall system and the most exterior columns of the building, helping in decreasing the sway of the building as presented in Figure 2.1. At least one storey deep outriggers should be accommodated in tall buildings in order to make them sufficiently effective and to increase the flexural and shear rigidity of building (Gadkari and Gore, 2016).

The above mechanism greatly assists in reducing the moment in the core system of building when compared to a free-standing core wall system without outriggers (Ho, 2016). In the above scenario, the restraint induced by the use of outriggers notably reduces the top storey drift while improving the structural stiffness of the building by 20% to 30% (Sitapara and Gore, 2016). Generally, the insertion of outriggers greatly reduces the available interior space of a building. Therefore in general they are placed at mechanical equipment floor levels not to hinder the floor function in normal floor levels.

Over the past years, outriggers have been extensively utilized in tall building structures (Choi and Joseph, 2012). Due to the rapid enhancements in technology and science, the choices have widened accordingly with time for the options of structural materials to be used in outriggers and as well as for structural forms to be used. In early days, outrigger structural systems were used only to provide additional structural stiffness to the building in order to reduce drift and deflection. However, nowadays they are used to facilitate additional damping and as a structural fuse against severe earthquake forces.

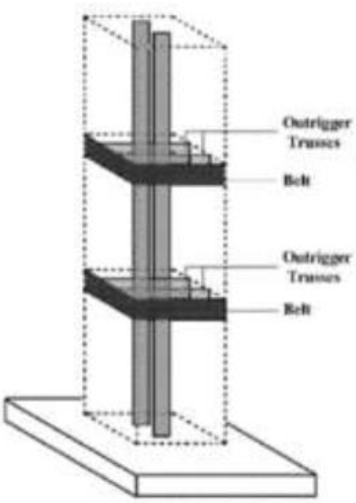


Figure 2.1: Multi Level Outrigger & Belt Truss System

(Source – Global Research and Development Journal for Engineering)

2.4.1 Structural Concept of Outriggers

In the primary lateral load resisting mechanism of the outrigger and belt truss system is, very stiff outriggers are connected in between the external columns and central core wall system or exterior columns are connected together with belt trusses in one level or several levels throughout its building height (Gadkari and Gore, 2016).

Outrigger structural form includes a central core system and horizontal trusses, which connects the core system to the exterior columns. The core system can be centrally located where the outriggers can be extended on both sides and either located on one side. Consequently the combined action of central core system and perimeter moment resisting frame withstand against lateral loads by pure cantilever structural action (Smith and Coull, 1991).

When lateral loads are applied on the building which consists of rigidly connected outriggers present in between the central core walls and exterior columns, eventually the core walls try to rotate result in some structural forces in outrigger trusses, where windward columns are subjected to tensile forces and leeward columns are subjected to compressive forces respectively. The above structural action originates a restoring moment which generates in core at outrigger level and thus the effective depth of structure is improved in due course in order to resist bending moment. To further improve the rotational restraint of outrigger trusses, this can be done by mobilizing all perimeter columns with a single or multi storey deep wall around the building which is commonly known as a "belt truss". The two floor diaphragms in above and below levels of belt truss will try to move right and left due to the rotation of the core and overturning moment. As a result of this belt truss will try to move against and will tend to rotate itself as one face in up and one face in down directions. Then perimeter columns will constrain this movement by developing opposing forces.

According to the above scenario the structural stiffness of the combined system is heavily increased, while reducing lateral drift, internal core moments and lateral displacement of building to a greater extent as described in Figure 2.2.

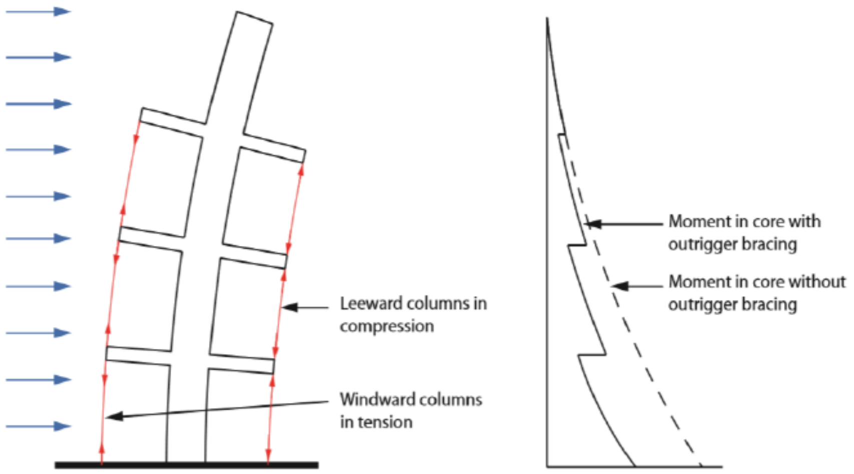


Figure 2.2: Outrigger structure displaced under lateral loading and resultant core moments
(Source – Outrigger Design for High-Rise Buildings: CTBUH)

2.4.2 Advantages & Disadvantages of Outrigger Systems

The benefits and challenges of outrigger system along with design considerations can be emphasized in terms of structural characteristics, load transferring paths, optimum location of outriggers in elevation, diaphragm action in floor plates to transfer the loads, stiffness reduction, differential column shortening effects and thermal effects induced by temperature differences between exterior and interior surfaces of building (Choi and Joseph, 2012). The major advantages and disadvantages can be categorized as follows.

Advantages

- Reduction of lateral displacements of building through reduced overturning moments
- Reduces shear and flexural demands of foundations
- Facilitate an alternate load transfer path for structural robustness to avoid disproportionate collapse
- The use of few exterior mega columns in each face of building allows to use a more flexible façade system and creates more aesthetic and architectural perspective
- Can be easily incorporated into any structure material steel, concrete or composite
- Columns and foundation uplift tension forces can be reduced

Disadvantages

- The available floor space occupied by diagonal outrigger trusses creates obstructions on intended floor functions in outrigger floor levels
- Large outrigger trusses can create disturbance for architectural perspective of building and perimeter facade
- Very complicated and detailed connections need to accommodate when connecting outrigger trusses to the core
- In generally, the core and outrigger columns will not compress to same amount under gravity loads. Therefore very stiff outrigger trusses need to be accommodate as they tend to severely stressed while restraining the induced differential shortening between the core and outrigger columns

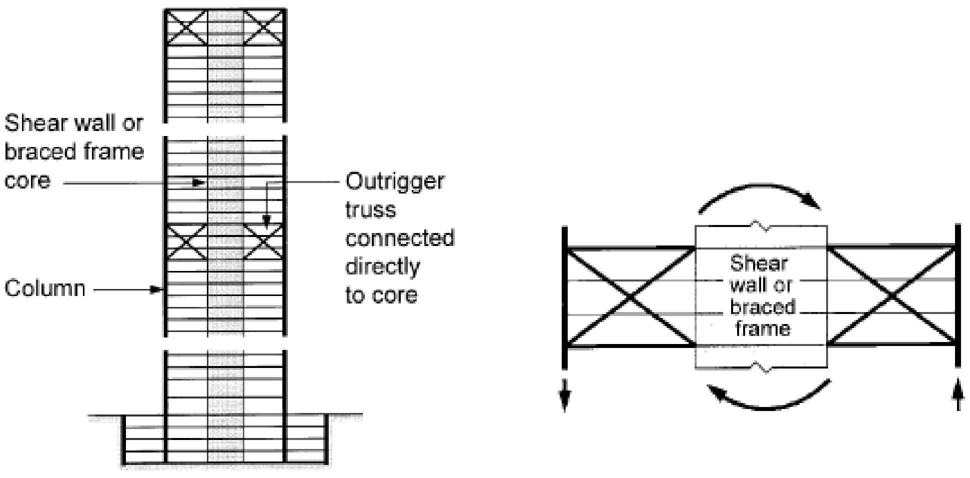
2.4.3 Types of Outrigger Systems

Two major forms of outrigger systems can be recognized based on the structural mechanism of connectivity in between outriggers and core wall system.

- Conventional outrigger system
- Virtual outrigger system

2.4.3.1 Conventional Outrigger system

Within this system outrigger girders are directly tied in between the core walls and exterior columns of the building. Those trusses prevent rotation in the central core and transform a certain part of the core moment produced due to lateral loads into a vertical couple at perimeter columns. The structural arrangement and the force transferring mechanism of conventional outriggers in tall buildings are presented in Figure 2.3. Elastic shortening and elongation effect in vertical members and deformations generated in trusses permits a certain rotation in core at the outrigger levels. Principally, the amount of this rotation is negligible and hence the core is subjected to a reverse curvature below the outrigger level.



(a) (b)

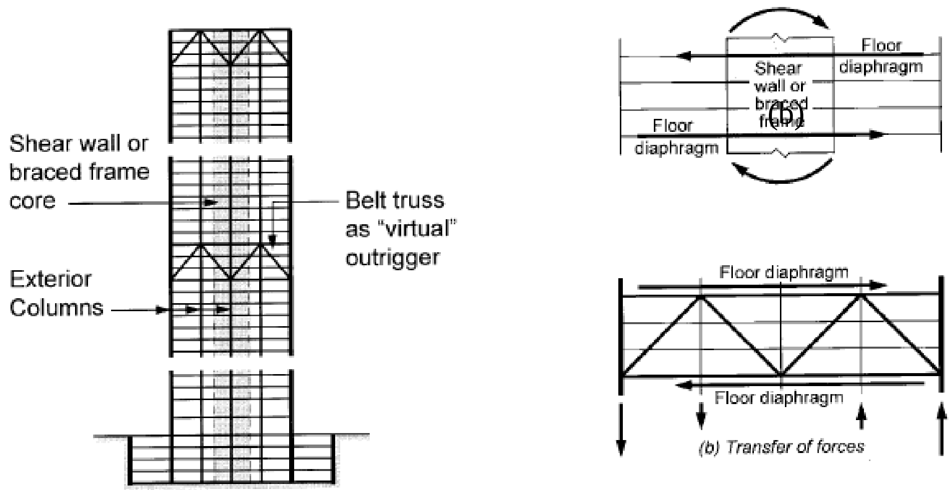
Figure 2.3: (a) Tall building with Conventional Outriggers (b) Force transfer in Conventional Outrigger System

(Source – Engineering Journal, American Institute of Steel Construction)

2.4.3.2 Virtual Outrigger system

In the virtual outrigger concept, the structure undergoes a similar type of structural action where the overturning moment is transmitted from the core to perimeter columns in a similar pattern, in absence of a direct connection in between outrigger trusses and core. Due to the curtailment of this direct connection it mitigates most of the drawbacks which were associated with the conventional outrigger system.

The use of floor diaphragms in the virtual outrigger system plays a vital role in its specific structural system. Normally floor diaphragms are very stiff and have the ability to transform the core moments into a horizontal couple in the belt trusses at the other end. In this mechanism, rotation in core is restricted by the structural action of floor diaphragms which are located at both top and bottom floors of belt trusses by converting a certain part of the core moment into a horizontal couple in respective floors. Eventually this horizontal couple is transmitted to the truss chords through above two floors and then converted into a vertical couple in exterior columns and other structural elements in belt truss. The structural arrangement and the force transferring mechanism of virtual outriggers in between the central core and the perimeter belt truss in tall buildings are presented in Figure 2.4.



(c)

(a)

Figure 2.4: (a) Tall building with Virtual Outriggers (b) Force transfer from core to floor diaphragms (c) Force transfer from floor diaphragms to columns
(Source – Engineering Journal, American Institute of Steel Construction)

Numerous advantages and many benefits can be achieved by using belt trusses in virtual outrigger systems, while diminishing majority of the complications associated in conventional outriggers. Though the structural effectiveness or efficiency is reduced in virtual outrigger systems it will be compensated by the following assistance extended by this structural concept.

- No any diagonal trusses connecting in between the core and the exterior columns and hence no any disturbance for floor spaces or intended floor functions
- There are fewer constraints in selecting the locations for exterior columns
- All perimeter columns can participate in resisting overturning moment against lateral loads
- No any complicated connections between outrigger trusses and central core
- Differential shortening or settlement between the core and the outer columns does not affect in this structural system

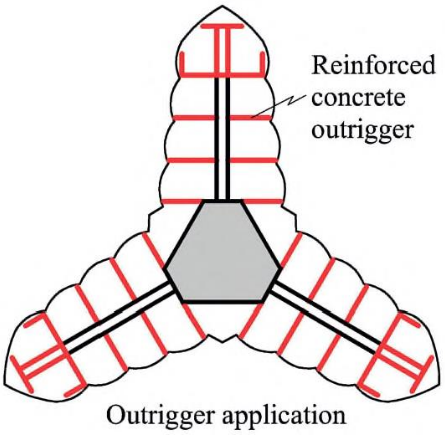
2.4.4 Existing buildings with outriggers

A wide range of tall buildings have been erected successfully across the globe using the principles of outrigger structural systems. Greater resistance to lateral loads and wider flexibility has enabled the popularity of this structural system. The following paragraphs outline a brief understanding of a few renowned sky-scrapers with outrigger frame structures.

- **Burj Khalifa**

Burj Khalifa in Dubai, UAE is a mixed-use development of hotel, residential and offices and it is the tallest building around the globe. The main structural system of above the building is combined with a hexagonal central core and outriggers as presented in Figure 2.5. The hexagonal core incorporates reinforced concrete shear walls of varying thickness from bottom to top throughout its height of structure and shear walls are located at each side in the perimeter of the building including circular columns at the tip. In this structural system, the core and the perimeter columns are connected through buttresses which are located at 5 individual levels basically in mechanical floor levels which increase the strength structure against lateral loads.

(a)



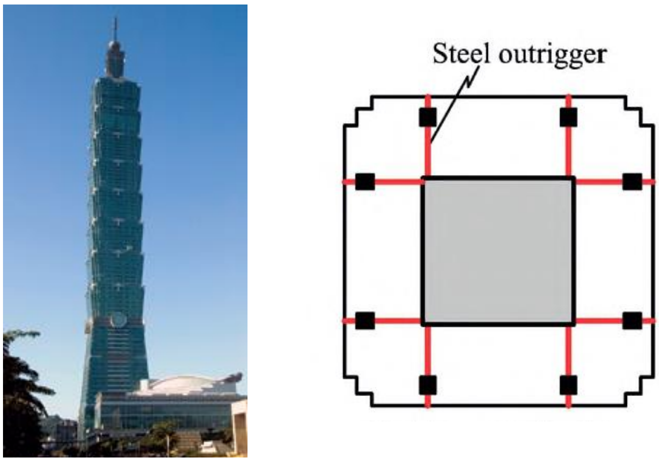
(b)

Figure 2.5: (a) Burj Khalifa (b) Structural Plan of Outrigger System

(Source – Mehmet Halis Gunel and Huseyin Emre Ilgin)

- **Taipei 101**

Taipei 101 in Taipei, Taiwan is an outrigger frame office building made out of composite material. On top of the building it has a 12- storey truncated pyramid. The building contains 8 number of mega columns in perimeter and 16 number of internal core columns fabricated by box-steel sections filled from C70 high strength concrete material. The external and internal core columns are connected to each other through single to two storey deep outriggers at 10 different levels along its total height of the building as presented in Figure 2.6.



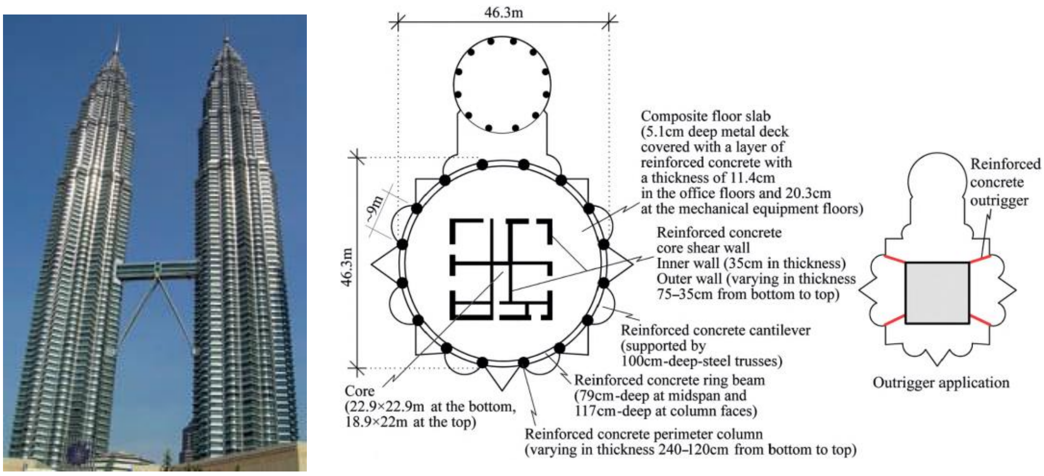
(a) (b)

Figure 2.6: (a) Thaipei 101 (b) Outrigger Application

(Source – Mehmet Halis Gunel and Huseyin Emre Ilgin)

- **Petronas Twin Towers**

Petronas Twin Towers in Kuala Lumpur, Malaysia is a reinforced concrete twin tower structure with outrigger frame systems. In the proposed structural system, reinforced concrete shear walls at core and perimeter columns are connected to each other by two storey deep outriggers at almost mid-height of the building in 38th - 40th floors which are basically the mechanical equipment floors supposing to obtain an additional stiffness to the structure as described in Figure 2.7.



(a) (b)

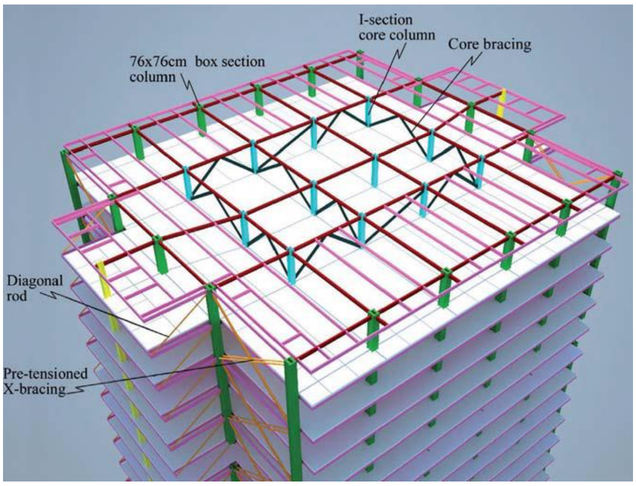
Figure 2.7: (a) Petronas Twin Towers (b) Outrigger Application

(Source – Mehmet Halis Gunel and Huseyin Emre Ilgin)

- **New York Times Tower**

New York Times in USA is an outrigger frame steel building. The structural core is a centrally located braced core which remains the same throughout the total height of building and tower has 30 columns made of built-up box sections. 2 storey deep pretension X-braces are located at almost mid height and top levels in building primarily in mechanical floors for the purpose of improving the lateral stiffness of outrigger frame system as presented in Figure 2.8.

(a)



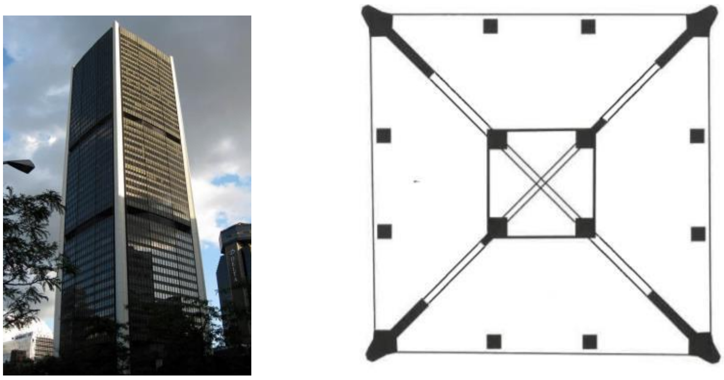
(b)

Figure 2.8: (a) New York Times Tower (b) Structural Bracings System

(Source – Mehmet Halis Gunel and Huseyin Emre Ilgin)

- **Tour de la Bourse**

Tour de la Bourse in Montreal, Canada was the foremost concrete building which employed the outrigger structural system. 4 mega columns were placed at each corner of the building accommodating X braced outrigger trusses connecting the core and the large perimeter columns at four different levels across the building as demonstrated in Figure 2.9. On each side of the building, there are two independent columns between the corner columns working as a backup system to the primary system.



(a) (b)

Figure 2.9: (a) Tour de la Bourse (b) Outrigger Floor layout

(Source – Outrigger Design for High-Rise Buildings: CTBUH)

- **U.S. Bank Center in Milwaukee, Wisconsin**

U.S. Bank Center building in Milwaukee, Wisconsin is a steel framed outrigger building occupied as an office tower. It consists of conventional outriggers and belt trusses almost at the mid and top levels of building as presented in Figure 2.10. Along with, they are placed at the bottom levels of the building to accommodate the change in column grids as well.

Figure 2.10: U.S. Bank Center in Milwaukee, Wisconsin

(Source – Outrigger Design for High-Rise Buildings: CTBUH)

2.5 Review of Literature

A comparative study and analysis have been carried out by Thejaswini and Rashmi to understand the performance of irregular shape building under different lateral load resisting structural systems for earthquake and wind loads (Thejaswini R M and Rashmi A R, 2015). The analysis was conducted for a 14 storey, geometrically irregular RC high rise building for separate forms of structural systems of rigid frame, core walls and shear walls structure, tube and outrigger structure. According to the study, lateral displacement, inter storey drift, columns stability for a particular storey due to lateral forces and torsion irregularity parameters were studied and compared. According to those results, stability of the tube and L shape shear wall structures are high in terms of torsion irregularity and displacement when compared to other general structures. The paper also outlines that when accommodating an outrigger at optimum location of the building drift can be fully controlled.

Ho has studied the progression of outrigger structural system with time in tall buildings and different applications in terms of optimum topology, design and construction considerations (Ho, 2016). The paper describes axial shortening effect as one of the major drawbacks in outrigger design and the necessity of reducing it during construction and life cycle phases of building. It explains the methods for adjustable outriggers in tall building construction such as retro-casting method and also damped outrigger systems provided for the best performance of buildings. The paper suggests outrigger as a modern lateral load resisting system giving examples from all around the world.

Nair has proposed the offset outrigger concept idea for belt truss system and use of basements as virtual outriggers in tall buildings, as it offers many benefits to overcome the problems associated with conventional outriggers (Nair, 1998). The paper describes the study of the effectiveness of using belt trusses as virtual outriggers in a 75 story steel frame office tower which contains three levels of 4-story deep outriggers, by comparing conventional and virtual outrigger systems. In the proposed system, maximum lateral displacement at top storey of 25.3 inches was achieved due to wind load and when the floor diaphragm and belt truss stiffness increased by 10-fold it was observed 26 inches. The paper concludes that due to the reduction in stiffness of the above mechanism, virtual outriggers are less effective than conventional direct outriggers.

Bayati et al. have studied the optimization in use of multi outrigger systems in tall buildings (Bayati, Mahdikhani and Rahaei, 2008). The paper introduces the results of an analysis conducted to identify the effectiveness of using belt trusses as virtual outriggers, for a case study of an 80-story steel-framed office tower in Tehran's Vanak Park (Iran). In the proposed building three levels of four storeys deep outriggers were accommodated at three different locations in the building. The analysis results exhibit that by using optimized multi outrigger levels it can beneficially minimize the seismic response of buildings. As well, it showcases that multi outrigger systems can reduce structural elements and foundation sizes also. The comparative study between conventional and virtual outrigger systems reveals that the maximum lateral displacement was resulted in the case of virtual outriggers as belt trusses. When the in-plane stiffness of both top and bottom floors and belt truss members were improved, the displacement was further decreased.

Shehu has studied on the performance characteristics of the building which was designed or redeveloped by conventional or virtual outrigger methods (Shehu, 2015). It highlights the ductile characteristic of the structures during post elastic phase and their performance during seismic events. Three buildings structural models with different heights of 25, 30 and 35 storeys are used to study three different structural systems of rigid outrigger, vierendel outrigger and bracing outrigger and those results have explained with regard to internal forces, deformations, capacity and ductility. Analysis results showed that outrigger structure has the highest performance compared to the structure without outriggers, but the ductility is reduced. At the same time structures with diagonal bracing contribute to the performance of structure without reducing its ductility. Vierendel outrigger system has a smaller effect on the stiffness and strength of structure, but it has a higher ductility compared with other structures.

Kamath et al. have considered the static and dynamic behavior of a 40 storey reinforced concrete outrigger structure when the relative flexural rigidity varies from 0.25 to 2.0 at a step of 0.25 (Kamath, 2012). Concurrently the outrigger position has been diversed across the total height of building from relative height of 0.975 to 0.4. Both static and dynamic analysis have been carried out considering parameters of bending moments and shear force variation, lateral deflection, peak acceleration and inter storey drift. The paper concludes that when the outrigger is located at mid height of structure, lateral displacement can be minimized and when it is placed at top level, similarly the peak acceleration can be reduced. Overall it has been found that the most efficient outrigger performance can be obtained when the outrigger is located at mid height.

Kogilgeri and Shanthapriya have studied the static and dynamic behavior of steel outrigger structural systems while reducing the outrigger depth (Kogilgeri and Shanthapriya, 2015). 40 story steel outrigger structure models with different depths of outriggers are compared and contrasted, while the outrigger depth is reduced to 2/3rd and 1/3rd of story height compared to full story height. In all structures, the belt-truss depth was maintained as it equals to the typical story height and lateral deflection and storey drift parameters were compared. When the outrigger depths is reduced to 2/3rd of story height, lateral displacement and inter story drift reduces by small percentage comparatively to full story height outriggers. Further reduction in outrigger depth to 1/3rd of story height, it does not indicate any significant reduction. Therefore results showed that there is an insignificant difference in resistance of lateral loads, between two structural systems of full storey depth and decreased depth.

Herath et al. have reviewed the performance characteristics of outrigger trusses in high rise buildings for earthquake loads to identify the optimum outrigger location in tall buildings (Herath *et al.*, 2009). Analysis was conducted for a 50 storey building under three different types of peak ground accelerations and frequency ratios using response spectrum analysis for different outrigger positions across the building height. The performances were evaluated considering response characteristics such as lateral displacement and inter storey drift for both options of single outrigger system and two outrigger systems. As per the results, selection of outrigger location plays a pivotal role on the lateral performance of building and the optimum outrigger location was identified as nearly mid height of building under earthquake loads.

Fawzia and Fathima have studied the most effective outrigger position for a composite building under lateral wind loads for different types of building plan layouts, different heights and different outrigger arrangements of structure (Fawzia and Fatima, 2016). A comprehensive dynamic cyclonic wind analysis was carried out for composite building models for three separate plan layouts of rectangular, octagonal and L shaped when the heights of buildings vary from 28, 42 and 57 storey amidst several combinations of belt trusses and outrigger bracings. The results showcase that all the above said key parameters significantly affect the resistance of building to the wind action.

Wu and Li have presented about the optimal design basis for a multi-outriggers tall structure, throughout a structural analysis of a braced outrigger frame-core structure (Wu and Li, 2003). The analysis was focused on evaluating the performance characteristics of base moment, top drift and fundamental vibration period by changing the outrigger locations throughout the building height. The paper discussed some numerical equations that can be referred to determine optimum core dimensions when the structure subjected to uniformly distributed load and horizontal triangular load. The major conclusions of the study are that when an outrigger-braced structure is exposed to horizontal triangular loads, it has more optimum numbers of outrigger locations when compared to a horizontal uniform loaded structure. When an outrigger is located at the top most level, the optimum locations of other movable outriggers are relatively lower than the corresponding optimum locations of the building without an outrigger at the top floor level.

According to the study done by Nanduri et al., they have determined the structural behavior, optimum location and structural efficiency of outrigger systems for a high-rise reinforced concrete building under wind and earthquake loads (Nanduri, Suresh and Hussain, 2013). A 3D model of a 30 storey building consisting of outriggers and belt truss systems were analyzed for wind and earthquake loads and studied the reduction in lateral displacement with respect to the outrigger and belt truss locations. As per the results it declares that the drift can be fully controlled remarkably by providing an either outrigger or combination of outrigger with belt truss system at the mid height of the building when compared to a single core building.

Vijay et al. have used regression analysis to optimize the outrigger position and outrigger depth in tall buildings (Vijay, James and Kurian, 2017). Numerical method of regression analysis was used to identify the respective variables which affect for top storey deflection in outrigger braced structure. Analysis results demonstrated that the optimum location for outriggers is the mid height of building and there is a linear variation in between the outrigger depth and top storey displacement.

Gawate and Bhusari have studied the optimum location for outriggers in tall buildings by changing the columns and shear walls cross sectional sizes throughout its height of building (Gawate and Bhusari, 2015). Analysis carried out for a 30 storey 3D model having numerous configurations of single and double storey deep outriggers when the cross sectional area of columns, shear walls vary accordingly in top levels. The conclusions were made based on lateral drift and formation of soft storey where in terms of drift, single storey outrigger structural system was not effective as double storey outrigger system, while no story was found to be a soft story.

Hangollahi et al. have compared the optimum outrigger locations of a steel framed high rise building under earthquake loads in reference to lateral displacement and inter story drift (Haghollahi, Ferdous and Kasiri, 2012). Response spectrum and time-history analysis have been conducted against different seven ground motions for 20 and 25 storey outrigger and belt truss steel building. As reported by response spectrum analysis, the most effective and optimum location for outrigger and belt truss systems to be mid height of building. According to time-history analysis, the optimum location to be 1/3rd of the structure's height from top. The findings of above study conclude that the optimized location of outrigger and belt trusses may change according to nonlinear time-history or response spectrum analysis.

Shivacharan et al. have investigated the optimum outrigger position for a vertical geometric irregular tall structure (Shivacharan, Chandrakala and Karthik, 2015). A 30 storey vertical irregular shape building where plan layout changes at 11th and 21st floor levels was analyzed as a bare frame and with 6 different arrangements of outrigger and belt trusses. The structural responses were evaluated in terms of lateral displacement, building drift and maximum story shear and column axial loads under linear static analysis. As per the study results it concluded that the optimum location of the outrigger is mid height of tall building.

Khanorkar et al. have presented a detailed review on using belt trusses as a lateral force resisting system in tall buildings for controlling deflections due to lateral loads (Khanorkar, Denge and Raut, 2016). It describes numerous methods and techniques for using belt trusses in tall buildings. It has identified the above structural system as an active, cost effective and developed system and it can be utilized in structures without outriggers. It says belt truss can control the deflection with increased stiffness as same as the outriggers and further innovation can be used to increase its efficiency.

Po Seng Kian has explained the application of outrigger and belt truss systems for a high-rise concrete building subjected to wind or earthquake loads (Po Seng Kian, 2001). 40 storey, 8 building models with outrigger and belt truss system were analyzed for wind loads and five, 60 storey models were analyzed for earthquake loads. Comparing the reduction in lateral displacement for wind loads related to the outrigger and belt truss location, the outrigger produced at the middle of the structure reduces the maximum displacement for wind loads. For earthquake loads minimum displacement can be achieved when the outrigger is provided at the middle and top levels of the building.

Prasad and Kumar have compared the performance of different mechanisms of only outrigger, combination of belt truss and outrigger and only belt truss for a reinforced concrete building where the outrigger positions remain constant in all the cases (Prasad and Kumar, 2016). The static and response spectrum analysis methods have been performed for a 30 storey vertical irregular structure comparing the parameters of base shear, lateral displacement and storey drift. Regarding base shear, the structure having only belt truss performed better than the other two structural systems. In terms of lateral displacement, structures with combined outrigger and belt truss and only belt truss systems have better performance characteristics than the only outrigger system. Comparing the storey drift, the combined outrigger and belt truss system exhibits the best structural characteristics. This paper summarized that combined outrigger and belt truss system performs efficiently to lateral loads compared to other cases.

Vijaya Kumari Gowda M R et al. have described a comparative study to investigate the more economical type of belt truss to be used in tall buildings for different seismic zones (Vijaya Kumari Gowda M R and Manohar B C, 2015). The static and response spectrum analysis methods were conducted for a 30 story building model that includes different types of X, V and inverted V belt trusses. The results conclude that the arrangement and location of the shear core across the building plays a vital role in decreasing the displacement and storey drift. And also for a concrete building, concrete belt truss system is the most acceptable material in reducing the lateral displacement and storey drift rather than steel belt trusses. Based on economic conditions, the inverted V-type belt truss system is one of the benefitting truss types for all seismic zones to increase the structural efficiency.

Hasan has carried out a comparison for behaviour of beam and wall outrigger in tall structures under lateral loads (Hasan, 2016). Response spectrum analysis was conducted for a 30 story models of three different mechanisms of bare structure, combination of beam outrigger and belt truss and combination of wall outrigger and belt truss. Both beam and wall outriggers are provided at the $1/3^{rd}$ and $2/3^{rd}$ of the structure height. According to the study it has been concluded that the wall outrigger structure is the most appropriate technique in reducing lateral displacement and storey drift than the beam outrigger structure.

2.6 Summary of Literature

- The use of outrigger and belt truss mechanism in high-rise structures improves the stiffness of structure by 20-30% and makes the structural form more efficient under lateral load.
- The conventional direct outriggers are more effective than virtual outriggers in high-rise structures
- The location of the outrigger across the building plan layout is more important for the lateral behavior of structure and therefore optimum outrigger locations needs to be selected thoughtfully during the design stage. A general guideline for location of single outrigger is to place it at half way of the building height. For two outriggers, 1/3 and 2/3 height would be optimum locations. If three outriggers are to be used, 1/4, 1/2 and 3/4 height is ideal to be used. In case of a three-outrigger system, if one outrigger is to be placed at the top storey, the remaining two outriggers should be located at 1/3 and 2/3 height of building
- Due to the reduction of cross-sectional area of columns and shear walls along with the increment of building height, no soft story was found
- The single storey outrigger structural system is not productive in controlling maximum drift. Therefore, a remarkable change in drift profile can be obtained in using two outrigger levels system

2.7 Gaps in Literature

According to above mentioned past studies, a research gap can be identified as follows:

- Most of the studies have been performed considering simple grids and plans. There is a lack of research work on actual architectural plans where the outrigger structural system has been used in irregular shape of buildings having vertical irregularity. And most of the studies were based on square and rectangular shaped building layouts

- Almost all researchers have investigated static and dynamic behavior of structure under elastic limits. Only some of the researchers have used non-linear time history analysis method
- During the majority of the studies structural models are done up to 30-60 storey buildings. Nevertheless, this study can be extended for 80-90 storey super high-rise buildings
- Researchers have studied on the optimum outrigger position for conventional outrigger systems, but there is lack of data on optimum location for virtual outrigger systems
- The necessity of multi-outrigger level approach and effects of two storey deep and three storey deep outrigger can be investigated and compared by adopting two or three number of outrigger levels in tall structure
- Only few researches were based on a single model with different outrigger types. Therefore, this study can extend to identify the optimum usage of outrigger systems. And also, different types of truss outriggers can be used

3. METHODOLOGY

3.1 Analytical Program

3.2.1 Structural Model

3.2.1.1 General Layout of building

The selection of the basic layout of the building is most important in the context of outrigger structural systems since it greatly affects the performance of structure. The proposed structure is a 55 storey, 197.5 m height RC high-rise building which is assumed to function as a mixed development of retail, offices and residential. The concrete core is located at the middle of the building as a central core, where it is surrounded by perimeter columns. The degree of structural stiffness and the percentage of drift control depend on the number and the positions of outrigger levels provided in structure. In reality, outriggers are bounded to install in mechanical or refuge floors in buildings. In this proposed structure, single storey deep two outrigger levels have been provided at two mechanical floor levels in fixed positions throughout its height of building to minimize the reduction of usable floor area and any disturbance to aesthetic appearance. As per the research findings (Shivacharan, Chandrakala and Karthik, 2015) , first outrigger is placed at 18^{th} level (1/3 of building height) and second outrigger is placed at 36^{th} level (2/3 of building height). The structural general arrangement of building including floor functions and respective floor heights of each floor level is described in Table 3.1.

Table 3.1: Structural model arrangement details

Storey	Shape of Building	Function	Floor Height (m)
G-4	Rectangular	Parking	3
5-8	Rectangular	Retail	4
9-17	Circular	Office	4
18	Circular	MEP-Outrigger Floor	4
19-35	Circular	Residential	3.5
36	Circular	MEP-Outrigger Floor	4
37-54	Circular	Residential	3.5
55	Circular	Roof	-

Almost every research has been conducted based on square or rectangular shaped building models having uniform plan layout throughout its height (Kamath, 2012), (Hasan, 2016). However, in reality most of the structures are having vertical irregularities due to architectural requirements and aesthetic appearance.

In this study, vertical irregularity of structure along its height shall be considered by changing the geometry of building from rectangular shape to circular shape beyond level 8 onwards, where bottom floors represent podium floors and upper floors represent a standalone single tower as in real structures as presented in Figure 3.1 and Figure 3.2 respectively. For the proposed structure, a circular shape building model is selected.

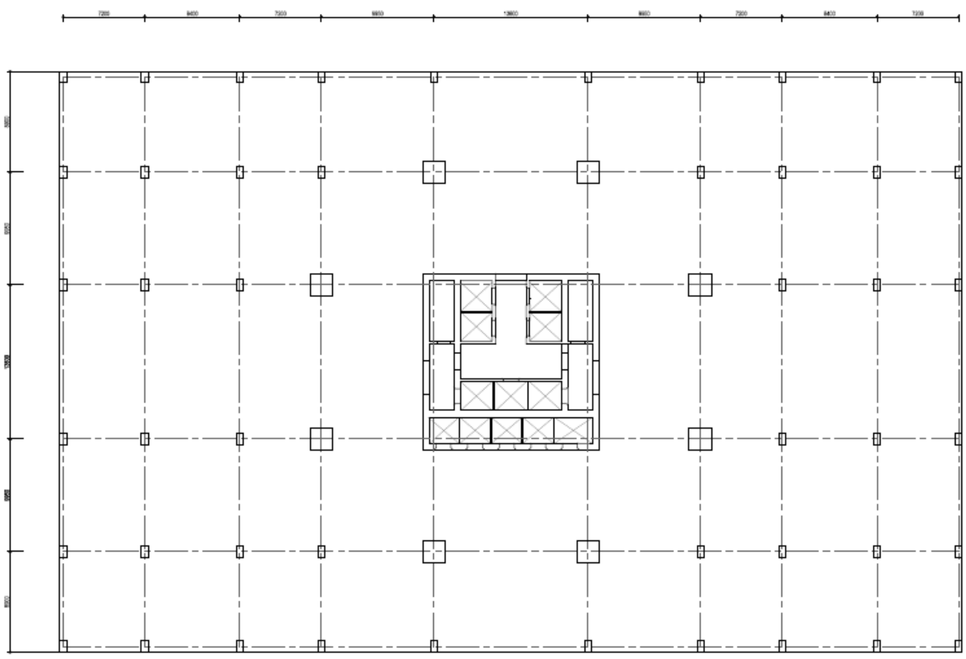


Figure 3.1: Layout of structural floor plan from Level 1-Level 8

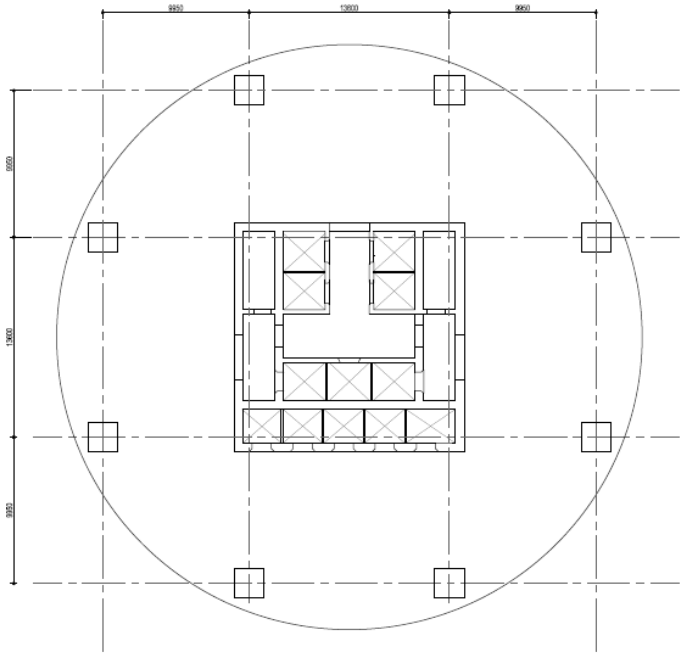


Figure 3.2: Layout of structural floor plan from Level 9-Level 55

3.2.1.2 Outrigger & Belt Truss Provisions in Models

The primary idea of this study is to identify the effectiveness of conventional and virtual outrigger systems on the structural performance of RC high-rise building through several combinations of belt-truss and outrigger arrangements under each category of different structural materials. Therefore, a total 10 number of models are carried out for different outrigger types; only outrigger, only belt truss & combination of both belt truss and outrigger under different structural materials; concrete, steel & composite.

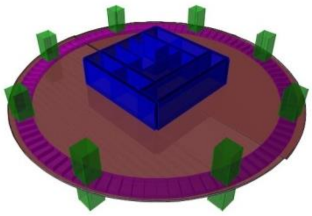
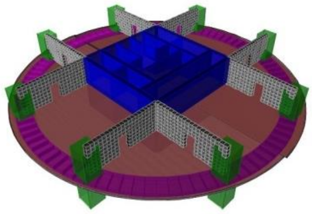
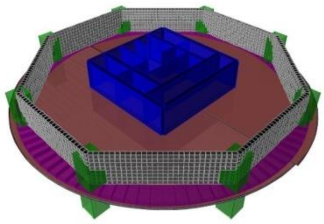
The crucial objective of this analysis is not to identify the number of outrigger levels to be used in structure or the optimum positions for outriggers to locate along its building height. Therefore, the number of outrigger levels used and the positions of outriggers along its building height are finalized through literature review and those arrangements are kept the same for all models in each category of outrigger systems and materials.

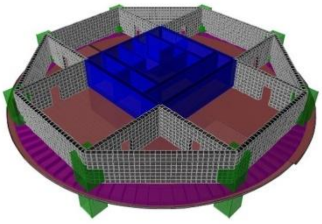
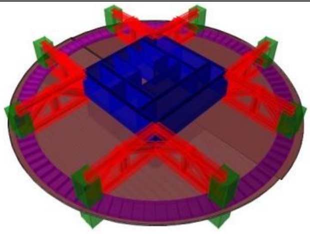
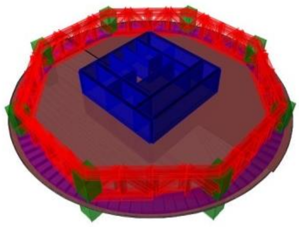
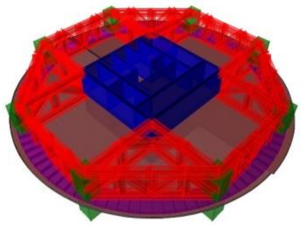
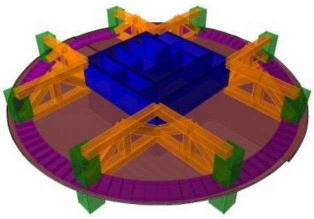
Both reinforced concrete beams and reinforced concrete walls have been commonly used as outrigger bracings in tall structures. However, from the comparison between the reinforced concrete beam and wall outriggers provided at the first third and second third of the structure height in tall building, the structure having wall outrigger was proven to be more efficient than the structure with beam outrigger (Hasan, 2016). Therefore, in this study, the most commonly used RC wall outrigger system option is adopted under the concrete material category.

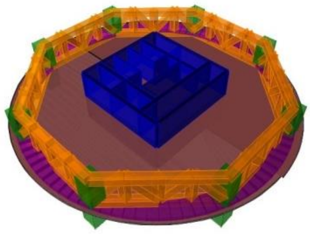
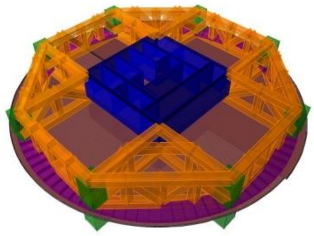
In tall buildings under wind loads, stiffness is the most crucial criteria to decrease the drift and displacement. From a sequence of studies, triangular shape topology with a vertical member at mid has been identified as the best outrigger topology to have highest stiffness and strength and therefore it is adopted as the optimum topology for both steel and composite outrigger bracing patterns (Ho, 2016).

As the general approach, same size structural members are applied for both conventional and the virtual outriggers systems of only belt truss, only outrigger and combination of belt truss and outrigger under each structural material category as it allows the direct comparison between the two outrigger system mechanisms. The details of 10 different structural model arrangements are presented in Table 3.2.

Table 3.2: Model Arrangements

Model ID	**Model Description**	**Model Arrangement**
NO	Structural model without outrigger	
Concrete Material		
O-CONCTERE	Structural model of concrete outrigger only	
B-CONCRETE	Structural model of concrete belt truss only	

OB-CONCRETE	Structural model of concrete outrigger with belt truss	
Steel Material		
O-STEEL	Structural model of steel outrigger only	
B- STEEL	Structural model of steel belt truss only	
OB- STEEL	Structural model of steel outrigger with belt truss	
Composite Material		
O-COMPOSITE	Structural model of composite outrigger only	

B- COMPOSITE	Structural model of composite belt truss only	
OB- COMPOSITE	Structural model of composite outrigger with belt truss	

3.2.1.3 Section Properties & Material Properties

Members are selected correspondingly in order to provide an adequate accuracy for the behavior of the structure and the effectiveness of the outriggers. Total number of rectangular shaped 8 mega columns are introduced at the perimeter of building for easier belt-truss connections. Both column and core bracing member sizes are identical for both outrigger types in conventional and virtual outrigger designs. Principally very stiff floor diaphragms are provided at the both top and bottom floors of each outrigger level to transfer horizontal force effectively in between the core and perimeter belt truss. Therefore 200 mm thick slabs are provided at top and bottom floors of each outrigger level. Section properties and material properties of each structural element including outriggers are presented in Table 3.3.

Table 3.3: Section properties & material properties

<table>
<tr><th colspan="2">Element</th><th colspan="2">Size (m)</th><th>Material Properties</th></tr>
<tr><td rowspan="2">Column</td><td>Mega Columns</td><td colspan="2">1.2 x 1.2</td><td rowspan="2">M50</td></tr>
<tr><td>Podium Columns</td><td colspan="2">0.6 x 0.6</td></tr>
<tr><td colspan="2"></td><td>Width (W)</td><td>Depth (D)</td><td></td></tr>
<tr><td rowspan="4">Beam</td><td rowspan="2">Perimeter Beams</td><td colspan="2">0.6 x 0.6</td><td rowspan="7">M30</td></tr>
<tr><td colspan="2">1.2 x 0.6</td></tr>
<tr><td>Internal Primary Beams</td><td colspan="2">0.6 x 0.6</td></tr>
<tr><td>Internal Secondary Beams</td><td colspan="2">0.6 x 0.4</td></tr>
<tr><td rowspan="3">Beams at Outrigger Levels</td><td>Perimeter Beams</td><td colspan="2">0.6 x 2</td></tr>
<tr><td>Internal Primary Beams</td><td colspan="2">0.6 x 0.6</td></tr>
<tr><td>Internal Secondary Beams</td><td colspan="2">0.4 x 0.6</td></tr>
<tr><td rowspan="2">Slab</td><td>At top & bottom of outrigger floors</td><td colspan="2">0.2</td><td rowspan="2">M30</td></tr>
<tr><td>Other levels</td><td colspan="2">0.15</td></tr>
<tr><td colspan="2">RC core walls</td><td colspan="2">0.4,0.3</td><td>M50</td></tr>
<tr><td colspan="2">Reinforced concrete wall outriggers</td><td colspan="2">0.4</td><td>M50</td></tr>
<tr><td>Steel outriggers</td><td>H Iron</td><td colspan="2">1 x 1 x 0.1 x 0.1</td><td>S355</td></tr>
<tr><td rowspan="2">Composite outrigger</td><td>Concrete Beam</td><td colspan="2">1 x 1</td><td>M50</td></tr>
<tr><td>H Iron</td><td colspan="2">0.6 x 0.6 x 0.06 x 0.06</td><td>S355</td></tr>
</table>

3.2.2 Design Loads

Dead loads, super imposed dead loads, live loads and wind loads are the primary loads considered in structural models. The dead load is considered as the self-weight of the structure.

3.2.2.1 Dead Loads

- Unit weight of concrete - 25 kN/m^3
- Unit weight of steel - 78 kN/m^3

Self-weight of structural elements is automatically generated by the software based on assigned material properties.

3.2.2.2 Super Imposed Dead Loads & Live Loads

Super imposed dead loads and live loads are considered as per BS EN 1991-1.1-2001 as highlighted in Table 3.4 below.

Table 3.4: SDead & live loads values

Floor Function	Super Imposed Dead Load (kN/m^2)	Live Load (kN/m^2)
Parking	2	2.5
Retail	3	5
Office	3	3
Residential	3	1.5
MEP Floor	2	7.5
Lobby	3	4
Roof	2	5

3.2.2.3 Wind Loads

Static wind loads are calculated as per BS EN 1991-1.4-2005. Basic parameters and detailed calculations are presented in Appendix A. Wind loads are applied as diaphragm forces for each floor in the building.

3.2.2.4 Load Combinations

The load combinations are established in accordance with BS EN 1990:2002. Basic load combinations to be used in the design are,

$1.0\ D + 1.0\ SD + 1.0\ W_x$

$1.0\ D + 1.0\ SD + 1.0\ W_y$

$1.0\ D + 1.0\ SD + 0.7\ L + 1.0\ W_x$

$1.0\ D + 1.0\ SD + 0.7\ L + 1.0\ W_y$

Where,

D – Dead loads,

SD – Super imposed dead loads

L – Live loads

W_i – Wind loads

3.2.3 Method of Analysis

The structure is analysed as a three-dimensional elastic structure, in CSI ETABS computer program. During the modelling, columns and beams are modeled as frame elements and shear walls and slabs are modeled as shell elements. Foundation deformations are neglected in the structural analysis and columns are assigned as pinned at the base supports. Auto meshing has been assigned for slab elements while manual meshing has been assigned for wall elements. 3D structural model of the proposed structure is presented in Figure 3.3 below.

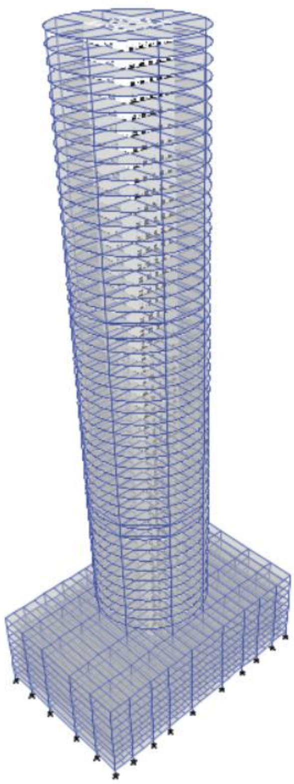


Figure 3.3: ETABS 3D model of a typical structure

4. RESULTS & DISCUSSION

In this chapter, performance of each structural material model of concrete, steel and composite outriggers were reviewed and compared with no outrigger structure model in terms of natural period and frequencies of structure, wind induced lateral displacements and inter storey drift ratios based on the results extracted from modal analysis and lateral load analysis.

4.1 Natural period & corresponding frequencies

Natural period and corresponding frequencies were summarized for the first two modes of each outrigger structural model of concrete, steel and composite with structural model without outriggers and those results were demonstrated in Table 4.1.

Table 4.1: Natural period & corresponding frequencies for structural model without outriggers and outrigger structure models of concrete, steel & composite materials

Modal Name	Period		Frequency		% Increment in frequency	
	Mode 1	Mode 2	Mode 1	Mode 2	Mode 1	Mode 2
	Y Direction	X Direction	Y Direction	X Direction	Y Direction	X Direction
	s	s	Hz	Hz	%	%
NO	7.613	6.989	0.131	0.143	-	-
O-CONCRETE	6.466	5.903	0.155	0.169	18	18
B-CONCRETE	6.576	6.043	0.152	0.165	16	16
OB-CONCRETE	6.425	5.843	0.156	0.171	18	20
O-STEEL	6.614	6.059	0.151	0.165	15	15
B-STEEL	6.749	6.223	0.148	0.161	13	12
OB-STEEL	6.503	5.944	0.154	0.168	17	18
O-COMPOSITE	6.684	6.128	0.150	0.163	14	14
B-COMPOSITE	6.823	6.296	0.147	0.159	12	11
OB-COMPOSITE	6.561	6.003	0.152	0.167	16	16

The frequency of a structure is a characteristic of stiffness and it directly affects the structural performance of a building. The structural model without outriggers has the highest building period for both Mode 1 (Y direction) & Mode 2 (X Direction) when compared to the other outrigger structure models of concrete, steel & composite materials. Therefore it indicates that insertion of conventional & virtual outrigger systems has a direct effect on reducing the natural period of building by increasing the structural stiffness.

Comparing the performance of outrigger structure models of different outrigger types; only outrigger, only belt truss & combination of belt truss and outrigger, it indicates a similar structural behavior in terms of building periods under each material category of concrete, steel and composite. Combination of both outrigger and belt truss structural system (OB) has the lowest building period for both Mode 1 & Mode 2 and only belt truss (B) outrigger structural system has the highest building period under each material category of concrete, steel and composite.

When comparing the different outrigger types of concrete material, the frequency in the structural model without outriggers was increased by maximum 18% in most critical direction of Y, when incorporating the outrigger systems of outrigger only (O) and combination of both outrigger and belt truss (OB). By incorporating only the belt truss (B) outrigger system, the frequency was increased by a maximum 16% only.

When comparing the different outrigger types of steel material, there is a significant difference in increasing the structural frequency in the most critical direction of Y in each model while incorporating different outrigger types. The combination of both outrigger and belt truss (OB) system has increased the frequency by a maximum 17% while the only outrigger (O) system and only belt truss (B) system have increased the frequency by 15% and 13% respectively.

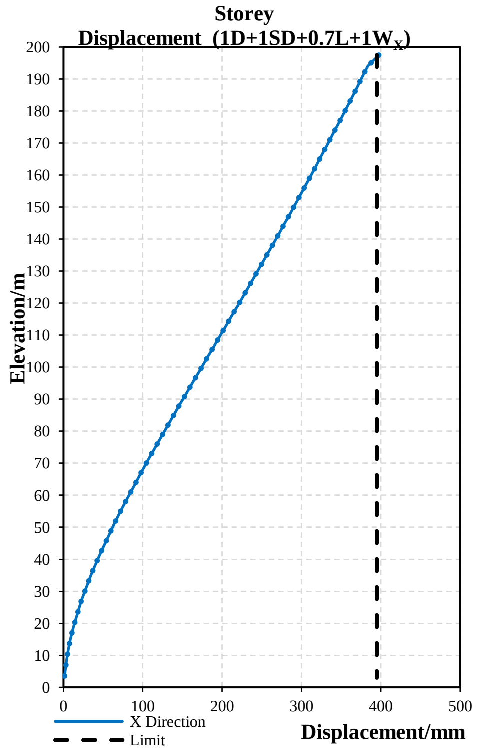
The same pattern of structural performance can be observed in different outrigger types of composite material where the combination of both outrigger and belt truss (OB) system has increased the frequency by maximum 16% while the only outrigger (O) system and only belt truss (B) system have increased the frequency by 14% and 12% respectively.

4.2 Maximum wind induced lateral displacement

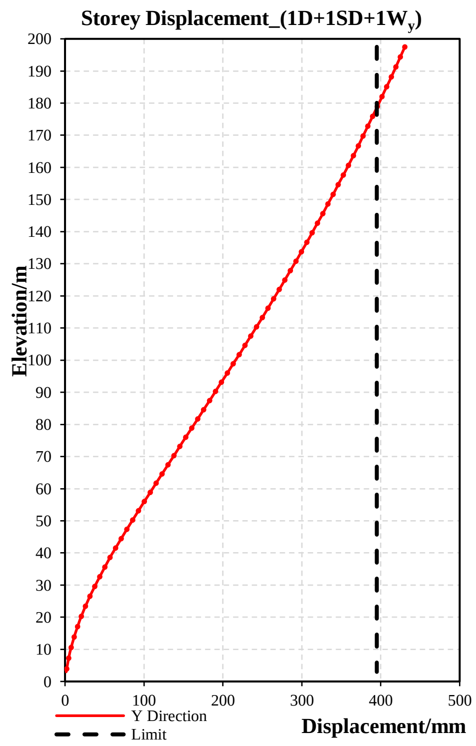
Maximum wind induced lateral deflection at the top storey were summarized in both X & Y directions for each structural model of without outriggers and with outriggers under different structure materials of concrete, steel and composite. Those results were compared with maximum allowable lateral displacement value of H/500 (H-Height of structure) as demonstrated in Table 4.2 to Table 4.5 and illustrated in Figure 4.2 to Figure 4.5 respectively.

Table 4.2: Maximum wind induced lateral displacement for structural model without outriggers

Modal Name	Displacement at Top		
	X Direction	Y Direction	Allowable Limit
	mm	mm	mm
NO	397.52	430.562	395



(a)

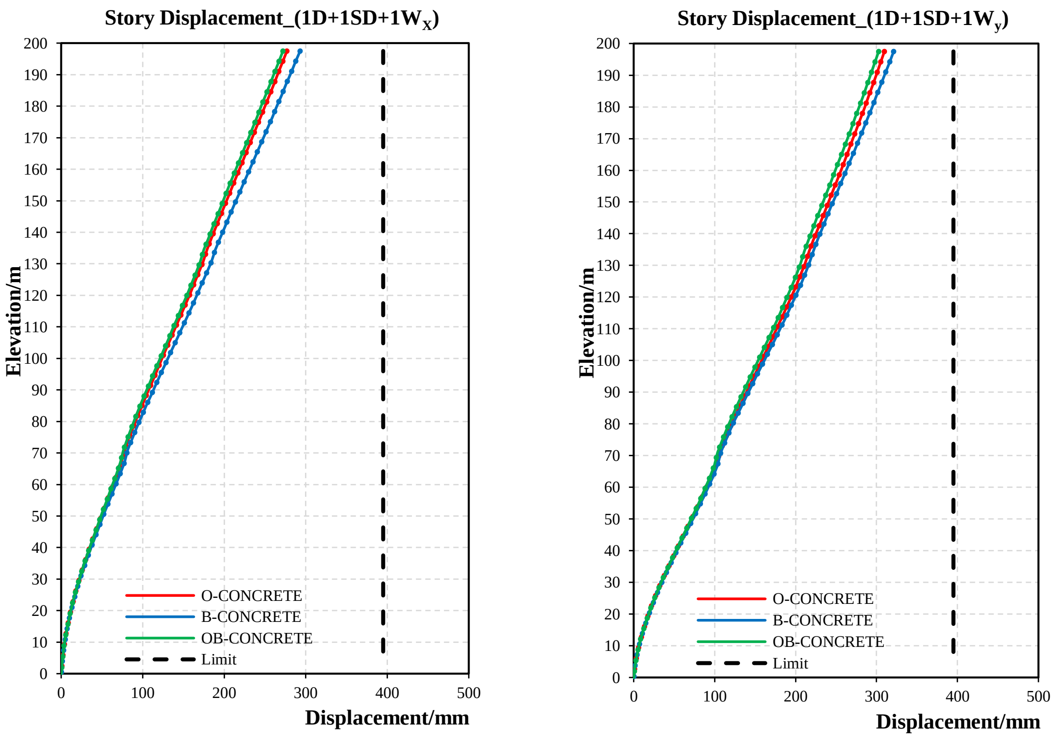


(b)

Figure 4.1: Maximum Storey Displacement for (a) X Direction (b) Y Direction for structural model without outriggers

Table 4.3: Maximum wind induced lateral displacement for outrigger structural model of concrete material

Modal Name	Displacement at Top			% Reduction in Displacement	
	X Direction	Y Direction	Allowable Limit	Δx	Δy
	mm	mm	mm	%	%
O-CONCRETE	276.919	309.734	395	30.3	28.1
B-CONCRETE	293.138	321.134		26.3	25.4
OB-CONCRETE	272.072	302.709		31.6	29.7

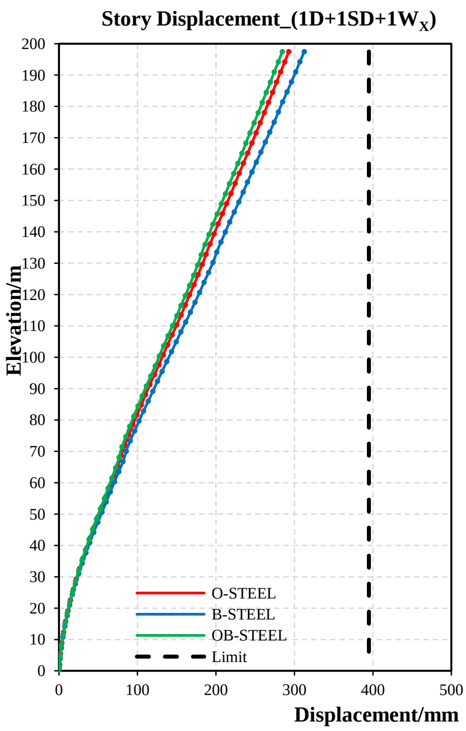


(a) (b)

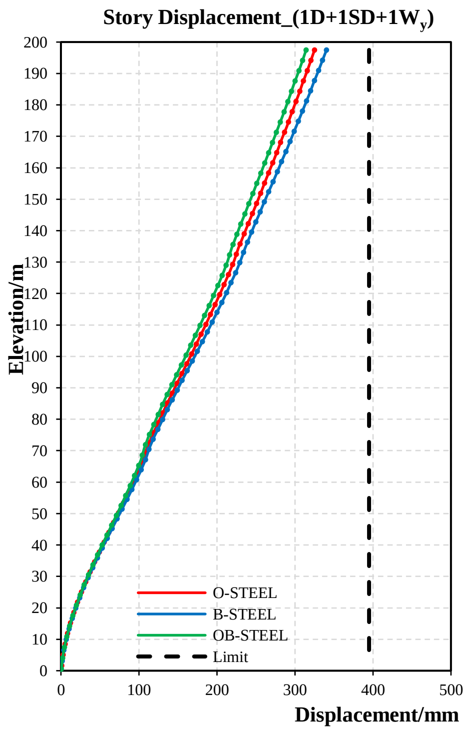
Figure 4.2: Maximum Storey Displacement for (a) X Direction (b) Y Direction for outrigger structural model of concrete material

Table 4.4: Maximum wind induced lateral displacement for outrigger structural model of steel material

Modal Name	Displacement at Top			% Reduction in Displacement	
	X Direction	Y Direction	Allowable Limit	Δx	Δy
	mm	mm	mm	%	%
O-STEEL	292.896	325.108	395	26.3	24.5
B-STEEL	312.624	340.454		21.4	20.9
OB-STEEL	284.691	314.316		28.4	27.0



(a)

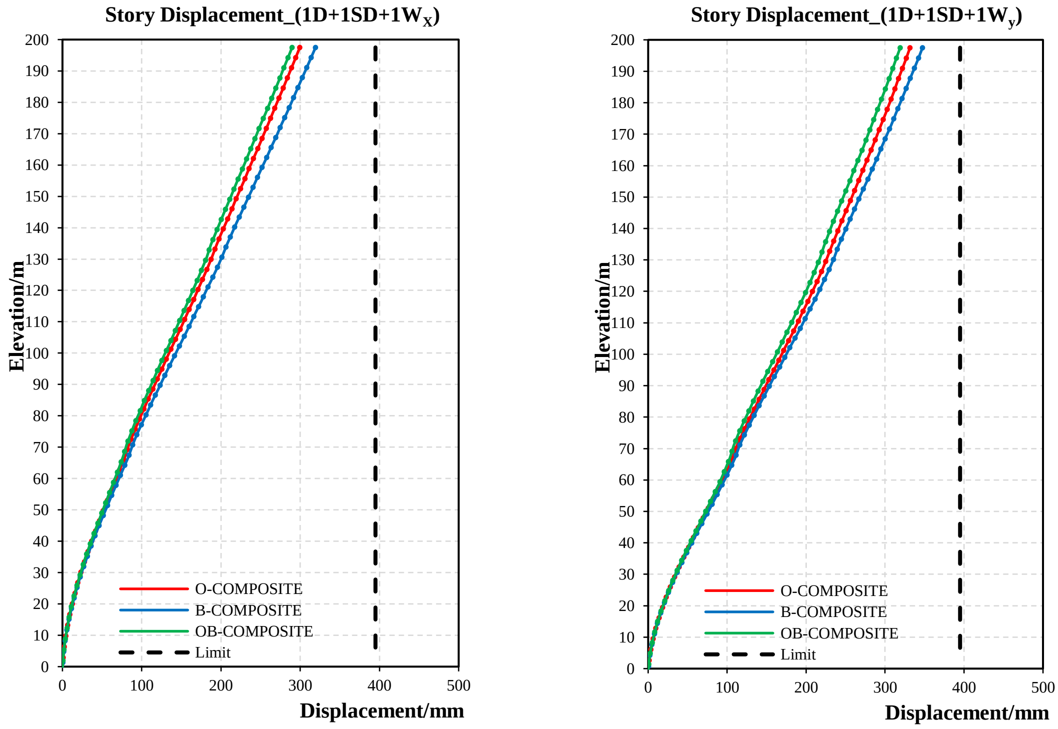


(b)

Figure 4.3: Maximum Storey Displacement for (a) X Direction (b) Y Direction for outrigger structural model of steel material

Table 4.5: Maximum wind induced lateral displacement for outrigger structural model of composite material

Modal Name	Displacement at Top			% Reduction in Displacement	
	X Direction	Y Direction	Allowable Limit	Δx	Δy
	mm	mm	mm	%	%
O-COMPOSITE	299.497	331.555	395	24.7	23.0
B-COMPOSITE	319.377	347.417		19.7	19.3
OB-COMPOSITE	289.792	319.202		27.1	25.9



(a) (b)

Figure 4.4: Maximum Storey Displacement for (a) X Direction (b) Y Direction for outrigger structural model of composite material

The structural model without outriggers has the maximum wind induced lateral deflection at top storey in both X & Y directions and those results exceed the maximum allowable lateral displacement value of H/500. Maximum wind induced lateral deflection at top storey values have reduced in all other outrigger structure models of concrete, steel & composite in both directions compared to structural model without outriggers and those values are less than the maximum allowable lateral displacement. This stipulates that the insertion of outrigger systems has provided a better control in reducing wind induced lateral deflection at top storey of the building by increasing restraint against lateral loads.

Comparing the performance of outrigger structure models of different outrigger types; only outrigger, only belt truss & combination of belt truss and outrigger, the pattern of varying the top storey lateral displacement values is almost unchanged under each material category of concrete, steel & composite, where the minimum deflection in both axes is achieved by the combination of both outrigger and belt truss structural system (OB) and maximum deflection in both axes is achieved by only belt truss (B) structural system .

When comparing the above results for different outrigger types of concrete material models, the maximum reduction in top storey lateral displacement of 29.7% was achieved by the combination of both outrigger and belt truss structural system (OB) in the most critical axis of Y. The outrigger structural system that utilizes outriggers only (O) also achieved a similar reduction value of 28.1% while the other structural system of only belt truss (B) system has reduced the lateral displacement by 25.4% only.

In steel structural material models, lateral displacement at top storey in critical Y direction was reduced in maximum 27.0% by the combination of both outrigger and belt truss (OB) structural system, while the other structural systems of only outriggers (O) and only belt truss (B) have reduced the lateral displacement by 24.5% & 20.9% respectively.

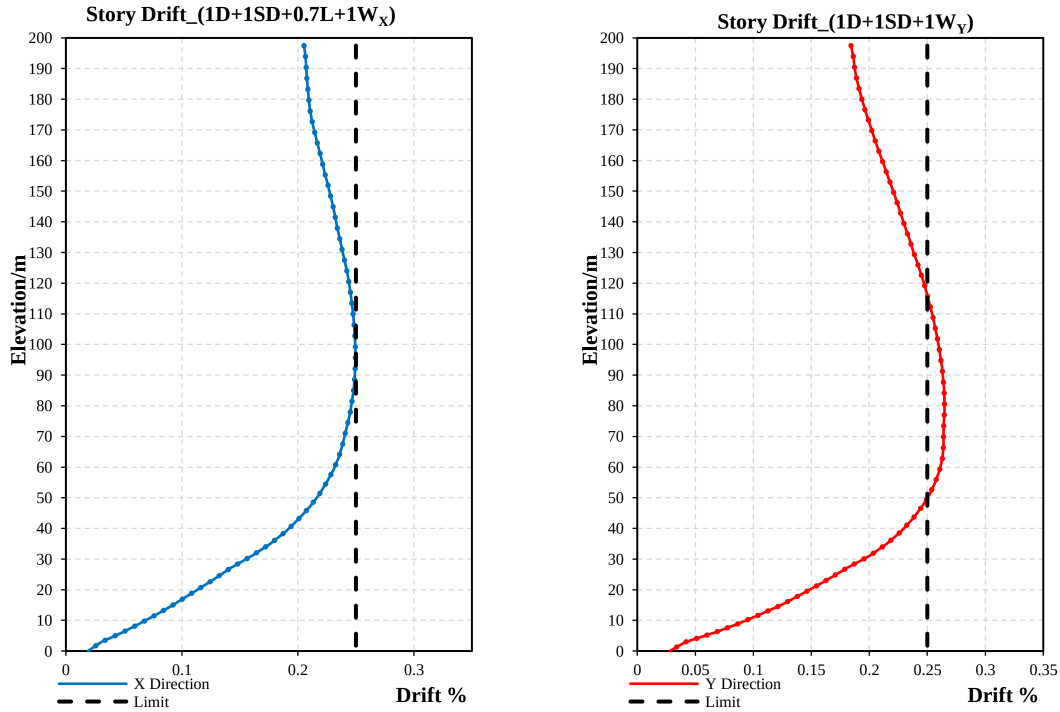
The same pattern of reduction in lateral displacement can be observed in composite structure material models, where the combination of both outrigger and belt truss (OB) system has reduced the displacement by maximum 25.9% while the only outrigger (O) system and only belt truss (B) system have reduced the displacements by 23.0% and 19.3% respectively.

4.3 Maximum inter storey drift

Maximum inter storey drift values were summarized in both X & Y directions for each structural model of without outriggers and with outriggers under different structure materials of concrete, steel and composite. Those results were compared with maximum allowable inter storey drift value of 0.25% as demonstrated in Table 4.6 to Table 4.9 and illustrated in Figure 4.5 to Figure 4.7 respectively.

Table 4.6: Maximum wind induced inter storey drift for structural model without outriggers

Modal Name	Maximum Storey Drift		
	X Direction	Y Direction	Allowable Limit
	%	%	%
NO	0.2495	0.2648	0.25

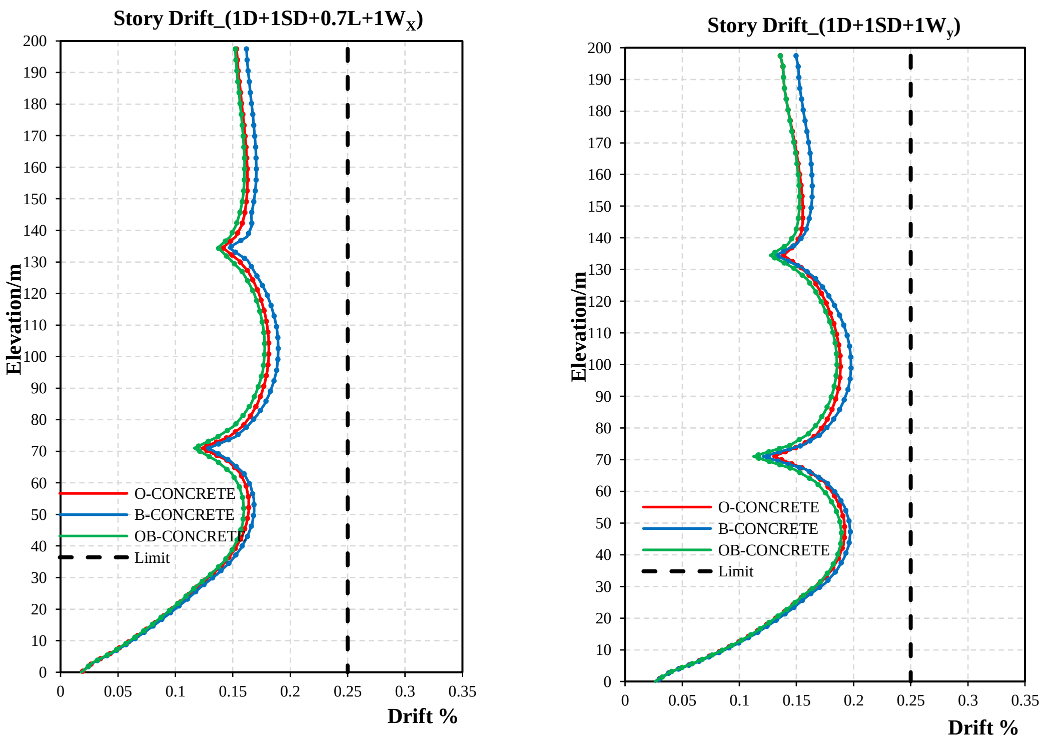


(a) (b)

Figure 4.5: Maximum Inter Storey Drift for (a) X Direction (b) Y Direction for structural model without outriggers

Table 4.7: Maximum wind induced inter storey drift for outrigger structural model of concrete material

Modal Name	Maximum Storey Drift			% Reduction in Storey Drift	
	X Direction	Y Direction	Allowable Limit	Δx	Δy
	%	%	%	%	%
O-CONCRETE	0.1814	0.1925	0.25	27.3	27.3
B-CONCRETE	0.1896	0.1978		24.0	25.3
OB-CONCRETE	0.1778	0.1894		28.7	28.5

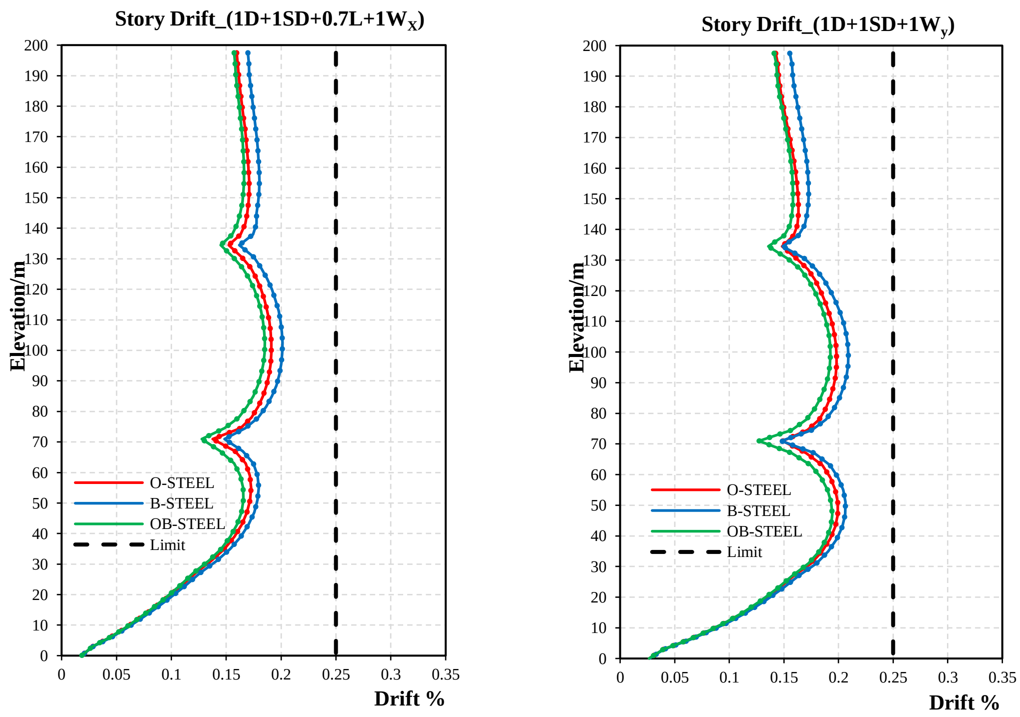


(a) (b)

Figure 4.6: Maximum Inter Storey Drift for (a) X Direction (b) Y Direction for outrigger structural model of concrete material

Table 4.8: Maximum wind induced inter storey drift for outrigger structural model of steel material

Modal Name	Maximum Storey Drift			% Reduction in Storey Drift	
	X Direction	Y Direction	Allowable Limit	Δx	Δy
	%	%	%	%	%
O-STEEL	0.1911	0.1993	0.25	23.4	24.7
B-STEEL	0.2013	0.209		19.3	21.1
OB-STEEL	0.1852	0.1943		25.8	26.6

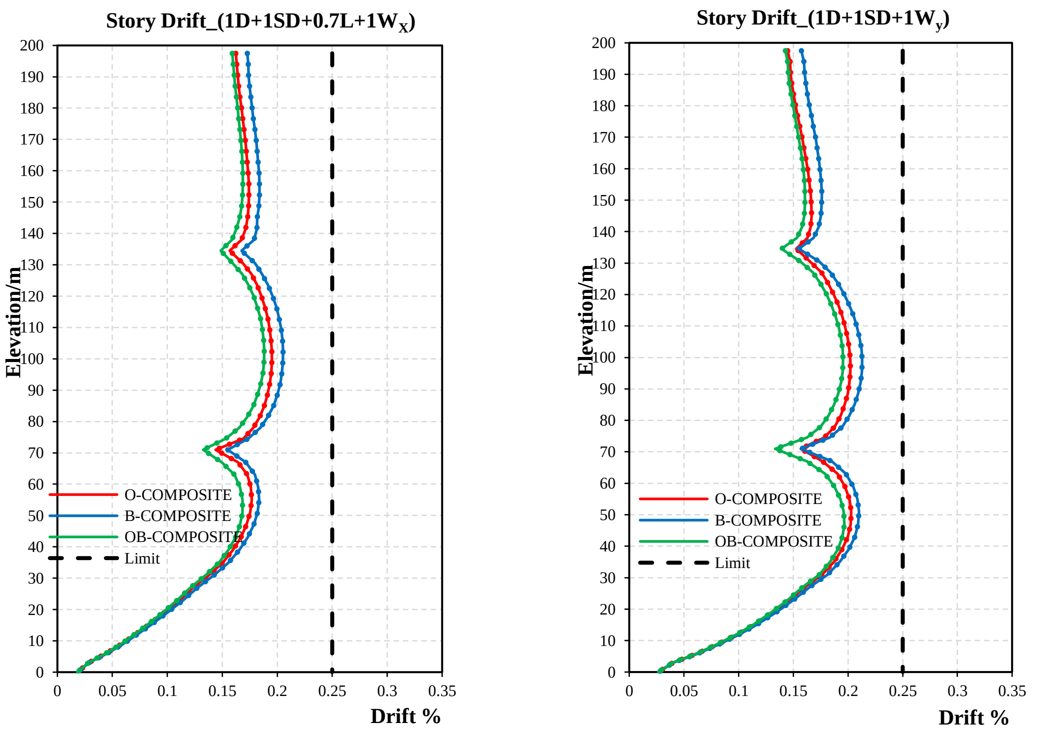


(a) (b)

Figure 4.7: Maximum Inter Storey Drift for (a) X Direction (b) Y Direction for outrigger structural model of steel material

Table 4.9: Maximum wind induced inter storey drift for outrigger structural model of composite material

Modal Name	Maximum Storey Drift			% Reduction in Storey Drift	
	X Direction	Y Direction	Allowable Limit	Δx	Δy
	%	%	%	%	%
O-COMPOSITE	0.1951	0.2029	0.25	21.8	23.4
B-COMPOSITE	0.2053	0.2129		17.7	19.6
OB-COMPOSITE	0.1882	0.1967		24.6	25.7



(a) (b)

Figure 4.8: Maximum Inter Storey Drift for (a) X Direction (b) Y Direction for outrigger structural model of composite material

The structural model without outriggers has the maximum inter storey drift in both X & Y directions and those results exceed the maximum allowable inter storey drift value of 0.25%. In all other outrigger structure models of concrete, steel & composite, maximum inter storey drift values have significantly reduced in both directions compared to structural model without outriggers and those values are less than the maximum allowable limit. This indicates that the insertion of outrigger systems for proposed building has effectively contributed in reducing the maximum inter storey drift significantly.

When comparing the performance of outrigger structure models of different outrigger types; only outrigger, only belt truss & combination of belt truss and outrigger, it indicates a similar pattern in decaying maximum inter storey drift under each material category of concrete, steel & composite, where the minimum inter storey drift in both axes is achieved by the combination of both belt truss and outrigger structural system (OB) and maximum inter storey drift is achieved by only belt truss (B) outrigger structural system .

Comparing the inter storey drift results in the most critical axis of Y for different outrigger types of concrete material models, the maximum reduction in inter storey drift of 28.5% was achieved by incorporating both outrigger and belt truss structural system (OB). The outrigger structural system that utilizes only outriggers (O) also achieved a much closer reduction value of 27.3% while the other structural system of only belt truss (B) system has reduced the inter storey drift by 25.3% only.

In steel structural material models, inter storey drift in critical Y direction was reduced in maximum 26.6% by the combination of both outrigger and belt truss (OB) structural system, while the other structural systems of only outriggers (O) and only belt truss (B) have reduced the inter storey drift by 24.7% & 21.1% respectively.

Similar decaying pattern inter storey drift can be observed in composite structure material models, where the combination of both outrigger and belt truss (OB) system has reduced the inter storey drift by maximum 25.7% while the only outrigger (O) system and only belt truss (B) system have reduced the inter storey drift by 23.4% and 19.6% respectively.

5. CONCLUSION & RECOMMENDATIONS

5.1 Conclusion

The current study investigated the behavior and effectiveness of various outrigger systems under different structural materials for a multi-storey reinforced concrete high-rise building when subjected to wind loads. 3 structural models of different outrigger structure types; only outriggers (O), only belt truss (B) & combination of both outriggers and belt truss (OB) were created per each material category of concrete, steel & composite and compared the performance with structural model without outriggers based on the parameters such as natural frequency, maximum lateral displacement of top storey and inter storey drift. The results demonstrate that addition of outriggers and belt trusses in different structural materials have significantly improved the structural performance of building against wind action. The findings of the investigation can be summarized as follows.

- The insertion of conventional & virtual outrigger systems has effectively contributed to reducing the natural period of building by increasing the structural stiffness and has achieved in decreasing maximum wind induced lateral deflection at top storey and maximum inter storey drift of structure by increasing resistance against lateral loads.
- For outrigger structure material of concrete, best structural performance can be seen in reduction of building period, top storey lateral displacement and inter storey drift by incorporating both outrigger systems of outrigger only (O) and combination of both outrigger and belt truss (OB) as it stipulates almost similar reduction percentages of frequency, top storey lateral displacement and inter storey drift for both types.
- For steel outrigger structure types, the combination of both outrigger and belt truss (OB) system is proven to be best outrigger structure type in reducing all the three parameters of building period, top storey lateral displacement and inter storey drift when compared to other two outrigger systems of outrigger only (O) and belt truss only (B).

- The structural performance of composite material models are more similar to steel material models where the combination of both outrigger and belt truss (OB) system has provided the best results in reducing building period, top storey lateral displacement and inter storey drift than other two outrigger systems of outrigger only (O) and belt truss only (B).

5.2 Recommendations

Outriggers which connect the internal core of the building to the outer perimeter columns are ordinary method of increasing the stiffness and strengthening of tall buildings against lateral forces. This current study differentiates the structural behavior between structural models of without outriggers and with various outrigger systems of different structural materials for a reinforced concrete high-rise building when subjected to wind loads. As per this research results several other subjects have been identified as key points which need further investigation as summarized below.

- Outrigger and belt trusses can place on different locations of building along its height and can identify the most optimum location for each outrigger structure type under each category of different structural materials; concrete, steel & composite
- The study can be made for different types of truss outriggers and belt trusses under different structural materials of concrete, steel & composite
- The similar study can be made by increasing the depth of outriggers into two or three stories

REFERENCES

1. Bayati, Z., Mahdikhani, M. and Rahaei, A. (2008) 'Optimized use of multi-outriggers system to stiffen tall buildings', *Proceedings of the 14th World Conference on Earthquake Engineering: Beijing, China, October 12-17, 2008*.
2. Choi, H. S. *et al.* (2012) *Outrigger Design for High-Rise Buildings: An output of the CTBUH Outrigger Working Group*. Chicago: Council on Tall Buildings and Urban Habitat (CTBUH).
3. Choi, H. S. and Joseph, L. (2012) 'Outrigger System Design Considerations', *International Journal of High-Rise Buildings*, 1(3), pp. 237–246.
4. Fawzia, S. and Fatima, T. (2016) 'Optimum Position of Steel Outrigger System for High Rise Composite Buildings Subjected to Wind Loads', *Advanced Steel Construction*, 12(2), pp. 134–153. doi: 10.18057/IJASC.2016.12.2.4.
5. Gadkari, A. P. and Gore, N. G. (2016) 'Review on Behaviour of Outrigger Structural System in High-Rise Building', 4(2), pp. 2065–2073.
6. Gawate, A. L. and Bhusari, J. P. (2015) 'Behavior of Outrigger Structural System for High-rise Building', *International Journal of Modern Trends in Engineering and Research*, 2(7), pp. 559–562.
7. Haghollahi, A., Ferdous, M. B. and Kasiri, M. (2012) 'Optimization of outrigger locations in steel tall buildings subjected to earthquake loads', *Proceedings of the 15th World Conference on Earthquake Engineering*.
8. Hasan, R. A. A. (2016) 'Behavior of Beam and Wall Outrigger in High -Rise Building and Their Comparison', *International Journal of Civil, Structural, Environmental and Infrastructure Engineering Research and Development*, 6(1), pp. 19–30.
9. Herath, N. *et al.* (2009) 'Behaviour of outrigger beams in high rise buildings under earthquake loads', *Australian Earthquake Engineering Society 2009 Conference*. Available at: http://www.aees.org.au/wp-content/uploads/2013/11/Herath-et-al.pdf.
10. Ho, G. W. M. (2016) 'The Evolution of Outrigger System in Tall Buildings', *International Journal of High-Rise Buildings*, 5(1), pp. 21–30. doi: 10.21022/ijhrb.2016.5.1.21.

11. Kamath, K. (2012) ‘A Study on Static and Dynamic Behavior of Outrigger Structural System for Tall Buildings’, *Bonfring International Journal of Industrial Engineering and Management Science,* 2(4), pp. 15–20. doi: 10.9756/bijiems.1655.
12. Khanorkar, A. A., Denge, S. V. and Raut, S. P. (2016) ‘Belt truss as lateral load resisting structural system for tall building: a review’, *International Journal of Science Technology & Engineering*, 2(10), pp. 658–662. Available at: www.ijste.org (Accessed: 22 May 2021).
13. Kogilgeri, S. S. and Shanthapriya, B. (2015) ‘A Study on Behaviour of Outrigger System on High Rise Steel Structure by Varying Outrigger Depth’, *International Journal of Research in Engineering and Technology,* 04(07), pp. 434–438. doi: 10.15623/ijret.2015.0407068.
14. Nair, R. S. (1998) ‘Belt Trusses and Basements as “Virtual” Outriggers for Tall Buildings’, *Engineering Journal*, 35(4), pp. 140–146.
15. Nanduri, P. . M. B. R. K., Suresh, B. and Hussain, I. (2013) ‘Optimum position of outrigger system for high-rise reinforced concrete buildings under wind and earthquake loadings’, *American Journal of Engineering Research*, 02(08), pp. 76–89. Available at: http://www.ajer.org/papers/v2(8)/J0287689.pdf.
16. Po Seng Kian (2001) ‘The Use of Outrigger and Belt Truss System for High-Rise Concrete Buildings’, *Civil Engineering Dimension*, 3(1), pp. 36–41. Available at: http://puslit2.petra.ac.id/ejournal/index.php/civ/article/view/15536.
17. Prasad, D. J. and Kumar, S. (2016) ‘Comparison of Seismic Performance of Outrigger and Belt Truss System in a Rcc Building With Vertical Irregularity’, *International Journal of Research in Engineering and Technology,* 05(20), pp. 125–132. doi: 10.15623/ijret.2016.0532019.
18. Shehu, M. R. (2015) ‘Ductility of Outrigger Typologies for Highrise Structures’, *IOSR Journal of Mechanical and Civil Engineering*, 12(2), pp. 34–41. doi: 10.9790/1684-12263441.
19. Shivacharan, K., Chandrakala, S. and Karthik, N. M. (2015) ‘Optimum Position of Outrigger System for Tall Vertical Irregularity Structures’, *Journal of Mechanical and Civil Engineering (IOSR-JMCE),* 12(2), pp. 54–63. doi: 10.9790/1684-12225463.

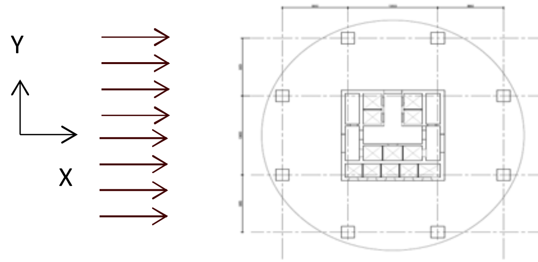
20. Sitapara, K. D. and Gore, G. (2016) ‘Review on Feasibility of High Rise Outrigger Structural System in Seismically Active Regions’, *International Research Journal of Engineering and Technology*, 3(5), pp. 1427–1432. Available at: www.irjet.net (Accessed: 25 May 2021).
21. Smith, B. S. and Coull, A. (1991) *Tall Building Structures : Analysis and Design*. John Wiley & Sons, Inc.
22. Thejaswini R M and Rashmi A R (2015) ‘Analysis and Comparison of Different Lateral Load Resisting Structural Forms’, *International Journal of Engineering Research and Technology*, V4(07), pp. 827–833. doi: 10.17577/ijertv4is070646.
23. Vijay, N. P., James, J. S. and Kurian, N. (2017) ‘Optimization of Outrigger Braced Structures Using Regression Analysis’, *International Research Journal of Engineering and Technology(IRJET)*, 4(6), pp. 1807–1810. Available at: www.irjet.net (Accessed: 22 May 2021).
24. Vijaya Kumari Gowda M R and Manohar B C (2015) ‘A Study on Dynamic Analysis of Tall Structure with Belt Truss Systems for Different Seismic Zones’, *International Journal of Engineering Research and Technology*, 4(08), pp. 158–167. doi: 10.17577/ijertv4is080254.
25. Wu, J. R. and Li, Q. S. (2003) ‘Structural performance of multi-outrigger-braced tall buildings’, *The Structural Design of Tall and Special Buildings*, 12(2), pp. 155–176. doi: 10.1002/tal.219.

APPENDIX A: WIND LOAD CALCULATION

Reference	Calculation -**Analysis of Wind Loads-BS EN 1991-1-4:2005**	Output

Calculation of Wind Forces in X Direction

Wind loads on the building at each floor level, when the wind is blowing in X direction are calculated in this section.



h ~ 197.5m

Assumptions

Proposed building is located at Colombo-Zone 3
Terrain category is Town
Effect of neighbouring structures are neglected (h_{dis}=0)
Terrain orography is not significant
Distance to Shore Line is 5 km

Calculation of Basic Wind Speed (V_b)

Reference				
SLS EN	$V_{b,zone}$	-	25	m/s
Table NA.1	Basic wind speed (V_b)	=	$C_{dir}C_{sea}C_{alt}V_{b,0}$	
4.2	$C_{dir}/C_{sea}/C_{alt}$	=	1	
		=	1x1x1x25	
		=	**25**	m/s

Calculation of Basic Velocity Pressure (q_b)

Reference				
BS EN 1991-1-4	Density of Air	=	**1.25**	kg/m^3
:2005	Basic Velocity Pressure (q_b)	=	$0.5\rho v_b^2$	
Cl 4.5		=	0.5x1.25x25x25	
		=	**390.63**	N/m^2

Calculation of Peak Velocity Pressure (q_p)

Reference			
BS EN 1991-1-4 :2005 Cl 4.5	Peak Velocity Pressure (q_p)	-	$C_{e(z)}\ C_{e(T)}q_b$

Table A.1 : Structural Dimensions of Building

Level	Story Height (m)	Height above Ground(m)	Length Along Wind-d (m)	Length Perpendicular to Wind-b(m)
L55	-	197.5	39.75	39.75
L54	3.5	194	39.75	39.75
L53	3.5	190.5	39.75	39.75
L52	3.5	187	39.75	39.75
L51	3.5	183.5	39.75	39.75
L50	3.5	180	39.75	39.75
L49	3.5	176.5	39.75	39.75
L48	3.5	173	39.75	39.75
L47	3.5	169.5	39.75	39.75
L46	3.5	166	39.75	39.75

Reference	Calculation -**Analysis of Wind Loads-SL EN 1991-1-4:2005**	Output

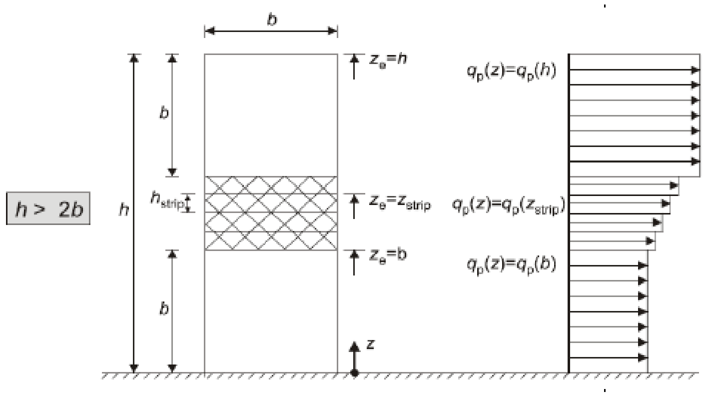
L45	3.5	162.5	39.75	39.75
L44	3.5	159	39.75	39.75
L43	3.5	155.5	39.75	39.75
L42	3.5	152	39.75	39.75
L41	3.5	148.5	39.75	39.75
L40	3.5	145	39.75	39.75
L39	3.5	141.5	39.75	39.75
L38	3.5	138	39.75	39.75
L37	3.5	134.5	39.75	39.75
L36	4	130.5	39.75	39.75
L35	3.5	127	39.75	39.75
L34	3.5	123.5	39.75	39.75
L33	3.5	120	39.75	39.75
L32	3.5	116.5	39.75	39.75
L31	3.5	113	39.75	39.75
L30	3.5	109.5	39.75	39.75
L29	3.5	106	39.75	39.75
L28	3.5	102.5	39.75	39.75
L27	3.5	99	39.75	39.75
L26	3.5	95.5	39.75	39.75
L25	3.5	92	39.75	39.75
L24	3.5	88.5	39.75	39.75
L23	3.5	85	39.75	39.75
L22	3.5	81.5	39.75	39.75
L21	3.5	78	39.75	39.75
L20	3.5	74.5	39.75	39.75
L19	3.5	71	39.75	39.75
L18	4	67	39.75	39.75
L17	4	63	39.75	39.75
L16	4	59	39.75	39.75
L15	4	55	39.75	39.75
L14	4	51	39.75	39.75
L13	4	47	39.75	39.75
L12	4	43	39.75	39.75
L11	4	39	39.75	39.75
L10	4	35	39.75	39.75
L9	4	31	39.75	39.75
L8	4	27	79.7	51.3
L7	4	23	79.7	51.3
L6	4	19	79.7	51.3
L5	4	15	79.7	51.3
L4	3	12	79.7	51.3
L3	3	9	79.7	51.3
L2	3	6	79.7	51.3
L1	3	3	79.7	51.3
GL	3	0	79.7	51.3

BS EN 1991-1-4	h	=	197.5	m
:2005	b	=	39.75	m
Cl 7.2.2	h>2b			

Reference	Calculation -**Analysis of Wind Loads-SL EN 1991-1-4:2005**	Output

BS EN 1991-1-4 :2005

Figure 7.4



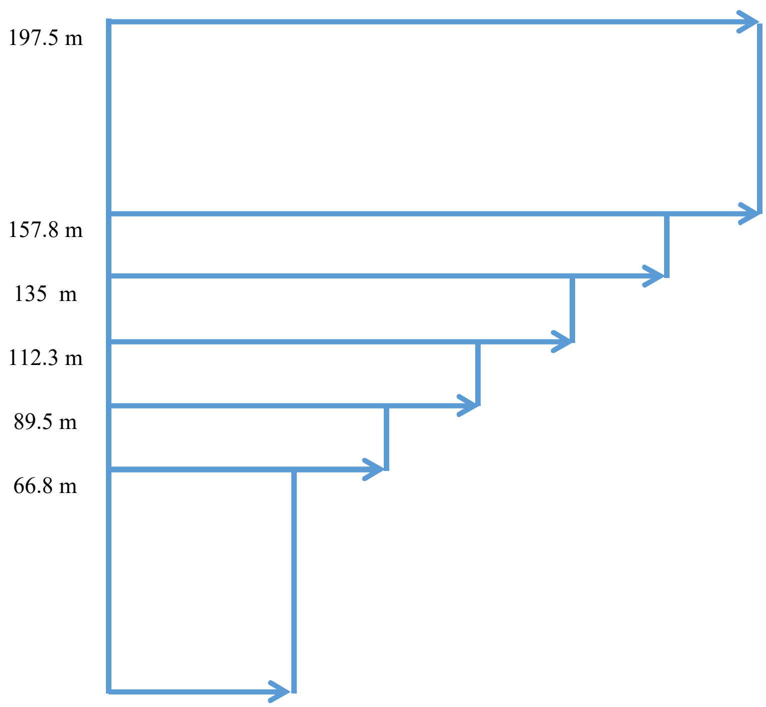


Table A.2 : Peak Velocity Pressure along the height of building

Reference Height (m)	q_b (kPa)	$c_{e(z)}$	$c_{e(T)}$	q_p (kPa)
197.5	0.39	4.2	1	1.641
157.8	0.39	4.15	1	1.621
135	0.39	4.1	1	1.602
112.3	0.39	4.05	1	1.582
89.5	0.39	3.95	1	1.543
66.8	0.39	3.8	1	1.484

Reference	Calculation -**Analysis of Wind Loads-SL EN 1991-1-4:2005**	Output

Calculation of Design Wind Forces -X Direction

BS EN 1991-1-4 :2005 Cl 5.3

Specimen Calculation

Wind loads that would act at 20 th floor of the building is calculated as a specimen calculation.

BS EN 1991-1-4 :2005 Figure 7.5

Wind is applied normal to 'b'

h/d = 197.5/39.75

= 5.0

Loaded Area > $10m^2$

BS EN 1991-1-4 :2005 Table 7.1

$C_{p,e\ (windward)}$ - 0.8

$C_{p,e\ (leeward)}$ - -0.7

$C_{p,e}$ - 0.8+0.7

= **1.5**

Cl 6.2

Structural Factors (C_sC_d) - 1

BS EN 1991-1-4 :2005 Cl 5.3

Wind force acting on the structure

$$F_w = C_s C_d \sum_{surface} wA_{ref}$$

$$W_e = q_p (Z_e)\ C_{pe}$$

Table A.3 : Pressure Coefficients at each floor level in X direction

Level	h/d	$C_{p,e}$ (Windward)	$C_{p,e}$ (Leeward)	$C_{p,e}$
L55	5.0	0.8	-0.7	1.50
L54	5.0	0.8	-0.7	1.50
L53	5.0	0.8	-0.7	1.50
L52	5.0	0.8	-0.7	1.50
L51	5.0	0.8	-0.7	1.50
L50	5.0	0.8	-0.7	1.50
L49	5.0	0.8	-0.7	1.50
L48	5.0	0.8	-0.7	1.50
L47	5.0	0.8	-0.7	1.50
L46	5.0	0.8	-0.7	1.50
L45	5.0	0.8	-0.7	1.50
L44	5.0	0.8	-0.7	1.50
L43	5.0	0.8	-0.7	1.50
L42	5.0	0.8	-0.7	1.50
L41	5.0	0.8	-0.7	1.50
L40	5.0	0.8	-0.7	1.50
L39	5.0	0.8	-0.7	1.50
L38	5.0	0.8	-0.7	1.50
L37	5.0	0.8	-0.7	1.50
L36	5.0	0.8	-0.7	1.50
L35	5.0	0.8	-0.7	1.50
L34	5.0	0.8	-0.7	1.50
L33	5.0	0.8	-0.7	1.50
L32	5.0	0.8	-0.7	1.50
L31	5.0	0.8	-0.7	1.50
L30	5.0	0.8	-0.7	1.50
L29	5.0	0.8	-0.7	1.50
L28	5.0	0.8	-0.7	1.50

Reference	Calculation -**Analysis of Wind Loads-SL EN 1991-1-4:2005**	Output

L27	5.0	0.8	-0.7	1.50
L26	5.0	0.8	-0.7	1.50
L25	5.0	0.8	-0.7	1.50
L24	5.0	0.8	-0.7	1.50
L23	5.0	0.8	-0.7	1.50
L22	5.0	0.8	-0.7	1.50
L21	5.0	0.8	-0.7	1.50
L20	5.0	0.8	-0.7	1.50
L19	5.0	0.8	-0.7	1.50
L18	5.0	0.8	-0.7	1.50
L17	5.0	0.8	-0.7	1.50
L16	5.0	0.8	-0.7	1.50
L15	5.0	0.8	-0.7	1.50
L14	5.0	0.8	-0.7	1.50
L13	5.0	0.8	-0.7	1.50
L12	5.0	0.8	-0.7	1.50
L11	5.0	0.8	-0.7	1.50
L10	5.0	0.8	-0.7	1.50
L9	5.0	0.8	-0.7	1.50
L8	2.5	0.8	-0.575	1.38
L7	2.5	0.8	-0.575	1.38
L6	2.5	0.8	-0.575	1.38
L5	2.5	0.8	-0.575	1.38
L4	2.5	0.8	-0.575	1.38
L3	2.5	0.8	-0.575	1.38
L2	2.5	0.8	-0.575	1.38
L1	2.5	0.8	-0.575	1.38
GL	2.5	0.8	-0.575	1.38

Table A.4 : Wind Forces at each floor level in X direction

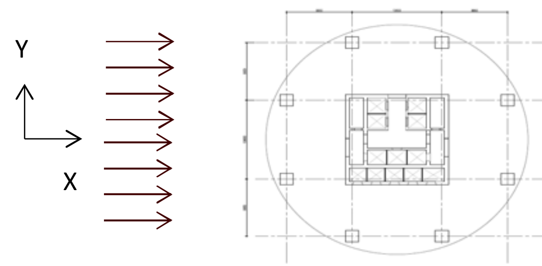
Level	Story Height (m)	Length Perpendicular Wind-b(m)	q_p (kPa)	$C_{p,e}$	Wind Force-F (kN)
L55	-	39.75	1.641	1.50	171.19
L54	3.5	39.75	1.641	1.50	342.38
L53	3.5	39.75	1.641	1.50	342.38
L52	3.5	39.75	1.641	1.50	342.38
L51	3.5	39.75	1.641	1.50	342.38
L50	3.5	39.75	1.641	1.50	342.38
L49	3.5	39.75	1.641	1.50	342.38
L48	3.5	39.75	1.641	1.50	342.38
L47	3.5	39.75	1.641	1.50	342.38
L46	3.5	39.75	1.641	1.50	342.38
L45	3.5	39.75	1.641	1.50	342.38
L44	3.5	39.75	1.621	1.50	338.30
L43	3.5	39.75	1.621	1.50	338.30
L42	3.5	39.75	1.621	1.50	338.30
L41	3.5	39.75	1.621	1.50	338.30
L40	3.5	39.75	1.621	1.50	338.30
L39	3.5	39.75	1.621	1.50	338.30
L38	3.5	39.75	1.621	1.50	338.30
L37	3.5	39.75	1.602	1.50	358.10
L36	4	39.75	1.602	1.50	358.10
L35	3.5	39.75	1.602	1.50	334.23

L34	3.5	39.75	1.602	1.50	334.23
L33	3.5	39.75	1.602	1.50	334.23
L32	3.5	39.75	1.602	1.50	334.23
L31	3.5	39.75	1.582	1.50	330.15
L30	3.5	39.75	1.582	1.50	330.15
L29	3.5	39.75	1.582	1.50	330.15
L28	3.5	39.75	1.582	1.50	330.15
L27	3.5	39.75	1.582	1.50	330.15
L26	3.5	39.75	1.582	1.50	330.15
L25	3.5	39.75	1.582	1.50	330.15
L24	3.5	39.75	1.543	1.50	322.00
L23	3.5	39.75	1.543	1.50	322.00
L22	3.5	39.75	1.543	1.50	322.00
L21	3.5	39.75	1.543	1.50	322.00
L20	3.5	39.75	1.543	1.50	322.00
L19	3.5	39.75	1.543	1.50	345.00
L18	4	39.75	1.484	1.50	354.02
L17	4	39.75	1.484	1.50	354.02
L16	4	39.75	1.484	1.50	354.02
L15	4	39.75	1.484	1.50	354.02
L14	4	39.75	1.484	1.50	354.02
L13	4	39.75	1.484	1.50	354.02
L12	4	39.75	1.484	1.50	354.02
L11	4	39.75	1.484	1.50	354.02
L10	4	39.75	1.484	1.50	354.02
L9	4	39.75	1.484	1.50	354.02
L8	4	51.3	1.484	1.38	418.82
L7	4	51.3	1.484	1.38	418.82
L6	4	51.3	1.484	1.38	418.82
L5	4	51.3	1.484	1.38	366.46
L4	3	51.3	1.484	1.38	314.11
L3	3	51.3	1.484	1.38	314.11
L2	3	51.3	1.484	1.38	314.11
L1	3	51.3	1.484	1.38	314.11
GL	3	51.3	1.484	1.38	157.06

Reference	Calculation - **Analysis of Wind Loads-BS EN 1991-1-4:2005**	Output

Calculation of Wind Forces in Y Direction

Wind loads on the building at each floor level, when the wind is blowing in X direction are calculated in this section.



h ~ 197.5m

Assumptions

Proposed building is located at Colombo-Zone 3
Terrain category is Town
Effect of neighbouring structures are neglected (h_{dis}=0)
Terrain orography is not significant
Distance to Shore Line is 5 km

Calculation of Basic Wind Speed (V_b)

Reference				
SLS EN	$V_{b,zone}$	-	25	m/s
Table NA.1	Basic wind speed (V_b)	=	$C_{dir}C_{sea}C_{alt}V_{b,0}$	
4.2	$C_{dir}/C_{sea}/C_{alt}$	=	1	
		=	1x1x1x25	
		=	**25**	m/s

Calculation of Basic Velocity Pressure (q_b)

Reference				
BS EN 1991-1-4	Density of Air	=	**1.25**	kg/m^3
:2005	Basic Velocity Pressure (q_b)	=	$0.5\rho v_b^2$	
Cl 4.5		=	0.5x1.25x25x25	
		=	**390.63**	N/m^2

Calculation of Peak Velocity Pressure (q_p)

Reference				
BS EN 1991-1-4	Peak Velocity Pressure (q_p)	-	$C_{e(z)}\ C_{e(T)}q_b$	
:2005				
Cl 4.5				

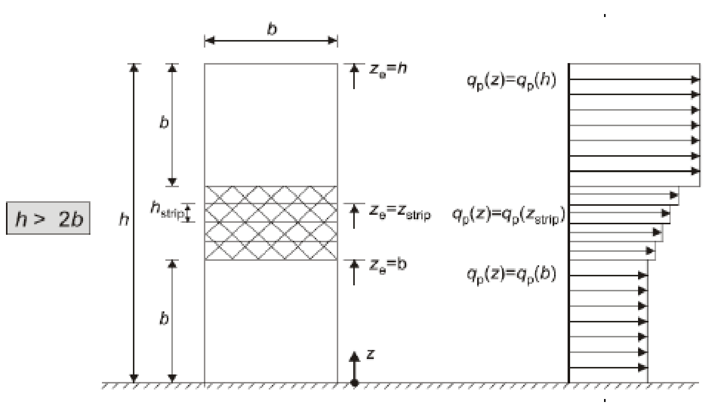
Table A.1 : Structural Dimensions of Building

Level	Story Height (m)	Height above Ground(m)	Length Along Wind-d (m)	Length Perpendicular to Wind-b(m)
L55	-	197.5	39.75	39.75
L54	3.5	194	39.75	39.75
L53	3.5	190.5	39.75	39.75
L52	3.5	187	39.75	39.75
L51	3.5	183.5	39.75	39.75
L50	3.5	180	39.75	39.75
L49	3.5	176.5	39.75	39.75
L48	3.5	173	39.75	39.75
L47	3.5	169.5	39.75	39.75
L46	3.5	166	39.75	39.75

L45	3.5	162.5	39.75	39.75
L44	3.5	159	39.75	39.75
L43	3.5	155.5	39.75	39.75
L42	3.5	152	39.75	39.75
L41	3.5	148.5	39.75	39.75
L40	3.5	145	39.75	39.75
L39	3.5	141.5	39.75	39.75
L38	3.5	138	39.75	39.75
L37	3.5	134.5	39.75	39.75
L36	4	130.5	39.75	39.75
L35	3.5	127	39.75	39.75
L34	3.5	123.5	39.75	39.75
L33	3.5	120	39.75	39.75
L32	3.5	116.5	39.75	39.75
L31	3.5	113	39.75	39.75
L30	3.5	109.5	39.75	39.75
L29	3.5	106	39.75	39.75
L28	3.5	102.5	39.75	39.75
L27	3.5	99	39.75	39.75
L26	3.5	95.5	39.75	39.75
L25	3.5	92	39.75	39.75
L24	3.5	88.5	39.75	39.75
L23	3.5	85	39.75	39.75
L22	3.5	81.5	39.75	39.75
L21	3.5	78	39.75	39.75
L20	3.5	74.5	39.75	39.75
L19	3.5	71	39.75	39.75
L18	4	67	39.75	39.75
L17	4	63	39.75	39.75
L16	4	59	39.75	39.75
L15	4	55	39.75	39.75
L14	4	51	39.75	39.75
L13	4	47	39.75	39.75
L12	4	43	39.75	39.75
L11	4	39	39.75	39.75
L10	4	35	39.75	39.75
L9	4	31	39.75	39.75
L8	4	27	51.3	79.7
L7	4	23	51.3	79.7
L6	4	19	51.3	79.7
L5	4	15	51.3	79.7
L4	3	12	51.3	79.7
L3	3	9	51.3	79.7
L2	3	6	51.3	79.7
L1	3	3	51.3	79.7
GL	3	0	51.3	79.7

Reference	Calculation			
BS EN 1991-1-4	h	=	197.5	m
:2005	b	=	39.75	m
Cl 7.2.2	h>2b			

Reference	Calculation - **Analysis of Wind Loads-SL EN 1991-1-4:2005**	Output
BS EN 1991-1-4 :2005 Figure 7.4		



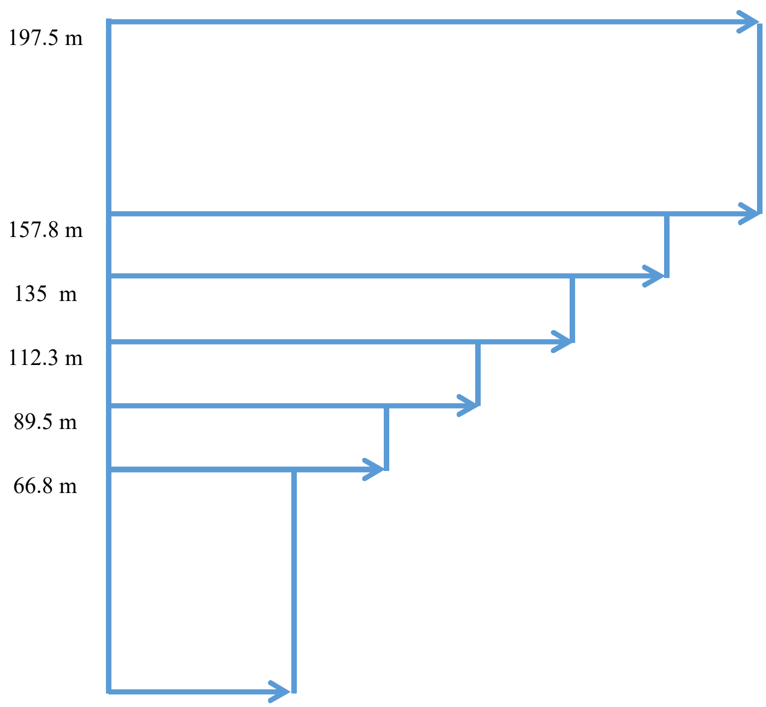


Table A.2 : Peak Velocity Pressure along the height of building

Reference Height (m)	q_b (kPa)	$c_{e(z)}$	$c_{e(T)}$	q_p (kPa)
197.5	0.39	4.2	1	1.641
157.8	0.39	4.15	1	1.621
135	0.39	4.1	1	1.602
112.3	0.39	4.05	1	1.582
89.5	0.39	3.95	1	1.543
66.8	0.39	3.8	1	1.484

Reference	Calculation -**Analysis of Wind Loads-SL EN 1991-1-4:2005**	Output

Calculation of Design Wind Forces -Y Direction

BS EN 1991-1-4 :2005 Cl 5.3

Specimen Calculation

Wind loads that would act at 20 th floor of the building is calculated as a specimen calculation.

BS EN 1991-1-4 :2005 Figure 7.5

Wind is applied normal to 'b'

h/d = 197.5/39.75
= 5.0

Loaded Area > 10m^2

BS EN 1991-1-4 :2005 Table 7.1

$C_{p,e\ (windward)}$ - 0.8
$C_{p,e\ (leeward)}$ - -0.7
$C_{p,e}$ - 0.8+0.7
= **1.5**

Cl 6.2

Structural Factors (C_sC_d) - 1

BS EN 1991-1-4 :2005 Cl 5.3

Wind force acting on the structure

$$F_w = C_s\,C_d \sum_{surface} wA_{ref}$$

$$W_e = q_p\,(Z_e)\,C_{pe}$$

Table A.3 : Pressure Coefficients at each floor level in Y direction

Level	h/d	$C_{p,e}$ (Windward)	$C_{p,e}$ (Leeward)	$C_{p,e}$
L55	5.0	0.8	-0.7	1.50
L54	5.0	0.8	-0.7	1.50
L53	5.0	0.8	-0.7	1.50
L52	5.0	0.8	-0.7	1.50
L51	5.0	0.8	-0.7	1.50
L50	5.0	0.8	-0.7	1.50
L49	5.0	0.8	-0.7	1.50
L48	5.0	0.8	-0.7	1.50
L47	5.0	0.8	-0.7	1.50
L46	5.0	0.8	-0.7	1.50
L45	5.0	0.8	-0.7	1.50
L44	5.0	0.8	-0.7	1.50
L43	5.0	0.8	-0.7	1.50
L42	5.0	0.8	-0.7	1.50
L41	5.0	0.8	-0.7	1.50
L40	5.0	0.8	-0.7	1.50
L39	5.0	0.8	-0.7	1.50
L38	5.0	0.8	-0.7	1.50
L37	5.0	0.8	-0.7	1.50
L36	5.0	0.8	-0.7	1.50
L35	5.0	0.8	-0.7	1.50
L34	5.0	0.8	-0.7	1.50
L33	5.0	0.8	-0.7	1.50
L32	5.0	0.8	-0.7	1.50
L31	5.0	0.8	-0.7	1.50
L30	5.0	0.8	-0.7	1.50
L29	5.0	0.8	-0.7	1.50
L28	5.0	0.8	-0.7	1.50

Reference	Calculation -**Analysis of Wind Loads-SL EN 1991-1-4:2005**	Output

L27	5.0	0.8	-0.7	1.50
L26	5.0	0.8	-0.7	1.50
L25	5.0	0.8	-0.7	1.50
L24	5.0	0.8	-0.7	1.50
L23	5.0	0.8	-0.7	1.50
L22	5.0	0.8	-0.7	1.50
L21	5.0	0.8	-0.7	1.50
L20	5.0	0.8	-0.7	1.50
L19	5.0	0.8	-0.7	1.50
L18	5.0	0.8	-0.7	1.50
L17	5.0	0.8	-0.7	1.50
L16	5.0	0.8	-0.7	1.50
L15	5.0	0.8	-0.7	1.50
L14	5.0	0.8	-0.7	1.50
L13	5.0	0.8	-0.7	1.50
L12	5.0	0.8	-0.7	1.50
L11	5.0	0.8	-0.7	1.50
L10	5.0	0.8	-0.7	1.50
L9	5.0	0.8	-0.7	1.50
L8	3.8	0.8	-0.64	1.44
L7	3.8	0.8	-0.64	1.44
L6	3.8	0.8	-0.64	1.44
L5	3.8	0.8	-0.64	1.44
L4	3.8	0.8	-0.64	1.44
L3	3.8	0.8	-0.64	1.44
L2	3.8	0.8	-0.64	1.44
L1	3.8	0.8	-0.64	1.44
GL	3.8	0.8	-0.64	1.44

Table A.4 : Wind Forces at each floor level in Y direction

Level	Story Height (m)	Length Perpendicular Wind-b(m)	q_p (kPa)	$C_{p,e}$	Wind Force-F (kN)
L55	-	39.75	1.641	1.50	171.19
L54	3.5	39.75	1.641	1.50	342.38
L53	3.5	39.75	1.641	1.50	342.38
L52	3.5	39.75	1.641	1.50	342.38
L51	3.5	39.75	1.641	1.50	342.38
L50	3.5	39.75	1.641	1.50	342.38
L49	3.5	39.75	1.641	1.50	342.38
L48	3.5	39.75	1.641	1.50	342.38
L47	3.5	39.75	1.641	1.50	342.38
L46	3.5	39.75	1.641	1.50	342.38
L45	3.5	39.75	1.641	1.50	342.38
L44	3.5	39.75	1.621	1.50	338.30
L43	3.5	39.75	1.621	1.50	338.30
L42	3.5	39.75	1.621	1.50	338.30
L41	3.5	39.75	1.621	1.50	338.30
L40	3.5	39.75	1.621	1.50	338.30
L39	3.5	39.75	1.621	1.50	338.30
L38	3.5	39.75	1.621	1.50	338.30
L37	3.5	39.75	1.602	1.50	358.10
L36	4	39.75	1.602	1.50	358.10
L35	3.5	39.75	1.602	1.50	334.23

Reference	Calculation -**Analysis of Wind Loads-SL EN 1991-1-4:2005**	Output

L34	3.5	39.75	1.602	1.50	334.23
L33	3.5	39.75	1.602	1.50	334.23
L32	3.5	39.75	1.602	1.50	334.23
L31	3.5	39.75	1.582	1.50	330.15
L30	3.5	39.75	1.582	1.50	330.15
L29	3.5	39.75	1.582	1.50	330.15
L28	3.5	39.75	1.582	1.50	330.15
L27	3.5	39.75	1.582	1.50	330.15
L26	3.5	39.75	1.582	1.50	330.15
L25	3.5	39.75	1.582	1.50	330.15
L24	3.5	39.75	1.543	1.50	322.00
L23	3.5	39.75	1.543	1.50	322.00
L22	3.5	39.75	1.543	1.50	322.00
L21	3.5	39.75	1.543	1.50	322.00
L20	3.5	39.75	1.543	1.50	322.00
L19	3.5	39.75	1.543	1.50	345.00
L18	4	39.75	1.484	1.50	354.02
L17	4	39.75	1.484	1.50	354.02
L16	4	39.75	1.484	1.50	354.02
L15	4	39.75	1.484	1.50	354.02
L14	4	39.75	1.484	1.50	354.02
L13	4	39.75	1.484	1.50	354.02
L12	4	39.75	1.484	1.50	354.02
L11	4	39.75	1.484	1.50	354.02
L10	4	39.75	1.484	1.50	354.02
L9	4	39.75	1.484	1.50	354.02
L8	4	79.7	1.484	1.44	681.44
L7	4	79.7	1.484	1.44	681.44
L6	4	79.7	1.484	1.44	681.44
L5	4	79.7	1.484	1.44	596.26
L4	3	79.7	1.484	1.44	511.08
L3	3	79.7	1.484	1.44	511.08
L2	3	79.7	1.484	1.44	511.08
L1	3	79.7	1.484	1.44	511.08
GL	3	79.7	1.484	1.44	255.54