THE APPROPRIATE STRUCTURAL SYSTEM FOR SUPER TALL BUILDINGS IN MALAYSIA

by

ZAID FADLI BIN MOHD NIZAM
13891

**Dissertation submitted in partial fulfillment of the requirements for the Bachelor of Engineering (Hons)
(Civil Engineering)**

MAY 2014

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

THE APPROPRIATE STRUCTURAL SYSTEM FOR SUPER TALL BUILDINGS IN MALAYSIA

by

ZAID FADLI BIN MOHD NIZAM
13891

**Dissertation submitted in partial fulfillment of the requirements for the Bachelor of Engineering (Hons)
(Civil Engineering)**

Approved by,

____

(DR NASIR SHAFIQ)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

May 2014

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the reference and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

____

(ZAID FADLI BIN MOHD NIZAM)

ABSTRACT

This project studies the appropriate structural system to be implemented to construct up to 500-meter super tall buildings in Malaysia. The existing primary structural systems for super tall building are first presented. Then, the main factors which affect the selection of the appropriate structural system are identified. Moreover, each factor is then thoroughly discussed in accordance to the Malaysian site conditions and is considered for the pre-selection of three structural systems to be used as the case studies for a 500-meter super tall office building. Certain criteria are assigned as the determination factor for all three pre-selected structural systems to satisfy. Based on the simulations conducted on all case studies using a computer software, performances comparison are made and the structural system which best satisfies the assigned criteria are considered as the optimum structural system to be implemented for super tall buildings in Malaysia.

ACKNOWLEDGEMENT

First and foremost the author would like to express his gratitude to Allah since His blessings has made the completion of the dissertation report possible.

Thanks to Universiti Teknologi PETRONAS (UTP) for providing the author the chance to conduct this study. Special thanks to the project's supervisor, Dr Nasir Shafiq for his useful guidance and assistances in completing the project. A thousand thanks to both coordinators, Dr Nurul Izma Mohammed and Dr Muhammad Raza Ul Mustafa for their efficient managements. The author is also grateful to all the academicians at the Civil Engineering Department who have been very helpful especially in sharing their knowledge and expertise.

Finally, the author wants to offer his gratitude to his family for their endless supports throughout the author's study years at UTP.

TABLE OF CONTENTS

CERTIFICATION OF APPROVAL…………………………………………….. ii

CERTIFICATION OF ORIGINALITY…………………………………… iii

ABSTRACT……………………………………………………………… iv

ACKNOWLEDGEMENT………………………………………………… v

TABLE OF CONTENTS……………………………………………….. vi

LIST OF FIGURES……………………………………………………... viii

LIST OF TABLES……………………………………………………..... x

CHAPTER 1 INTRODUCTION…………..……………………………… 1

1.1 Background of Study…......……………………………………… 1
1.2 Problem Statement..…………………..………………………….. 2
1.3 Objective..…...……………………..…………………………..... 3
1.4 Scope of Study..…...……………….……………........................ 4
1.5 Project Relevancy and Feasibility…...…..……………………….. 4

CHAPTER 2 LITERATURE REVIEW……...…………………………. 5

2.1 Interior Structures....……………………………………………… 5
2.1.1 Rigid Frames……………………………………………... 5
2.1.2 Braced Hinged Frames…………………………………... 6
2.1.3 Shear Walls / Hinged Frames……………………………. 7
2.1.4 Shear Wall / Frame Interaction System………………….. 7
2.1.5 Outrigger Structures……………………………………… 7
2.2 Exterior Structures....……...…………………….……………… 10
2.2.1 Tube……………………………………………………… 10
2.2.2 Diagrid…………………………………………………… 11
2.2.3 Space Truss Structures…………………………………… 12
2.2.4 Superframes……………………………………………… 12
2.2.5 Exo-skeleton……………………………………………... 13
2.3 Structural System General Selection Criteria…………..………… 15
2.3.1 Building Type/Function………………………………….. 16
2.3.2 Weather and Climate Conditions………………………… 16
2.3.3 Building Height Limit……………………………………. 17
2.3.4 Material’s Cost and Availability…………………………. 17
2.3.5 Strength, Stiffness and Stability…………………………. 17
2.3.6 Maintenance Cost………………………………………... 17
2.3.7 Sustainability…………………………………………….. 18
2.4 Wind Effects on Tall Buildings……….………………………… 18
2.4.1 Static Wind Effects……………………………………… 18
2.4.2 Dynamic Wind Effects………………………………….. 19

CHAPTER 3 METHODOLOGY…………..…………………………….. 20

3.1 The Factors………………………....………………………… 21
3.1.1 Building Descriptions……………………………………. 21
3.1.2 Location………………………………………………….. 21
3.1.3 Wind Conditions…………………………………………. 21

3.1.4 Type of Material……………………………………………. 22
3.1.5 Sustainability Development……………………………… 22
3.2 The Appropriate Structural System……..………………………. 22
3.3 Tools Required...………………..…………………………… 23
3.4 Project Key Milestones…………...……………………………… 23
3.5 Project Gantt Chart……………...……………………………….. 23

CHAPTER 4 RESULTS AND DISCUSSION...………………………….. 24

4.1 Site Conditions……………………….....…………………….. 24
4.2 Cost of Materials……………………………………………….. 29
4.3 Sustainability...............…………………………………………….. 29
4.4 Potential Structural Systems…..…..……………………………… 30
4.4.1 Widely-Spaced Braced Tube…………………………….. 31
4.4.2 Bundled Tube……………………………………………. 31
4.4.3 Superframes……………………………………………… 32
4.5 Lateral Drift Simulation…..…..…………………………………... 33
4.5.1 Constant Simulation Parameter………………………….. 33
4.5.2 Simulation Assumption………………………………….. 34
4.5.3 Simulation Results……………………………………….. 34
4.6 Optimum Structural System Evaluation………………………….. 38

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS…………. 43

REFERENCES...………………………………………………………… 44

LIST OF FIGURES

Figure 1.1	Building's height classification according to CTBUH.	1
Figure 2.1	Example of a rigid frame configuration.	16
Figure 2.2	Example of a braced hinged frame configuration.	16
Figure 2.3	Example of an outrigger structure configuration.	18
Figure 2.4	The interior structures with their relative efficient height limit.	9
Figure 2.5	Example of a closely spaced tube configuration.	10
Figure 2.6	Example of a widely spaced tube configuration.	11
Figure 2.7	Example of a bundled tube configuration.	11
Figure 2.8	Example of a diagrid configuration.	12
Figure 2.9	Example of a superframes configuration.	13
Figure 2.10	Example of an exo-skeleton configuration.	13
Figure 2.11	The exterior structures and their relative efficient height limit.	15
Figure 2.12	Vortex shedding effect on tall structure.	19
Figure 2.13	The cross-wind phenomena.	19
Figure 3.1	The flowchart of the methodology.	20
Figure 4.1	The monsoon winds phenomena.	24
Figure 4.2	Typhoons, cyclones and hurricanes paths.	25
Figure 4.3	The types of site exposure.	27
Figure 4.4	Widely-spaced braced tube structural system configuration for simulation.	31
Figure 4.5	Bundled tube structural system configuration for simulation.	32
Figure 4.6	Superframes structural system configuration for simulation.	32

Figure 4.7 Widely-spaced braced tube in 3D. 34

Figure 4.8 Widely-spaced braced tube under wind loading simulation 34

Figure 4.9 Concrete widely-spaced braced tube’s lateral drift graph. 35

Figure 4.10 Steel widely-spaced braced tube’s lateral drift graph. 35

Figure 4.11 Bundled tube in 3D. 36

Figure 4.12 Bundled tube under wind loading simulation. 36

Figure 4.13 Concrete bundled tube’s lateral drift graph. 36

Figure 4.14 Steel bundled tube’s lateral drift graph. 37

Figure 4.15 Superframes structure in 3D. 37

Figure 4.16 Superframes structure under wind loading simulation. 37

Figure 4.17 Concrete superframes’ lateral drift graph. 38

Figure 4.18 Steel superframes’ lateral drift graph. 38

Figure 4.19 Lateral drift efficiency bar chart. 40

Figure 4.20 Cost comparison bar chart. 41

Figure 4.21 Cost efficiency bar chart. 41

Figure 4.22 All 3 structural systems’ lateral drift and cost comparison graph. 42

LIST OF TABLES

Table 2.1	The advantages and disadvantages of the interior structures.	8
Table 2.2	The advantages and disadvantages of the exterior structures.	14
Table 3.1	Project Key Milestones table.	23
Table 3.2	Project Gantt Chart.	23
Table 4.1	Basic wind speed for major towns in Malaysia.	25
Table 4.2	The wind pressure coefficient table.	28
Table 4.3	The wind importance factor table.	29
Table 4.4	Widely-spaced braced tube's lateral drift and estimated cost.	34
Table 4.5	Bundled tube's lateral drift and estimated cost.	36
Table 4.6	Superframes structure's lateral drift and estimated cost.	37
Table 4.7	All 3 structural systems' lateral drift and estimated cost comparison.	39

CHAPTER 1

INTRODUCTION

1.1 Background of Study

According to Hackney Tall Building Strategy (2005), the definition of tall buildings is buildings or structures that are significantly taller than the surrounding development. Nonetheless, Council on Tall Buildings and Urban Habitat (CTBUH) has given height classification to differentiate between buildings in which the height of a normal tall building is from 40 to 300-meter tall, super tall building is in the range of 300 to 600-meter tall and mega tall building is over 600-meter tall.

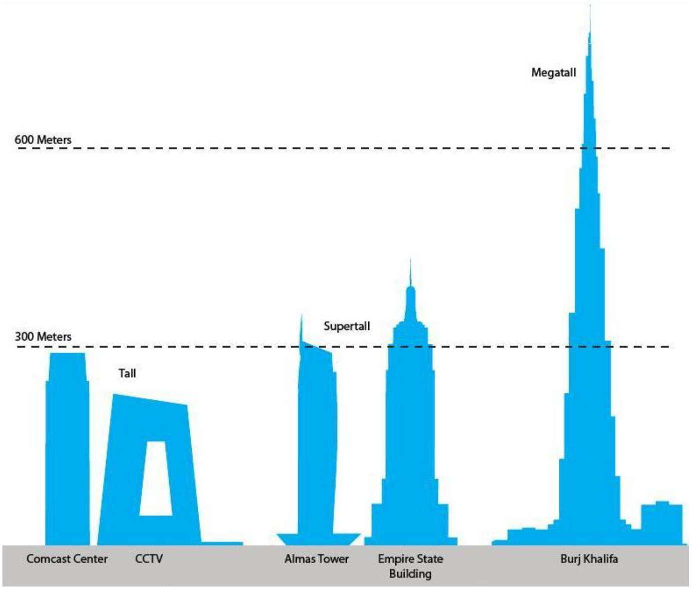


Figure 1.1: Building's height classification according to CTBUH. Retrieved from CTBUH (2005).

Tall buildings have been the goal of ancient civilizations in which the structures symbolize power and wisdom of their kingdoms. This is still proven true today, as big nations are competing against each other in constructing the tallest man-made structure. Nevertheless, the main reason for building such tall structures has slowly been shifted to as simple reason as to fully benefit land space. This is a serious matter in fact as the human populations grow, more lands are being occupied and leaving less lands available for development (D'souza, B., 2013). Land becomes an essential asset and land wastage would not be tolerated.

Because of these reasons, the demands for vertical space increases thus buildings are designed to be as tall as possible. But without proper designs, tall buildings tend to be overtopped or collapsed. Hence, the need for appropriate structural systems for super tall building has never been this crucial. With appropriate structural system, it does not just guaranteeing the stability of the building, but it also minimized the costs for construction and maintenance as well as achieving the sustainability development.

1.2 Problem Statement

In order to construct a super tall building, two main factors need to be considered, which are the vertical load and the lateral load (Ali, M. M., & Moon, K., 2007). Vertical load can be defined as the gravity loads that act vertically to the structure, in which comes from the weight of the structure itself. On the other hand, there are two types of lateral loads – the wind load and the seismic load. The wind load acts laterally to the building and is influenced by the magnitude of the wind's velocity. In general, the greater the building's height from the ground level, the greater the wind load acting upon it (Alshamrani, O. S., 2007). Conversely, seismic load also acts at the sideways of the building but comes from the seismic activity of the earth, for example, an earthquake.

Super tall building usually is a massive structure that span hundred of meters from the ground, thus contributes to considerable magnitude of vertical load. Moreover, according to Fazlur Khan (1969), when the building's height is going super tall, the lateral drift influence increases and the building's stiffness rather than strength plays the larger role in providing the stability. Therefore, to minimize the effects of lateral drift, an appropriate structural system for super tall building is essential.

There are many structural systems for super tall buildings being introduced over the time. Nevertheless, as been stated by A. Hameed, I. Azeem, A. Qazi, B. Sharif and N. M. Khan (2013), there is always an optimum structural system for each condition. The most appropriate structural systems to be implemented are influenced by a lot of factors as been stated by Othman S. Alshamrani (2007). Among them, the main factors are:

1. the purpose of the building
2. the building site's conditions
3. the main materials for the building

The purpose of the building will determine its recommended height and its design. Furthermore, the location of the building will determine the wind conditions and the seismic activities of the area. In addition, the main materials to be used for construction of the building are selected based on their availabilities and costs at that particular area. These materials ultimately will determine the weight, strength and stiffness of the building. Thus, from these three main factors, the vertical and lateral loads could be estimated hence the appropriate structural system for the super tall building could be designed.

1.3 Objective

The main objective of this study is to generally determine the most appropriate structural system of super tall buildings in Malaysia; based on the main criteria proposed:

1. Minimizing the lateral drift
2. Minimizing the cost in material used
3. Sustainability development.

1.4 Scope of Study

The project will proposed a construction of a super tall building at a location in Malaysia. In order to select the appropriate structural system for the building, researches will be conducted to gain knowledge regarding:

1. The available structural systems.
2. The main materials to be used for the construction based on their characteristics (strength, stiffness, weight, etc), availabilities and costs.
3. The lateral load imposed on the building based on the wind's maximum velocity at the building's maximum height.

Seismic load shall be ignored since Malaysia is located outside of the Pacific Ring of Fire hence will not experience any significant earthquakes.

1.5 Project Relevancy and Feasibility

This study is highly relevant to the civil engineering program which falls under the course of Building Design and Construction Technology. The study assists in providing deeper understanding to the course and gives the opportunity to apply the knowledge in practical software simulation.

The utilization of computer software to simulate the performance evaluation of the structural systems for super tall buildings with reliable results offers feasibility in this study.

CHAPTER 2

LITERATURE REVIEW

Structural system is the main part of the building which transfers both the vertical and lateral loads safely to the ground (Alshamrani, O. S., 2007). The vertical gravity loads are consisted of dead and live loads while the lateral loads are caused by the wind and seismic loads. In the case of super tall building, the lateral load is the major concern since as the building get taller, the lateral drift or lateral displacement experienced by the building also increases (Khan, F., 1969). Hence, the structural systems for super tall buildings are designed specifically to resist both vertical and lateral loads, and mostly the wind load since it is of the utmost concern. In his research, Fazlur Khan (1969) has strategically organized the structural systems for super tall building into two categories – the interior structures and the exterior structures. His research then became the fundamental references for super tall building structural systems and is still relevant even at today. For the interior structures, the major part of the lateral load resisting system is located within the interior of the building. Conversely, the major part of the lateral load resisting system is situated at the perimeter of the building for the exterior structures. Nonetheless, any interior structures may have minor lateral load resisting system at the building perimeter and vice versa for the exterior structures.

2.1 Interior Structures

2.1.1 Rigid Frames

The moment-resisting frame (MRF) is made up of horizontal and vertical member connected together rigidly in a grid form. The frames resist load mainly using the flexural stiffness of the members. The gravity load determines the size of the column and usually, the size increases towards the base of the building to resist the gravity load accumulated there. On the other hand, the size of the girders is influenced by the stiffness of the frame to ensure tolerable sway of the building.

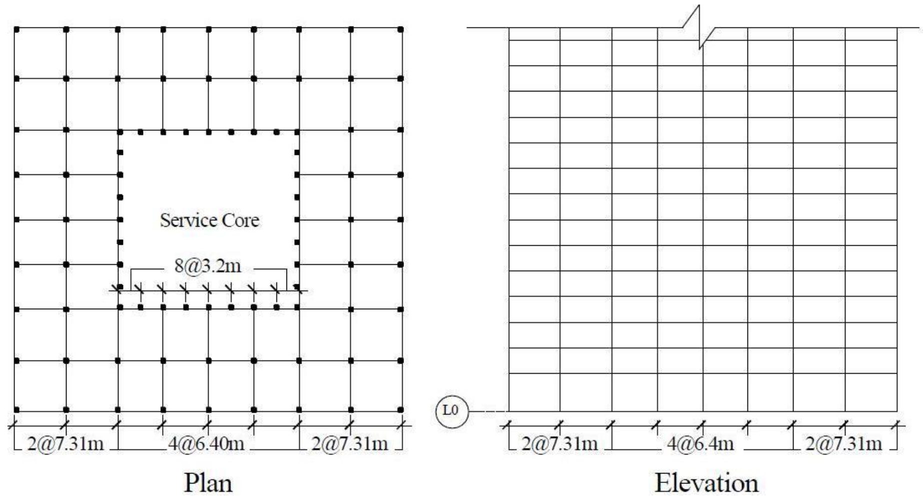


Figure 2.1: Example of a rigid frame configuration. Retrieved from Hameed, A., Azeem, I., Qazi, A., Sharif, B. and Khan, N. M. (2013).

2.1.2 Braced Hinged Frames

Braced frames are supported laterally by vertical trusses and through the axial stiffness of the members, resist the lateral loads. The columns operate as chord members while the web members are played by the concentric K, V, or X braces. Together, they act as the vertical cantilever trusses.

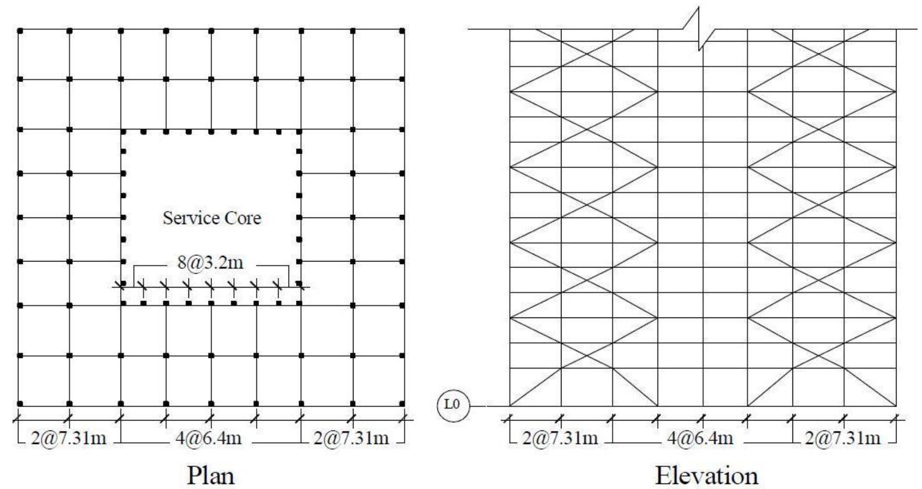


Figure 2.2: Example of a braced hinged frame configuration. Retrieved from Hameed, A., Azeem, I., Qazi, A., Sharif, B. and Khan, N. M. (2013).

2.1.3 Shear Wall / Hinged Frames

When beams or slabs interconnected with two or more shear walls in the same plane, the system's total stiffness surpasses the sum of stiffness of the individual wall. This is due to the walls acting as a single unit forced via the connecting beam by restraining their individual cantilever actions. This is called as coupled shear walls.

2.1.4 Shear Wall - Frame Interaction System

Rigid frames are inefficient in building structure with more than 30-storey height because the bending of column and girders causes shear racking component of deflection hence the building will sway excessively. Nevertheless, when combined with vertical steel shear trusses or concrete shear walls, a shear truss or shear wall-frame interaction system is produced. The frame restrains the upper part of the truss, while the shear wall or truss restrains the lower part. This combination resulted in improved lateral rigidity of the building.

2.1.5 Outrigger Structures

The use of strong masts to resist the wind force acting on the sails by the sailing ships is known as the outrigger system. The concept of mast of a ship is applied as the core in a tall building, with horizontal outrigger acting as the spreaders to connect the core with the exterior columns. The core usually is located at the center with outriggers extending on both sides. However in some cases, the core may be positioned at one side of the building with the outriggers extending to the building's column at the other side. For steel structures, the outriggers are usually in the form of trusses whereas for concrete structures, the outriggers are usually in the form of walls. Taipei 101 is an example of a tall building which uses outriggers structure as its structural system.

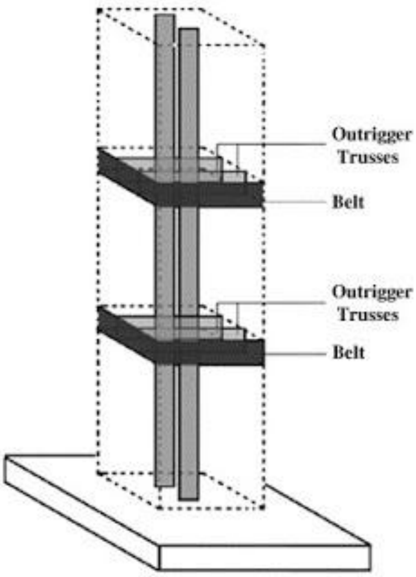


Figure 2.3: Example of an outrigger structure configuration. Retrieved from Gunel, M. H. and Ilgin, H. E. (2006).

The table below shows the types of interior structures for super tall building with their advantages and disadvantages, as been listed by Mir M. Ali and Kyoung Sun Moon (2007).

Table 2.1: The advantages and disadvantages of the interior structures. Retrieved from Ali, M. M. and Moon, K. S. (2007).

Category	Sub-category	Material / Configuration	Efficient Height Limit (storey)	Advantages	Disadvantages
Rigid Frames	-	Steel	30	Flexibility in floor planning. Fast construction.	Expensive moment connection. Expensive fire proofing.
		Concrete	20	Flexibility in floor planning. Easily moldable.	Expensive formwork. Slow construction.
Braced Hinged Frames	-	Steel Shear Trusses + Steel Hinged Frames	10	Efficiently resist lateral shear by axial forces in the diagonal members.	Interior planning limitation due to diagonals in the shear trusses.
Shear Wall / Hinged Frames	-	Concrete Shear Wall + Steel Hinged Frames	35	Efficiently resist lateral shear by concrete shear walls.	Interior planning limitation due to shear walls.
Frame Interaction System	Braced Rigid Frames	Steel Shear Trusses + Steel Rigid Frame	40	Efficiently resist lateral shear by producing shear truss	Interior planning limitation due to

				– frame interacting system.	shear trusses.
	Shear Wall / Rigid Frames	Concrete Shear Wall + Steel Rigid Frame	60	Efficiently resist lateral shear by producing shear wall – frame interacting system.	Interior planning limitation due to shear walls.
		Concrete Shear Wall + Concrete Frame	70	"	"
Outrigger Structures	-	Shear Cores (Steel Trusses or Concrete Shear Walls) + Outriggers (Steel Trusses or Concrete Walls) + Belt Trusses + Steel or Concrete Composite (Super) Columns	150	Effectively resists bending by exterior columns connected to outriggers extended from the core.	Outrigger structure does not add shear resistance.

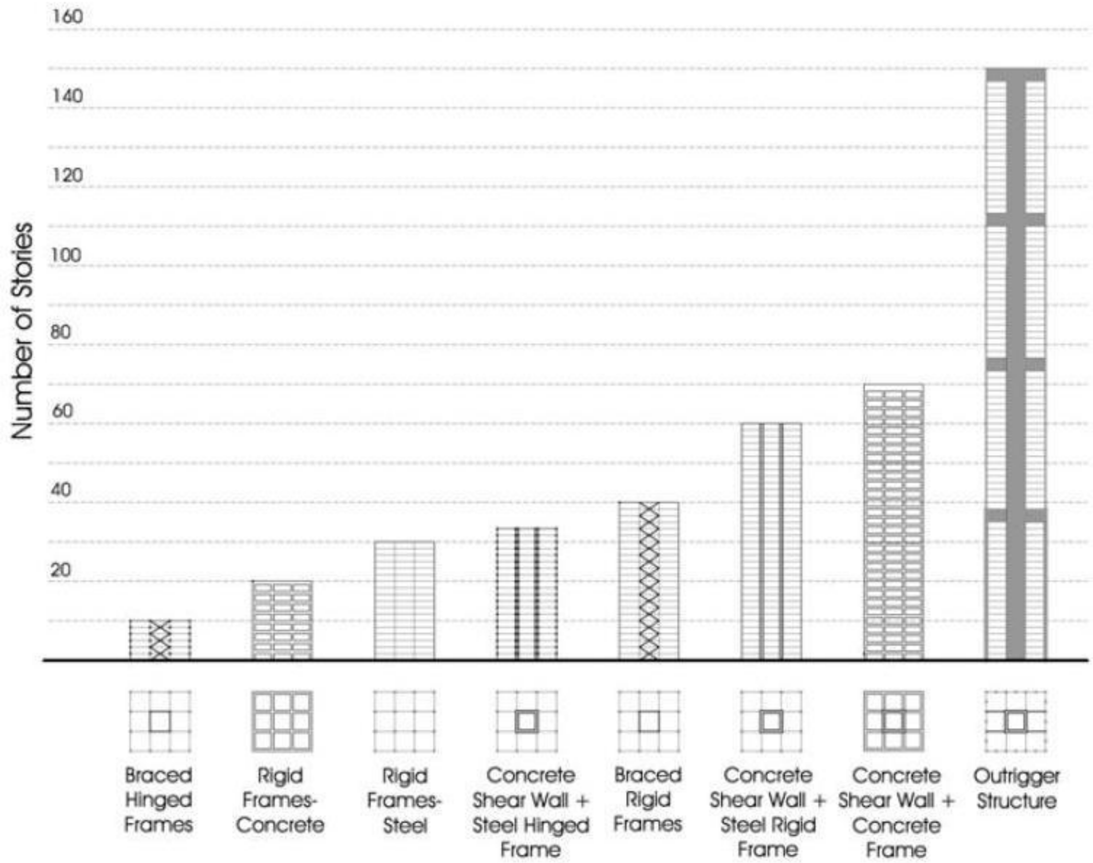


Figure 2.4: The interior structures with their relative efficient height limit. Retrieved from Ali, M. M. and Moon, K. S. (2007).

2.2 Exterior Structures

2.2.1 Tube

Tube is a three-dimensional structural system that employs the whole building perimeter to resist lateral loads. In the framed tube system, the columns of the building are placed closely to each other and deep spandrel beam are connected rigidly together throughout the exterior frames. Framed tube is design for the purpose of limiting the shear lag effect and targeting for more cantilever-type behavior of the structure.

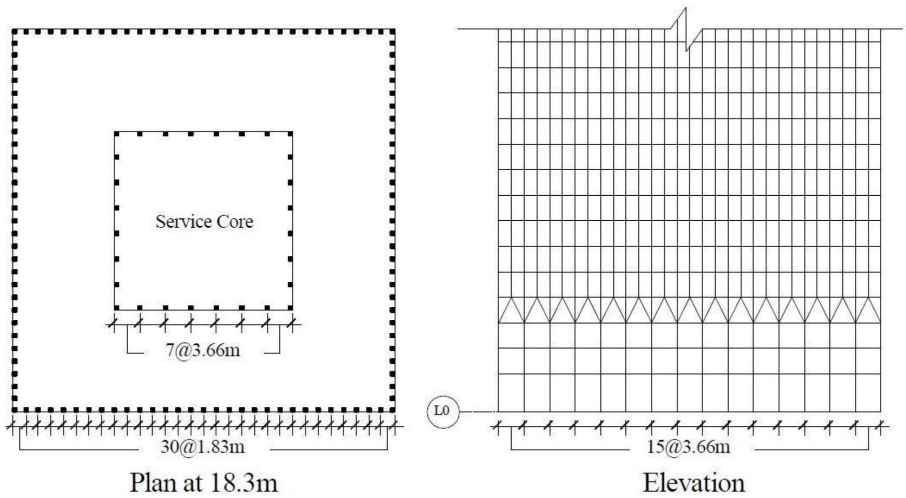


Figure 2.5: Example of a closely spaced tube configuration. Retrieved from Hameed, A., Azeem, I., Qazi, A., Sharif, B. and Khan, N. M. (2013).

In the braced tube system, instead of using closely spaced perimeter columns, the widely spaced columns is stiffen by diagonal braces to induce wall-like characteristics. This concept overcomes the problem of framed tube becoming inefficient for height over 60 stories due to web frames starts to behave like conventional rigid frames and the cantilever behavior of the structure is undermined thus the shear lag effect is provoked. An example of building which uses this structural system is the Bank of China in Hong Kong.

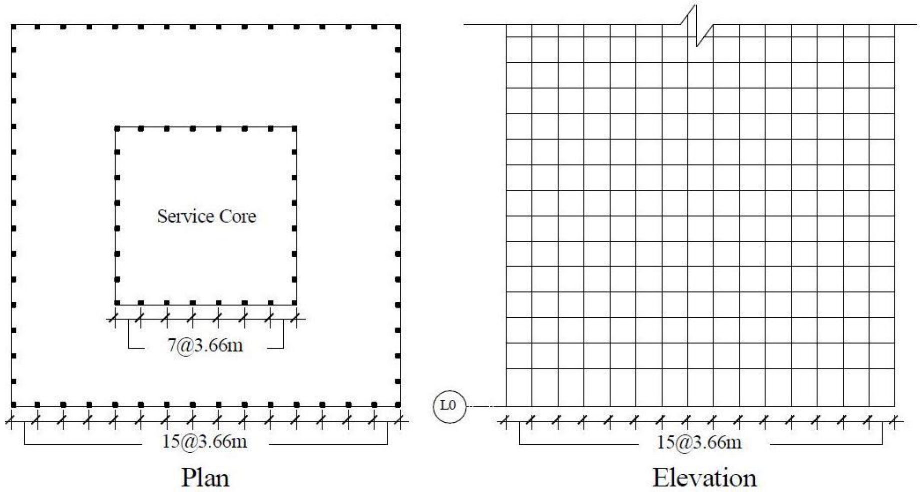


Figure 2.6: Example of a widely spaced tube configuration. Retrieved from Hameed, A., Azeem, I., Qazi, A., Sharif, B. and Khan, N. M. (2013).

When a bunch of individual tubes attached together to perform as a single unit, the concept is called as a bundled tube. This concept allows for wider columns spacing in the tubular walls.

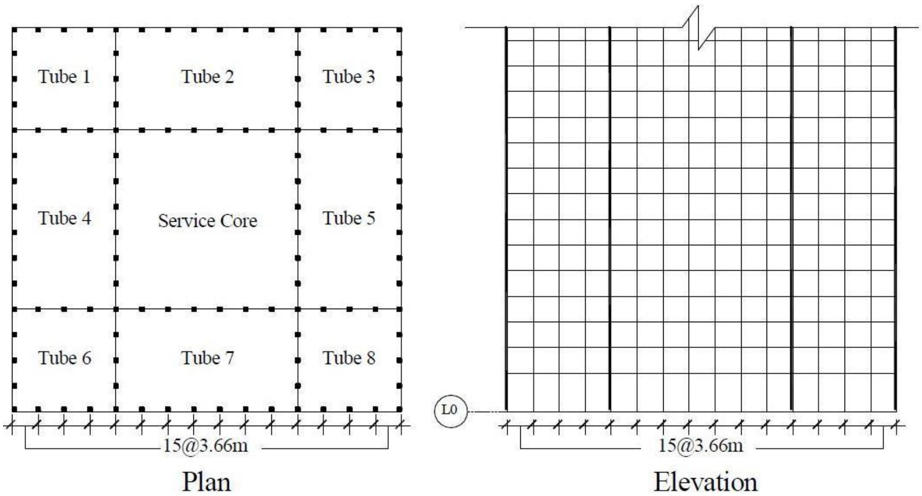


Figure 2.7: Example of a bundled tube configuration. Retrieved from Hameed, A., Azeem, I., Qazi, A., Sharif, B. and Khan, N. M. (2013).

2.2.2 Diagrid

The effectiveness of diagonal bracing members in resisting lateral forces is acknowledged in the early designs of tall buildings. However, since diagonal bracing hinders the outdoors viewing, the concept is not well appreciated. Thus, the system is generally applied within the building cores, which located in the interior of the building.

A diagrid structure is when the diagonal members are positioned at the whole exterior perimeter of the building to make the most of their structural effectiveness. Diagrid structure eliminates almost all external vertical columns, which makes this system different from the conventional external brace frame structure. The uniform triangulated configuration of the diagonal members makes it possible for this system to transfer both gravity loads and lateral forces to the ground.

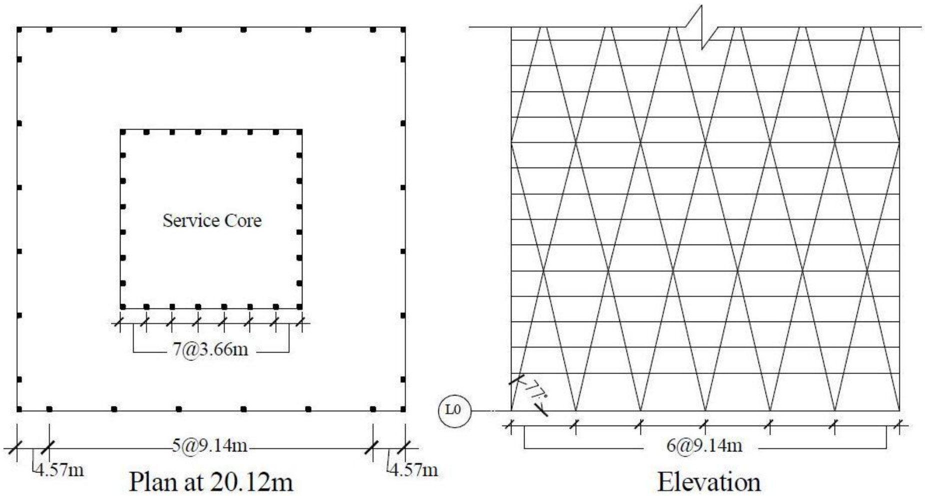


Figure 2.8: Example of a diagrid configuration. Retrieved from Hameed, A., Azeem, I., Qazi, A., Sharif, B. and Khan, N. M. (2013).

2.2.3 Space Truss Structures

Space truss structure is a form of improvised braced tubes which uses diagonals member to join the exterior to interior. Unlike in the braced tube system in which all the diagonal members are placed on the plane parallel to the facade, some diagonal members in the space trusses structure penetrate into the interior of the building.

2.2.4 Superframes

A superframes is consisted of usually more than three super size or mega columns at the building corners. The mega columns are connected by multi-level deep trusses with or without diagonal bracing members at every specific number of floors. The superframes concept can be use in a variety of ways in tall buildings. Chicago World Trade Center building implements the superframes concept.

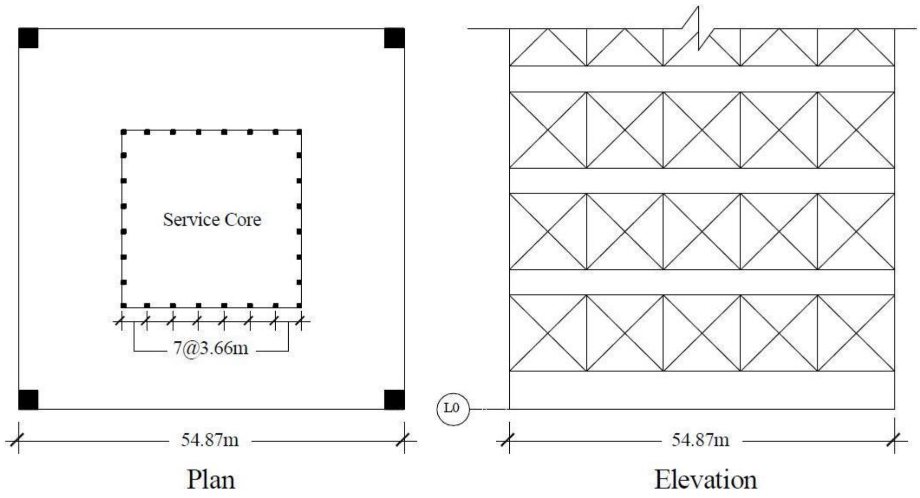


Figure 2.9: Example of a superframes configuration. Retrieved from Hameed, A., Azeem, I., Qazi, A., Sharif, B. and Khan, N. M. (2013).

2.2.5 Exo-skeleton

Exo-skeleton structural system consists of independent vertical and lateral load resisting subsystems. The lateral load-resisting subsystems are located at the perimeter of the building. The lateral load resisting subsystem can be selected from any of the basic forms, such as braced tube. Since the systems are placed outside of the building, the aspects of thermal expansion as well as contraction of the system and exposure to the different kind of outdoor weather should be carefully considered in the design.

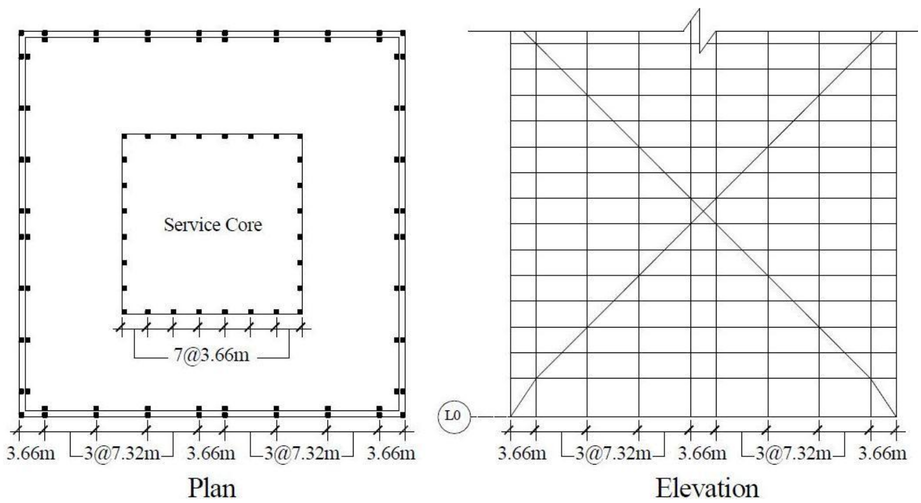


Figure 2.10: Example of an exo-skeleton configuration. Retrieved from Hameed, A., Azeem, I., Qazi, A., Sharif, B. and Khan, N. M. (2013).

The table below shows the types of exterior structures for super tall building with their advantages and disadvantages, as been listed by Mir M. Ali and Kyoung Sun Moon (2007).

Table 2.2: The advantages and disadvantages of the exterior structures. Retrieved from Ali, M. M. and Moon, K. S. (2007).

Category	Sub-category	Material / Configuration	Efficient Height Limit (storey)	Advantages	Disadvantages
Tube	Framed Tube	Steel	80	Efficiently resists lateral loads by locating lateral load resisting system at building's perimeter.	Shear lag hinder true tubular behavior. Narrow column obstructs the view.
		Concrete	60	"	"
	Braced Tube	Steel	150	Efficiently resist lateral shear by axial forces in the diagonal members. Wider column spacing possible compared to framed tube. Reduce shear lag.	Bracings obstruct the view.
		Concrete	100	"	"
	Bundled Tube	Steel	110	Reduced shear lag.	Interior planning limitation due to the bundle tube configuration.
		Concrete	110	"	"
Diagrid	-	Steel	100	Efficiently resist lateral shear by axial forces in the diagonal members.	Complicated joints.
		Concrete	60	"	Expensive formwork. Slow construction
Space Truss Structures	-	Steel	150	Efficiently resist lateral shear by axial forces in the space truss members.	May obstruct the view.
Super -frames	-	Steel	160	Have high efficient height limit.	Building form depends to a great degree on the structural system.
		Concrete	100	"	"

Exo-skeleton	-	Steel	100	Interior floor is not obstructed by interior columns.	Thermal expansion / contraction. Systemic thermal bridges.

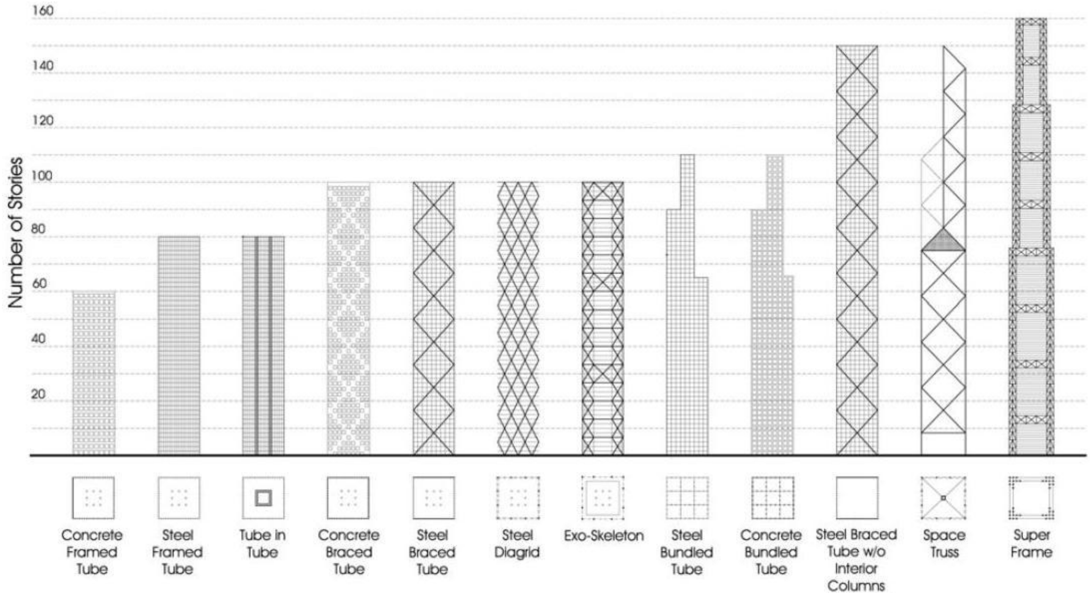


Figure 2.11: The exterior structures and their relative efficient height limit. Retrieved from Ali, M. M. and Moon, K. S. (2007).

2.3 Structural System General Selection Criteria

Othman S. Alshamrani (2007) clearly stated that there are numerous criteria that affect the selection of the structural system for tall building. The selection criteria are broad in scope and cover not just the structural parts, but also the architectural aspects. Commonly, the engineer will determine the structural system based on the criteria agreed by the building owner and architect. Below are some of the significant selection criteria:

- Building type/function
- Weather and climate conditions
- Building's height limit
- Material's cost and availability
- Strength, stiffness and stability
- Maintenance cost
- Sustainability

2.3.1 Building Type/Function

Generally, tall buildings are usually constructed for office uses during their early development in the United States (Colaco, J., P., 2005). However, Colaco argued that the current trends have witnessed the appearance of tall apartment towers and tall buildings with mixed uses. He also added that the functions of the tall building will favor specific kind of structural systems.

For example, A. Sev and A. Özgen (2009) strongly suggested that office-type tall building favors wide floor space with minimum internal column hence exterior structures such as tube, diagrid and superframe are preferred. Sears Tower, Chicago World Trade Center and Bank of China are fine examples of such buildings.

Apartment-type tower, on the other hand, favor narrower floor plan as to be closed with the exterior walls and it demands for unobstructed outside views. These preferences have eliminated the exterior structures as potential systems since most of their lateral load resisting systems are located at the perimeter of the building, in which obstruct the view. Interior structures such as shear wall-frame interaction system and outrigger structures, however, are the perfect candidates since they provide just the aspects sought by the apartment-type tower.

Nonetheless, the classification that specifies exterior structures for office-type building and interior structures for apartment-type building is not rigid but rather flexible according to the desires of the building owner, architect and engineer involved.

2.3.1 Weather and Climate Conditions

The weather and climate conditions at the proposed tall building's location is an important aspect since it will determine the vertical load and lateral load imposed on the structure. For example, locations which experience winter season with high probability of snowing need to consider the snow load in the building design. Furthermore, the building's location will also determine the probability of earthquake occurrences and the wind maximum velocity with the probability of cyclone occurrences. Only when all of these aspects are taken into considerations then can a structural system could be selected.

2.3.3 Building Height Limit

Based on the efficient height limit defined by Fazlur Khan (1969) as been illustrated in Figure 2.4 and Figure 2.11, a structural system can be strategically chosen based on the proposed building's height.

2.3.4 Material's Cost and Availability

There are two types of materials generally used in the construction of tall buildings, which are steel and concrete. Both of these materials' costs typically depend on their availability, as local materials usually cost cheaper than imported materials. Transportation of materials to the project site also contributes to the cost, in which it depends on the means of transportation and the distance of the material's source to the site.

2.3.5 Strength, Stiffness and Stability

A structural system should provide strength to the building to prevent and resist breaking. It should also provide stiffness in order to avoid extreme deformation. Moreover, structural overturning, sliding as well as uplift can be opposed and prevented by providing stability. Nevertheless, Alshamrani (2007) argued that, unlike resisting wind load by providing stiffness, a structural system should be flexible to resist seismic load.

The elements of strength, stiffness and stability of the structural systems originated from the material used in the system itself. Steel typically possessed higher strength to weight ratio than concrete, but provide lower stability due to its lightweight characteristic. In term of stiffness, concrete is stiffer than steel hence is excellent to resist wind load while steel is more flexible and suitable to resist the seismic load.

2.3.6 Maintenance Cost

Maintenance cost should also be put into consideration along with the construction cost due to the long life-cycle of super tall building. According to Ilze Liepina (2011), in general, structural steel has a high maintenance cost since it needs periodically paintwork to prevent corrosion and provide fireproofing. Concrete-based structural system, conversely, has a very low maintenance cost since it is more durable against corrosion and fire.

2.3.7 Sustainability

Sustainability can be defined as strategic use of resources to meet the demand of the presence, without compromising the resources for future use. The main materials used in the structural system are steel and concrete. Steel can be obtained by recycling used steels (Liepina, I., 2011). On the other hand, concrete's main elements – aggregate and water are considered natural resources and are widely available. Furthermore, the aggregate used can also be obtained from recycled concrete. Addictive such as fly ash comes from the waste of coal burning. In addition, cement as one of the element of concrete can be optionally replaced with geopolymer concrete, which does not require combustion during the manufacturing process.

2.4 Wind Effects on Tall Building

Wind effects on tall buildings are phenomenon with great complexity and almost unpredictable. The effects of wind load when in contact with a structure are negligible in low-rise buildings. However, as been argued by J. Zils and J. Viise (2003), the wind load is the main factor contributing to the lateral drift in tall buildings due to their tall and slender nature. Moreover, according to P. Mendis, T. Ngo, N. Haritos, A. Hira, B. Samali, and J. Cheung (2007), tall buildings respond to two types of wind effects, the static wind effects the dynamic wind effects. The building's responses to wind effects are significantly influenced by the architectural design of the building, in which aerodynamically designs are much preferable.

2.4.1 Static Wind Effects

Static wind effects involve only predicting the pressure created by the wind's velocity at different height of the building and the lateral drift experienced by the structure. The wind velocity is influenced by the weather and climate conditions of the building's location and is usually predicted in a period of specific year return period. Due to its simple nature, static wind effects can be simulated using computer software.

2.4.2 Dynamic Wind Effects

Tall buildings are more vulnerable to the dynamic effects of wind, which are almost unpredictable in nature. The effects include buffeting, vortex shedding, galloping and flutter. Slender structures are sensitive to dynamic response parallel with the wind direction due to turbulence buffeting. Furthermore, cross-wind might form from the result of vortex shedding or galloping. Vortex shedding usually forms fluctuating pressures to the building's structure.

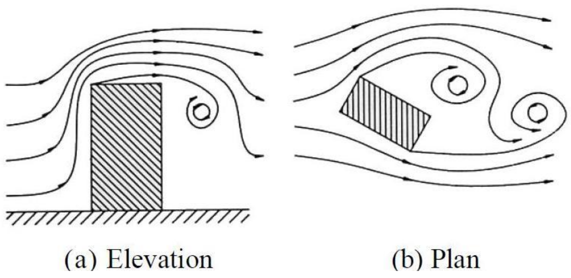


Figure 2.12: Vortex shedding effect on tall structure. Retrieved from Mendis, P. et al. (2007).

A combination of bending and torsion resulted in the coupled motion of flutter, and can contribute to structure's instability. Commonly, galloping and fluttering are not major issues in building structures. The high uncertainties in computing the dynamic effects of wind are countered by carrying out simulation of tall building's response in a wind tunnel test.

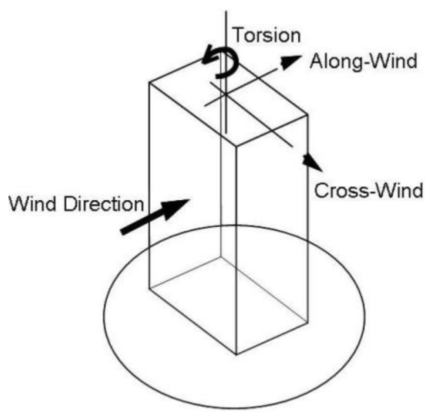


Figure 2.13: The cross-wind phenomena. Retrieved from Mendis, P. et al. (2007).

CHAPTER 3

METHODOLOGY

The methodology to select the optimum structural system according to certain conditions is inspired from the “The Selection of Structural Systems and Materials” research by Alshamrani (2007). The first step in the selection of appropriate structural system for super tall buildings in Malaysia is to determine the main criteria and factors of the system. Then, the corresponding factors are applied to different structural systems as case studies. After that, the structural systems performance will be evaluated using a computer software simulation in the aim of achieving the criteria proposed. Finally, the structural system which best achieved the criteria in the performance evaluation shall be selected as the optimum and appropriate system to be used in Malaysia.

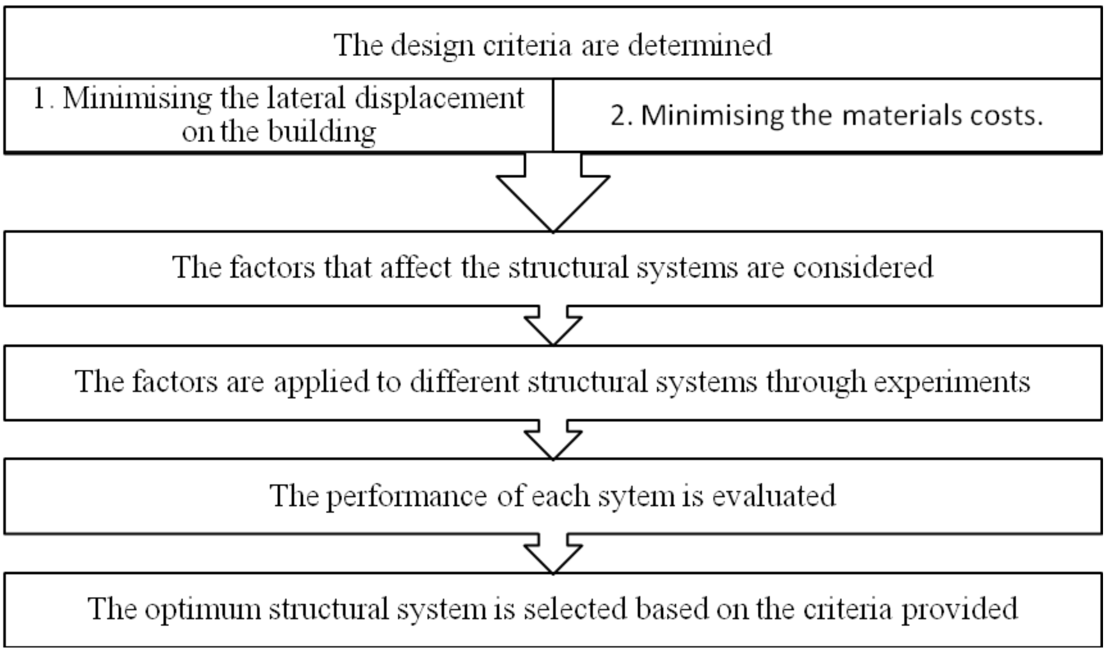


Figure 3.1: The flowchart of the methodology.

The design main criteria in the selection of the structural system for super tall building in Malaysia are:

1. Minimizing the lateral displacement of the structure

2. Minimizing the cost in material used

3.1 The Factors

3.1.1 Building Descriptions

This project proposes a construction of an office-type super tall building, with 500-meter height.

3.1.2 Location

A location for the construction of the super tall building shall be chosen at a site in Malaysia. This location is significant since it will determine the weather and climate conditions thus will define the wind peak velocity that will influence the structural system of the building. The seismic lateral load shall be ignored since Malaysia is positioned outside of the Pacific Ring of Fire hence will not experience any significant earthquakes. This consideration is taken to minimize the construction cost.

3.1.3 Wind Conditions

The wind conditions at the proposed building's location shall be investigated at various heights. Only static effects of wind will be considered and serve as a fundamental guidance in the selection of structural system of super tall building in Malaysia. Wind tunnel simulation could not be carried out since there is limitation in equipment required. Any dynamic wind effects shall only be put into consideration when there is architectural design of the building involved. There are several assumptions made in this project:

1. The architectural design of the building shall be in its simplest form, which is a square shape building from the plan layout.
2. Dynamic effects of wind to the structure shall be ignored since there is no consideration taken into the architectural design of the building.
3. This project only serves as the basic guidance to select the appropriate structural system up to the static response of the building against wind load.

3.1.4 Type of Material

The type of main materials for the building shall be chosen while considering the factors of their characteristics (the strength, stiffness, weight, etc), their availabilities in Malaysia and their costs. The materials considered shall be steel and concrete.

3.1.5 Sustainability Development

Sustainability development of the building shall be considered in the form of the structural system continuous maintenance cost, environmental impacts, and durability.

3.2 The Appropriate Structural System

The appropriate structural systems shall be selected using following procedure:

1. Three structural systems shall be selected as case studies based on the factors of building's function, weather and climate conditions, lateral loads, vertical loads and type of main materials.
2. All three systems shall be simulated under the wind static effect at 500-meter height using the Extended Three-Dimensional (3D) Analysis of Building Systems (ETABS) 9.5 software to evaluate the performance of each system against lateral drift.
3. The first design criterion for the case studies is minimizing the drift (lateral displacement) of the building.
4. The second design criterion for the case studies is minimizing the materials cost for the construction of the building.
5. The structural system that best satisfies both criteria is selected as the optimum and appropriate structural system for super tall building in Malaysia.

3.3 Tools Required

Extended Three-Dimensional (3D) Analysis of Building Systems (ETABS) 9.5 software is one of the most widely used applications for analysis and design of structures. ETABS 9.5 software will be used to simulate static wind loading on the pre-selected structural systems, to evaluate each system performance against lateral drift.

3.4 Project Key Milestones

Table 3.1: Project Key Milestones table.

Number	Key Milestone	Approximate Period (week)
1	Obtaining data on the wind conditions in Malaysia	1
2	Obtaining data on the cost of materials (steel and concrete) in Malaysia	1 to 2
3	Pre-select three of the potential structural systems based on the factors considered as case studies	3
4	Structural systems performance against lateral drift simulation using ETABS software	5
5	Simulation data evaluation and selection of the appropriate structural system	1

3.5 Project Gantt Chart

Table 3.2: Project Gantt Chart.

Activities / Period (week)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Malaysia wind data collection	●													
Cost of materials data collection		●	●											
Pre-select potential structural systems based on study				●	●	●								
Structural systems simulation using ETABS 9.5						●	●	●	●	●				
Simulation data evaluation and selection of optimum system											●	○		
Submission of Dissertation Report													○	
FYPII Viva														○

CHAPTER 4

RESULTS & DISCUSSION

4.1 Site Conditions

Malaysia is located in Southeast Asia, at the most southern tip of the Asian continent. Situated at the Equator Line, Malaysia experienced tropical climate all year round, which only consist of wet and dry seasons. The features of climate in Malaysia are uniform temperature, high humidity and vast rainfall. On the other hand, both East and West Malaysia are positioned outside of the Pacific Ring of Fire, thus avoiding the risk of major earthquake occurrences. Hence, seismic effects shall not be considered in the simulations.

Like most of the countries in Southeast Asia, Malaysia is affected by the monsoon winds – the southwest monsoon wind from May to September and the northeast monsoon wind from November to March. There are also two inter-monsoon seasons, occurring in between the monsoon seasons, in which the wind is light and variable.

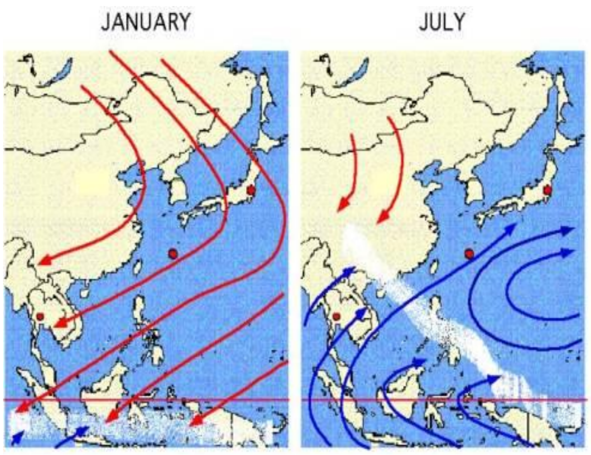


Figure 4.1: The monsoon winds phenomena.

Due to the strategic location of the country, Malaysia is blessed since it does not stand in the way of the tropical typhoon path.

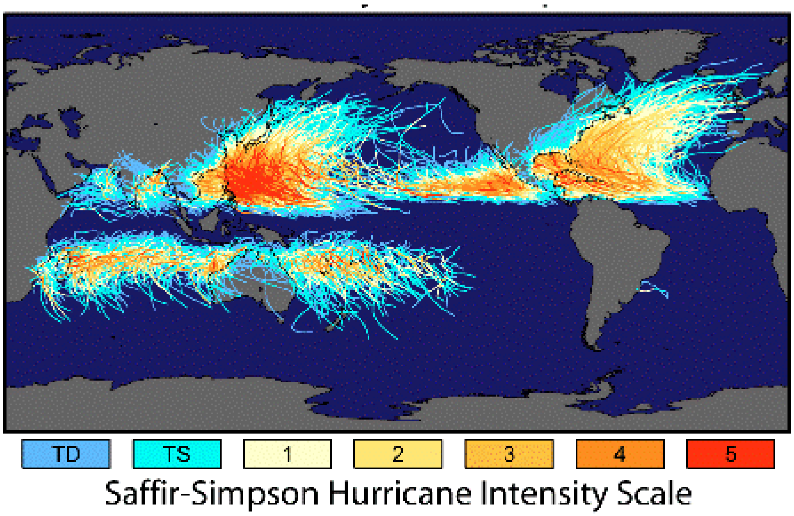


Figure 4.2: Typhoons, cyclones and hurricanes paths.

According to the Malaysian Meteorological Department (2008), the highest basic wind speed among major towns in Malaysia is 33.2 m/s for 50-year return period. For 100-year return period, the greatest basic wind speed is 35.4 m/s, which was recorded at Ipoh, Perak.

Table 4.1: Basic wind speed for major towns in Malaysia. Retrieved from Malaysian Meteorological Department (2008).

Station	**50-Year Return Period (m/s)**	**100-Year Return Period (m/s)**
Alor Setar	29.4	31.4
Butterworth	24.6	25.7
Bayan Lepas	27.2	28.6
Ipoh	33.2	35.4
Sitiawan	25.4	26.9
Cameron Highlands	28.8	30.4
Subang	31.5	33.6
Petaling Jaya	30.1	31.9

Melaka	28.8	30.7
Kluang	31.6	34.1
Senai	29.5	31.4
Mersing	31.8	33.6
Kuantan	30.3	32.2
Kuala Terengganu	30.8	33.1
Kota Bahru	32.8	34.9
Kota Kinabalu	30.9	32.7
Kudat	30.9	32.8
Tawau	27.2	29.0
Sandakan	25.6	27.3
Labuan	28.3	29.7
Kuching	32.0	34.3
Miri	28.8	30.5
Sri Aman	29.3	31.4
Sibu	29.0	30.9
Bintulu	25.3	26.6

The design of the super tall building against wind load is considered among Uniform Building Code (UBC) 1997, Malaysia Standard (MS) 1553:2002 Code of Practice on Wind Loading for Building Structure, and American Society of Civil Engineers (ASCE) 7. Since both UBC 97 and MS 1553:2002 codes lack in the estimation of wind loading for building taller than 400-feet, ASCE 7 code shall be used for of the super tall building against wind load.

In the simulation, ASCE 7 code will consider the following aspect:

- Basic wind speed
- Site exposure
- Design wind pressure
- Design factors and coefficients
- Wind importance factor

Basic wind speed can be defined as the 3-second gust speed estimated to be exceeded on the average once in 50 years measured at a point 10-meter above the ground (Malaysian Meteorological Department, 2008). It is assumed that the wind may be from any horizontal direction.

There are three types of site exposures, namely Exposure B, Exposure C and Exposure D (Taranath, B. S., 2005). Exposure B has terrain with at least 20% of the ground level area covered by buildings, forest or surface irregularities, extending 1-mile (1.61 km) or more from the site. Exposure C includes flat and generally open terrain, extending 0.5-mile (0.81 km) or more from the site in any full quadrant. Exposure D includes flat and unobstructed facing large bodies of water over 1-mile or more in width relative to any quadrant of the building site and is exposed to basic wind speed of 80 miles per hour (mph) or greater. Exposure D extends inland 0.25-mile (0.4 km) or 10 times the building height, whichever is greater, from the shoreline.

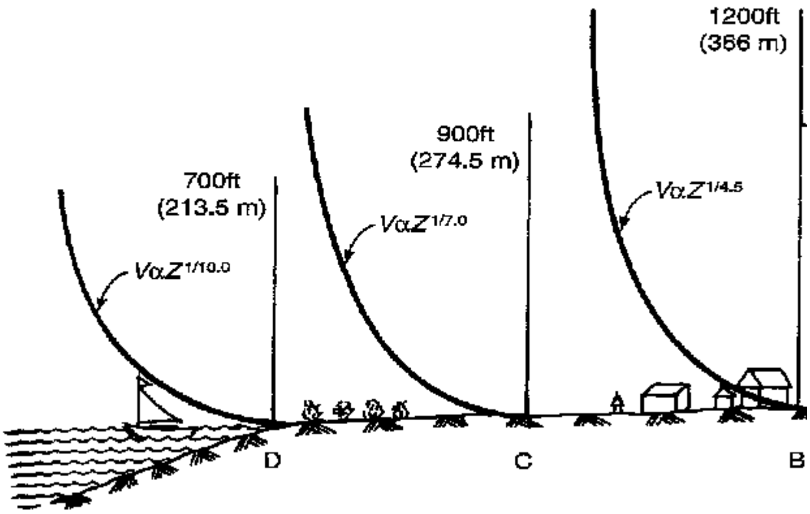


Figure 4.3: The types of site exposure. Retrieved from Taranath, B. S. (2005).

The wind pressure coefficient is influenced by the structure shapes as well as types of structure of the building. The wind pressure coefficient usually is considered at the windward which is the structure's direction facing the wind load and the leeward which is the structure's direction of opposing the wind load. The value of the wind pressure coefficient according to the structure is summarized in the table (Taranath, B. S., 2005), as been shown below:

Table 4.2: The wind pressure coefficient table. Retrieved from Taranath, B. S. (2005).

STRUCTURE OR PART THEREOF	DESCRIPTION	C_q FACTOR
1. Primary frames and systems	**Method 1** (Normal force method)	
	Walls:	
	Windward wall	0.8 inward
	Leeward wall	0.5 outward
	Roofs[1]:	
	Wind perpendicular to ridge	
	Leeward roof or flat roof	0.7 outward
	Windward roof	
	less than 2:12 (16.7%)	0.7 outward
	Slope 2:12 (16.7%) to less than 9:12 (75%)	0.9 outward or 0.3 inward
	Slope 9:12 (75%) to 12:12 (100%)	0.4 inward
	Slope > 12:12 (100%)	0.7 inward
	Wind parallel to ridge and flat roofs	0.7 outward
	Method 2 (Projected area method)	
	On vertical projected area	
	Structures 40 feet (12 192 mm) or less in height	1.3 horizontal any direction
	Structures over 40 feet (12 192 mm) in height	1.4 horizontal any direction
	On horizontal projected area[1]	0.7 upward
2. Elements and components not in areas of discontinuity[2]	Wall elements	
	All structures	1.2 inward
	Enclosed and unenclosed structures	1.2 outward
	Partially enclosed structures	1.6 outward
	Parapets walls	1.3 inward or outward
	Roof elements[3]	
	Enclosed and unenclosed structures	
	Slope < 7:12 (58.3%)	1.3 outward
	Slope 7:12 (58.3%) to 12:12 (100%)	1.3 outward or inward
	Partially enclosed structures	
	Slope < 2:12 (16.7%)	1.7 outward
	Slope 2:12 (16.7%) to 7:12 (58.3%)	1.6 outward or 0.8 inward
	Slope > 7:12 (58.3%) to 12:12 (100%)	1.7 outward or inward
3. Elements and components in areas of discontinuities[2,4,5]	Wall corners[6]	1.5 outward or 1.2 inward
	Roof eaves, rakes or ridges without overhangs[6]	
	Slope < 2:12 (16.7%)	2.3 upward
	Slope 2:12 (16.7%) to 7:12 (58.3%)	2.6 outward
	Slope > 7:12 (58.3%) to 12:12 (100%)	1.6 outward
	For slopes less than 2:12 (16.7%)	
	Overhangs at roof eaves, rakes or ridges, and canopies	0.5 added to values above
4. Chimneys, tanks and solid towers	Square or rectangular	1.4 any direction
	Hexagonal or octagonal	1.1 any direction
	Round or elliptical	0.8 any direction
5. Open-frame towers[7,8]	Square and rectangular	
	Diagonal	4.0
	Normal	3.6
	Triangular	3.2
6. Tower accessories (such as ladders, conduit, lights and elevators)	Cylindrical members	
	2 inches (51 mm) or less in diameter	1.0
	Over 2 inches (51 mm) in diameter	0.8
	Flat or angular members	1.3
7. Signs, flagpoles, lightpoles, minor structures[8]		1.4 any direction

[1]For one story or the top story of multistory partially enclosed structures, an additional value of 0.5 shall be added to the outward C_q. The most critical combination shall be used for design. For definition of partially enclosed structures, see Section 1616.

[2]C_q values listed are for 10-square-foot (0.93 m^2) tributary areas. For tributary areas of 100 square feet (9.29 m^2), the value of 0.3 may be subtracted from C_q, except for areas at discontinuities with slopes less than 7 units vertical in 12 units horizontal (58.3% slope) where the value of 0.8 may be subtracted from C_q. Interpolation may be used for tributary areas between 10 and 100 square feet (0.93 m^2 and 9.29 m^2). For tributary areas greater than 1,000 square feet (92.9 m^2), use primary frame values.

[3]For slopes greater than 12 units vertical in 12 units horizontal (100% slope), use wall element values.

[4]Local pressures shall apply over a distance from the discontinuity of 10 feet (3048 mm) or 0.1 times the least width of the structure, whichever is smaller.

[5]Discontinuities at wall corners or roof ridges are defined as discontinuous breaks in the surface where the included interior angle measures 170 degrees or less.

[6]Load is to be applied on either side of discontinuity but not simultaneously on both sides.

[7]Wind pressures shall be applied to the total normal projected area of all elements on one face. The forces shall be assumed to act parallel to the wind direction.

[8]Factors for cylindrical elements are two thirds of those for flat or angular elements.

The wind importance factor can be derived according to the function of the building and its occupancy, which is shown in the table (Taranath, B. S., 2005):

Table 4.3: The wind importance factor table. Retrieved from Taranath, B. S. (2005).

OCCUPANCY CATEGORY	OCCUPANCY OR FUNCTIONS OF STRUCTURE	SEISMIC IMPORTANCE FACTOR, I	SEISMIC IMPORTANCE[1] FACTOR, I_p	WIND IMPORTANCE FACTOR, I_w
1. Essential facilities[2]	Group I, Division 1 Occupancies having surgery and emergency treatment areas Fire and police stations Garages and shelters for emergency vehicles and emergency aircraft Structures and shelters in emergency-preparedness centers Aviation control towers Structures and equipment in government communication centers and other facilities required for emergency response Standby power-generating equipment for Category 1 facilities Tanks or other structures containing housing or supporting water or other fire-suppression material or equipment required for the protection of Category 1, 2 or 3 structures	1.25	1.50	1.15
2. Hazardous facilities	Group H, Divisions 1, 2, 6 and 7 Occupancies and structures therein housing or supporting toxic or explosive chemicals or substances Nonbuilding structures housing, supporting or containing quantities of toxic or explosive substances that, if contained within a building, would cause that building to be classified as a Group H, Division 1, 2 or 7 Occupancy	1.25	1.50	1.15
3. Special occupancy structures[3]	Group A, Divisions 1, 2 and 2.1 Occupancies Buildings housing Group E, Divisions 1 and 3 Occupancies with a capacity greater than 300 students Buildings housing Group B Occupancies used for college or adult education with a capacity greater than 500 students Group I, Divisions 1 and 2 Occupancies with 50 or more resident incapacitated patients, but not included in Category 1 Group I, Division 3 Occupancies All structures with an occupancy greater than 5,000 persons Structures and equipment in power-generating stations, and other public utility facilities not included in Category 1 or Category 2 above, and required for continued operation	1.00	1.00	1.00
4. Standard occupancy structures[3]	All structures housing occupancies or having functions not listed in Category 1, 2 or 3 and Group U Occupancy towers	1.00	1.00	1.00
5. Miscellaneous structures	Group U Occupancies except for towers	1.00	1.00	1.00

[1]The limitation of I_p for panel connections in Section 1633.2.4 shall be 1.0 for the entire connector.
[2]Structural observation requirements are given in Section 1702.
[3]For anchorage of machinery and equipment required for life-safety systems, the value of I_p shall be taken as 1.5

4.2 Cost of Materials

According to Quantity Surveyor Online (2012), the average price rate for high grade concrete in Malaysia is RM332 / m^3 including the transportation cost and labor cost. The density of concrete is assumed to be 2400 kg/m^3.

On the other hand, KPK Quantity Surveyors (2012) stated that the average price for steel is RM4500 / metric ton in Malaysia.

Generally, the price of concrete is cheaper than steel in Malaysia since the abundance of aggregate resources in the country, especially granite. Plus, along its life span, steel has a very high maintenance cost including paint, fire-proofing and corrosion resistance. Unlike steel, concrete’s maintenance cost is very low.

4.3 Sustainability

Generally, as been stated by Ilze Liepina (2011), the manufacturing of 1 ton of steel releases about 1 ton of carbon dioxide (CO_2). On the other hand, the manufacturing of 1kg of cement, an element of concrete, releases about 0.8kg of CO_2. The amount of CO_2 released is based on the manufacturing technique. In this aspect, concrete is more sustainable than steel by a hair breadth. In term of material's heat absorption, Liepina (2011) also confirmed that concrete performs better than steel based on Malaysia's climate, since concrete gain and loss of heat is less compared to steel, hence providing cooler interior temperature in a sunny day. Thus, concrete save more energy in the mechanical cooling and ventilation aspect.

4.4 Potential Structural Systems

Office type building favors customizable, wide internal space. Hence, only exterior structural systems which placed the majority of the lateral load resisting system at the perimeter of the building shall be considered as the potential structural systems. The interior structural systems with their many internal columns and lateral load resisting systems inside the building itself shall be eliminated as the candidates.

For feasibility in comparison, the architectural design of the building shall be in its simplest form - a square shape from the plan layout. The design of super tall building for the simulation shall have the following features:

Length of building (L) = 70 m

Width of building (B) = 70 m

Roof level = 500 m

Total height of building (H) = 500 m

Floor height = 4 m

Number of stories = 125

Horizontal aspect ratio (L/B) = 1

Vertical aspect ratio (H/L, H/B) = 7.14

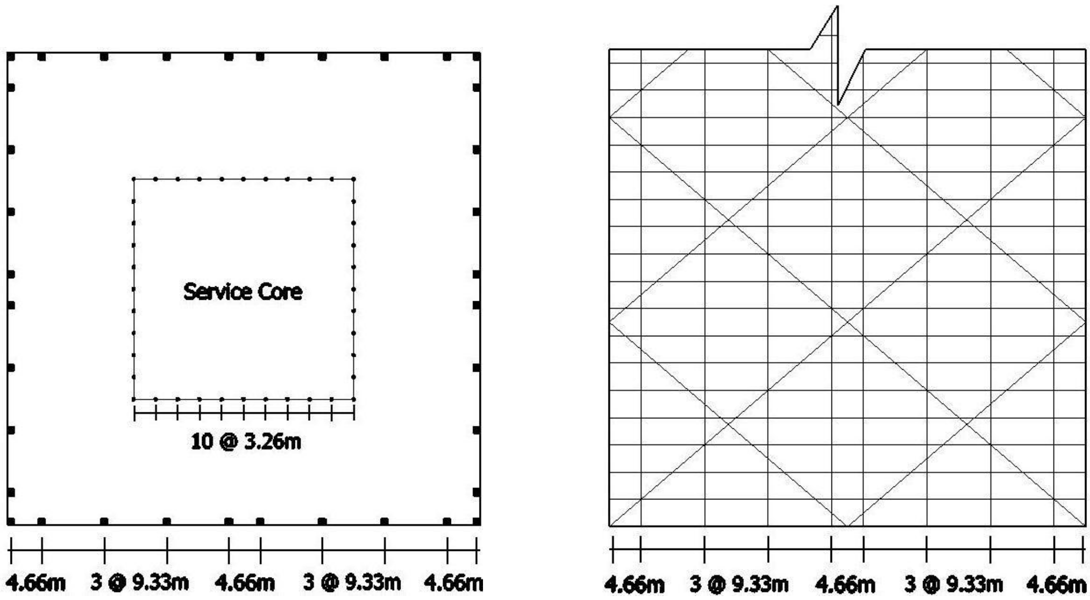
Floor area (A) = 4900 m^2

Service core area (A') = 1062.76 m^2

Three exterior structural systems that are pre-selected are the widely-spaced braced tube, bundled tube and superframes structure. The selections are made based on their relatives efficient height limit as been shown in *Table 2.2*.

4.4.1 Widely-Spaced Braced Tube

The structure consists of vertical columns and diagonal members joined by moment connections at the perimeter of the building. The spacings of the columns at the perimeter are at 4.66m and 9.33m. The service core substructure is consisted of framed tube with columns spaced at 3.26m from each other.

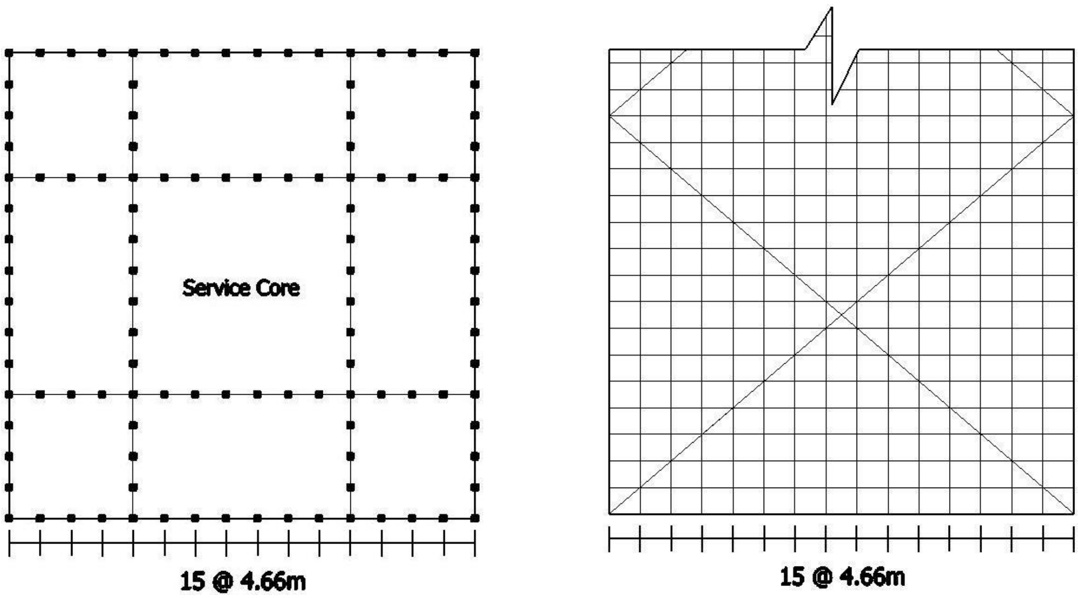


Plan Elevation

Figure 4.4: Widely-spaced braced tube structural system configuration for simulation.

4.4.2 Bundled Tube

This structural system consists of individual tubes connected and bundled together to increase the performance of the structure. Bracing at the structure's perimeter is also introduced in this system as to further raise the lateral load resistance. The column spacing at the perimeter of each tube is 4.66m from each other. The service core substructure is consisted of framed tube with columns spaced at 3.26m from each other.

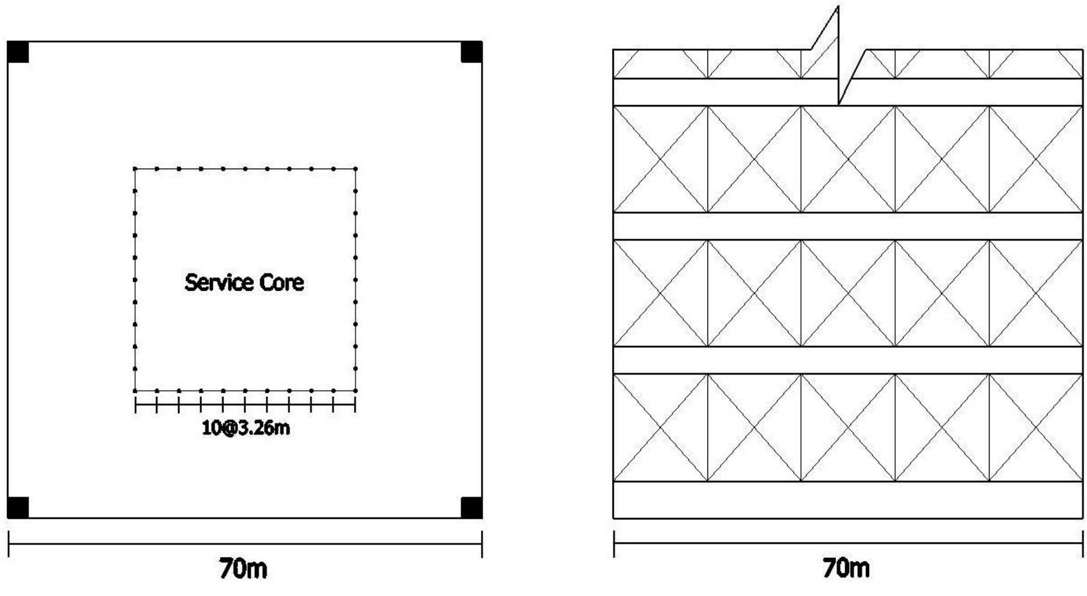


Plan Elevation

Figure 4.5: Bundled tube structural system configuration for simulation.

4.4.3 Superframes

Four mega columns are placed at each corner of the building, each with the dimension of 3m x 3m. Level deep trusses with bracing will join the columns together at every 4th floor. The service core substructure is consisted of framed tube with columns spaced at 3.26m from each other.



Plan Elevation

Figure 4.6: Superframes structural system configuration for simulation.

4.5 Lateral Drift Simulation

The simulation is carried out using the Extended Three-Dimensional (3D) Analysis of Building Systems (ETABS) 9.5 software.

4.5.1 Constant Simulation Parameter

The following parameters are taken as constant to all potential structural systems as control:

i) The service core area is the same for all cases of structural systems.

ii) Material specification for both concrete and steel for all cases are the same.

iii) All cases have the same lateral drift limit value.

iv) According to Malaysian Meteorological Department (2008), the highest basic wind speed in Malaysia is 35.4 m/s. Hence, in the simulation, the design wind speed is taken as 37 m/s or 133.2 km/h which is equivalent to 82.8 mph for safety factor.

v) The building shall be located at terrain exposure type B and the wind importance factor of 1.00 according to American Society of Civil Engineers (ASCE) 7.

vi) The wind pressure coefficient for primary frames and systems shall be set as 0.8 for windward direction and 0.5 for leeward direction according to ASCE 7.

vii) The uniform surface dead load is taken as 35 lb/ft or 1.6758kN/m for each floor.

viii) The uniform surface live load is taken as 100 lb/ft or 4.788kN/m for each floor.

ix) The cladding frame distributed load for structural steel only is taken as 250 lb/ft or 3.6485kN/m.

4.5.2 Simulation Assumption

Following assumptions are made for the simulation process:

i) Horizontal floors are assumed as rigid diaphragms.

ii) Hull and core are assumed jointed through rigid diaphragms.

4.5.3 Simulation Results

i) Widely-Spaced Braced Tube

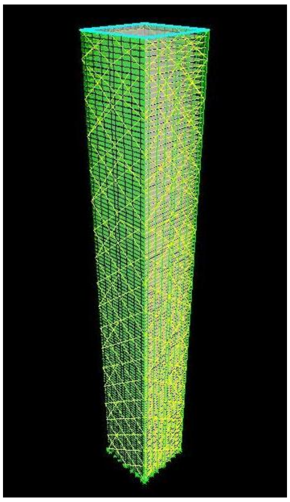


Figure 4.7: Widely-spaced braced tube in 3D.

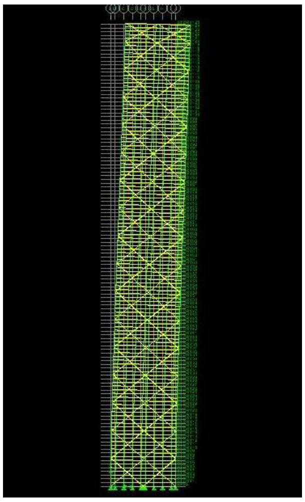


Figure 4.8: Widely-spaced braced tube under wind loading simulation.

Table 4.4: Widely-spaced braced tube's lateral drift and estimated cost.

Material	Lateral Drift (mm)	Total Material Mass (kg)	Cost (RM)
Concrete	2698	64, 367, 067.26	8, 904, 110.97
Steel	1317	74, 734, 323.73	336, 304, 456.80

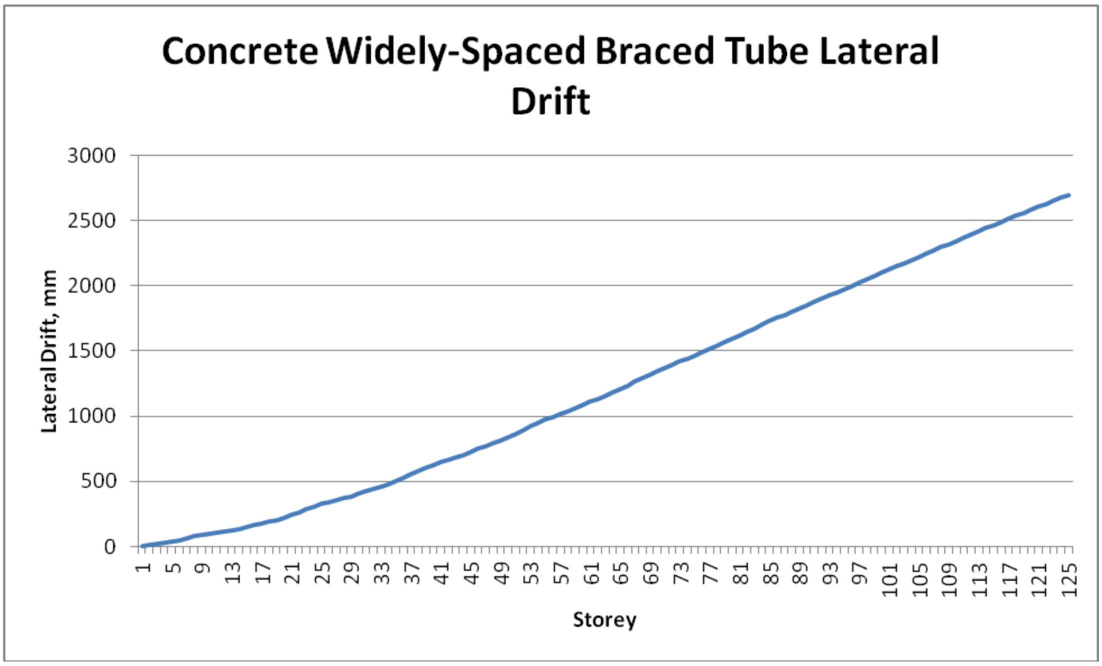


Figure 4.9: Concrete widely-spaced braced tube's lateral drift graph.

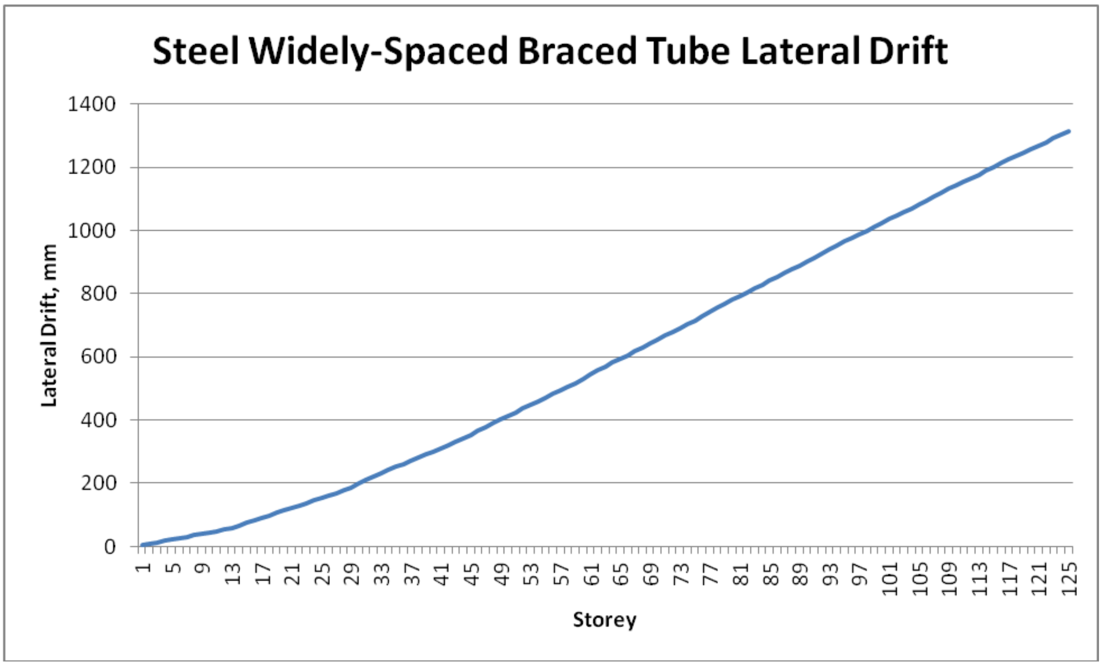


Figure 4.10: Steel widely-spaced braced tube's lateral drift graph.

ii) Bundled Tube

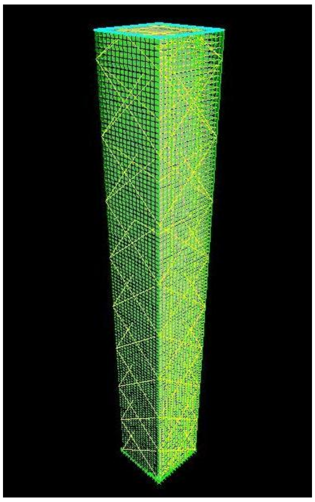


Figure 4.11: Bundled tube in 3D.

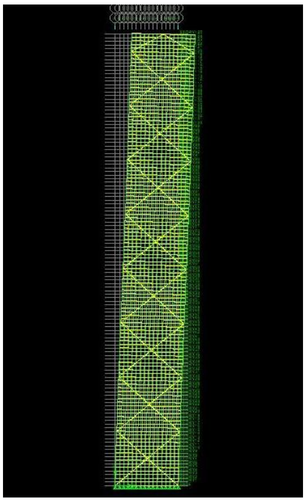


Figure 4.12: Bundled tube under wind loading simulation.

Table 4.5: Bundled tube's lateral drift and estimated cost.

Material	Lateral Drift (mm)	Total Material Mass (kg)	Cost (RM)
Concrete	1830	74, 387, 162. 43	10, 290, 224.14
Steel	1043	74, 892, 829.91	337, 017, 734.60

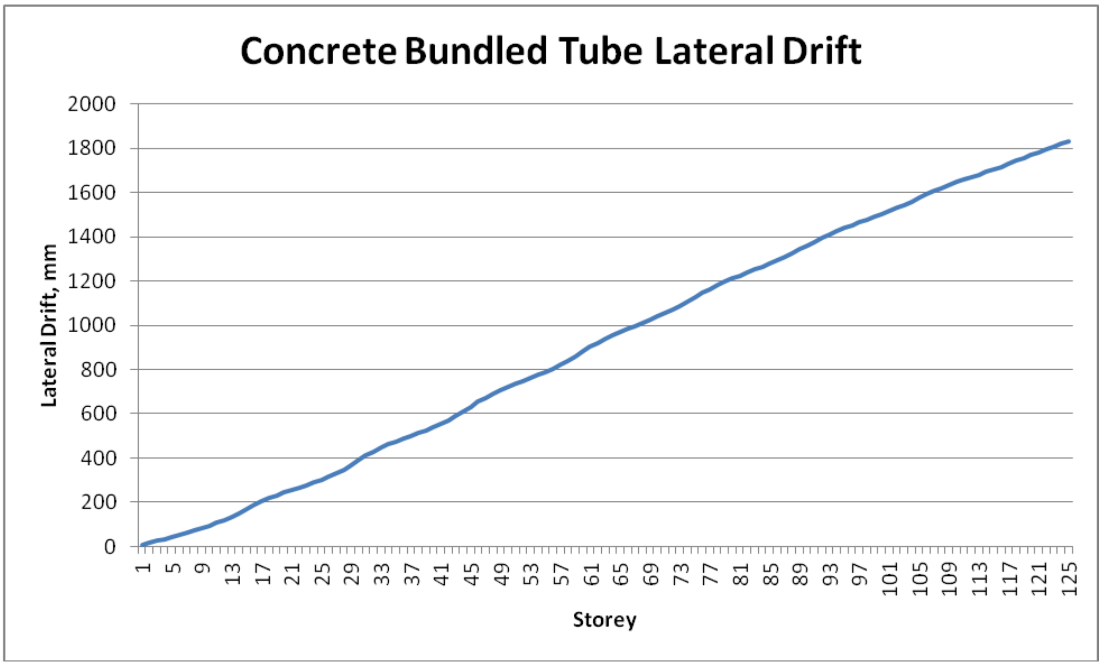


Figure 4.13: Concrete bundled tube's lateral drift graph.

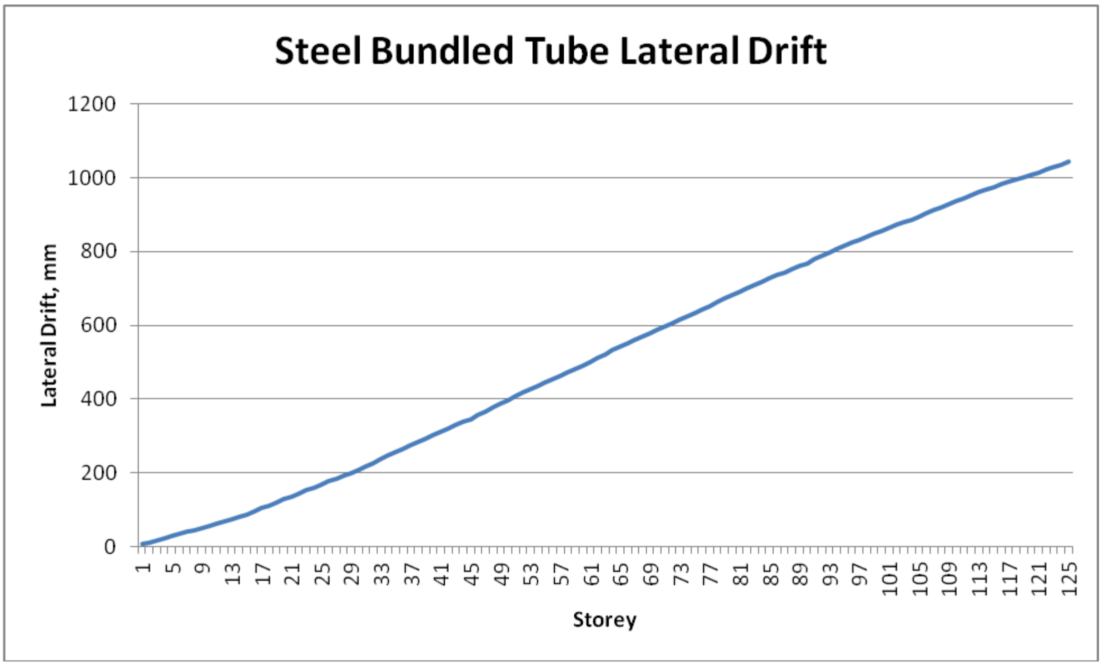


Figure 4.14: Steel bundled tube's lateral drift graph.

ii) Superframes

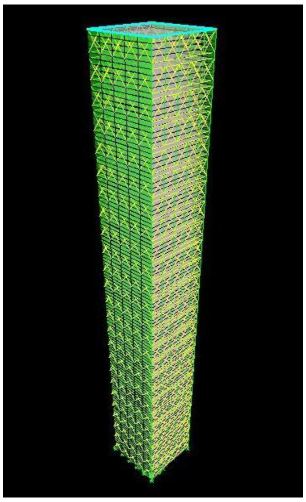


Figure 4.15: Superframes structure in 3D.

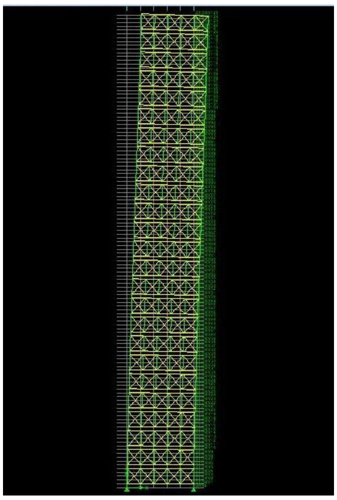


Figure 4.16: Superframes structure under wind loading simulation.

Table 4.6: Superframes structure's lateral drift and estimated cost.

Material	Lateral Drift (mm)	Total Material Mass (kg)	Cost (RM)
Concrete	1549	64, 467, 750.93	8, 918, 038.88
Steel	936	76, 769, 280.22	345, 461, 761.00

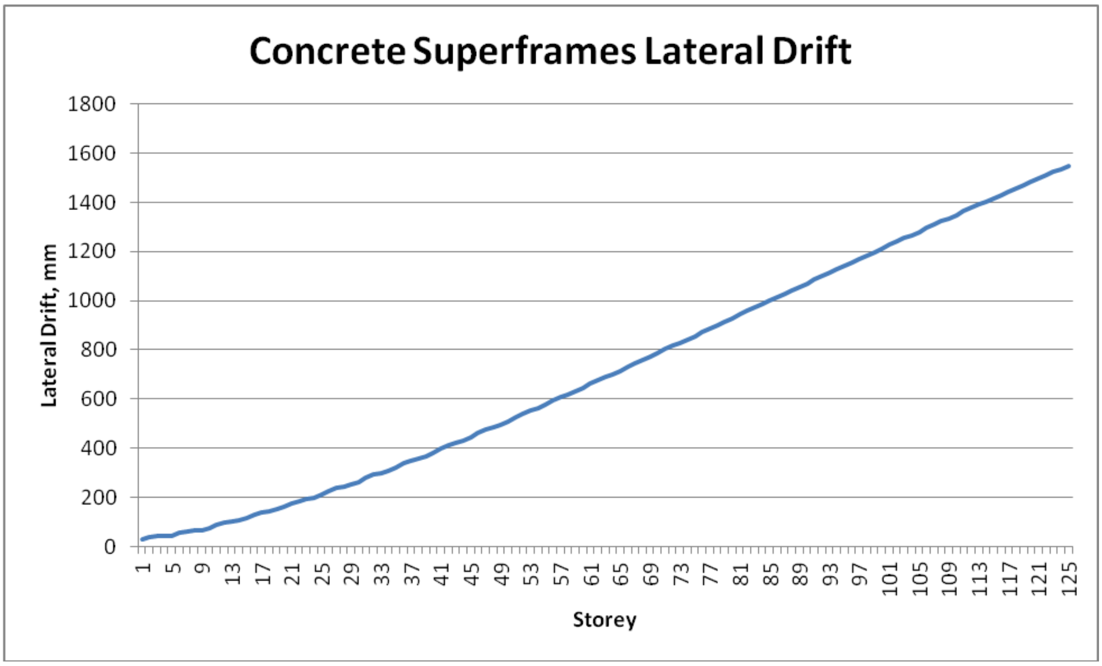


Figure 4.17: Concrete superframes' lateral drift graph.

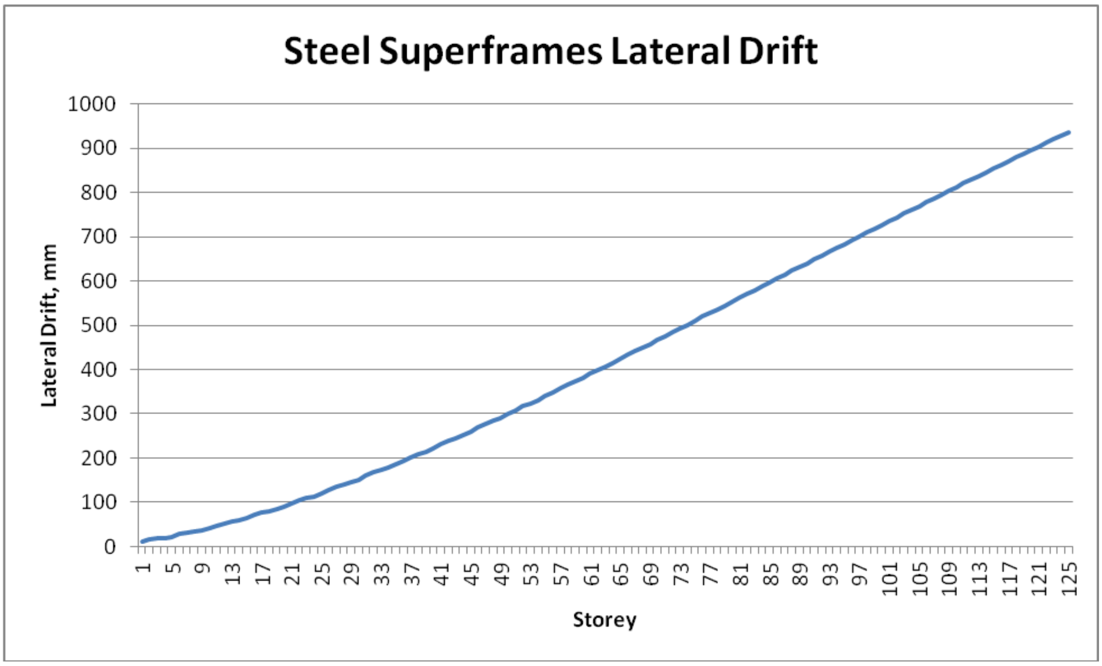


Figure 4.18: Steel superframes' lateral drift graph.

4.6 Optimum Structural System Evaluation

The following table shows the total cost comparison among the three pre-selected structural systems according to their main material used:

Table 4.7: All 3 structural systems' lateral drift and estimated cost comparison.

Structural System	**Main Material**	**Lateral Drift (mm)**	**Total Cost Estimation (RM)**
Widely-spaced Braced Tube	Concrete	2698	8, 904, 110.97
	Steel	1317	336, 304, 456.80
Bundled Tube	Concrete	1830	10, 290, 224.14
	Steel	1043	337, 017, 734.60
Superframes	Concrete	1549	8, 918, 038.88
	Steel	936	345, 461, 761.00
		Total sum of cost estimation	1, 046, 896, 326.00
		Average cost per structural system	174, 482, 721.10

The maximum allowable drift for the office building is set to H/300. Since the height of the structure is 500-meter, hence:

$$\boxed{\text{Maximum allowable drift} = 500/300 = 1.67\text{m}}$$

The lateral drift for concrete widely-spaced braced tube structural system is 2698mm, failing the allowable drift by -61.56%. Concrete bundled tube structure also suffers from the same fate as its lateral drift is 1830mm, falls short of the maximum drift by -9.58%. Concrete superframes structure, on the other hand, with the lateral drift of 1549mm, minimizes the lateral drift by 7.25% compared to the maximum allowable drift.

Alternatively, steel widely-spaced braced tube structure displaced 1317mm laterally, decreasing the maximum lateral drift by 21.14%. In addition, bundled tube system minimizes the lateral drift by 37.55%, since it drifts horizontally by 1043mm. Steel superframes structural system contributed in the lateral displacement of 936mm, hence reducing the lateral drift by 43.95%.

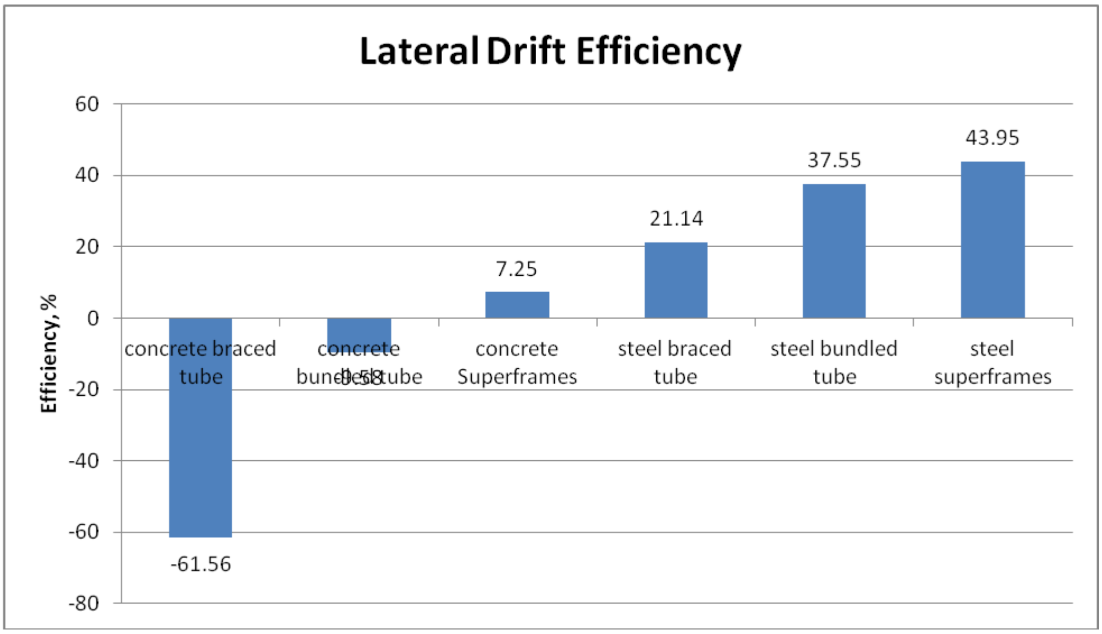


Figure 4.19: Lateral drift efficiency bar chart.

The total cost estimation for concrete widely-spaced braced tube is RM8,904,110.97, 94.89% cheaper than the average cost. Meanwhile, bundled tube system's estimated cost is RM10,290,224.14, lowering the average cost by 94.1%. Furthermore, by having the cost of RM8,918,038.88, superframes structural system has minimizes the average cost by 94.88%.

Conversely, the cost of steel widely-spaced braced tube is RM336,304,456.80, falls short of the average cost by -92.74%. Furthermore, steel bundled tube has the cost of RM337,017,734.60, -93.15% failing the average cost. Finally, by having the cost of RM345,461,761, steel superframes structure has failed the average cost by -97.99%.

Generally, the cost for concrete structural system is cheaper compared to steel structural system due to the development of high strength concrete.

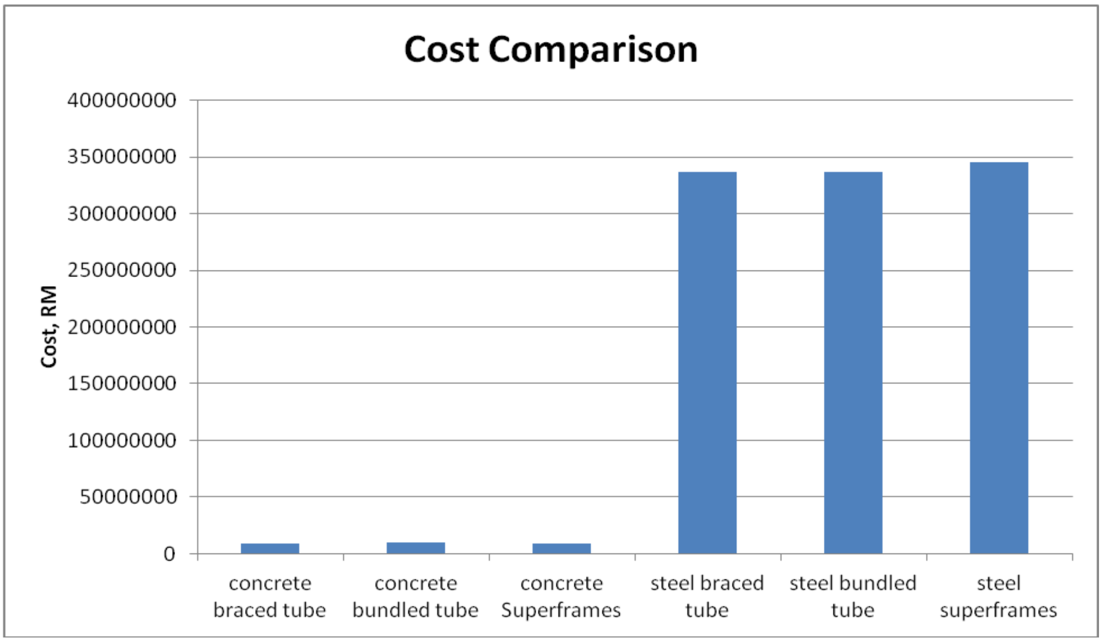


Figure 4.20: Cost comparison bar chart.

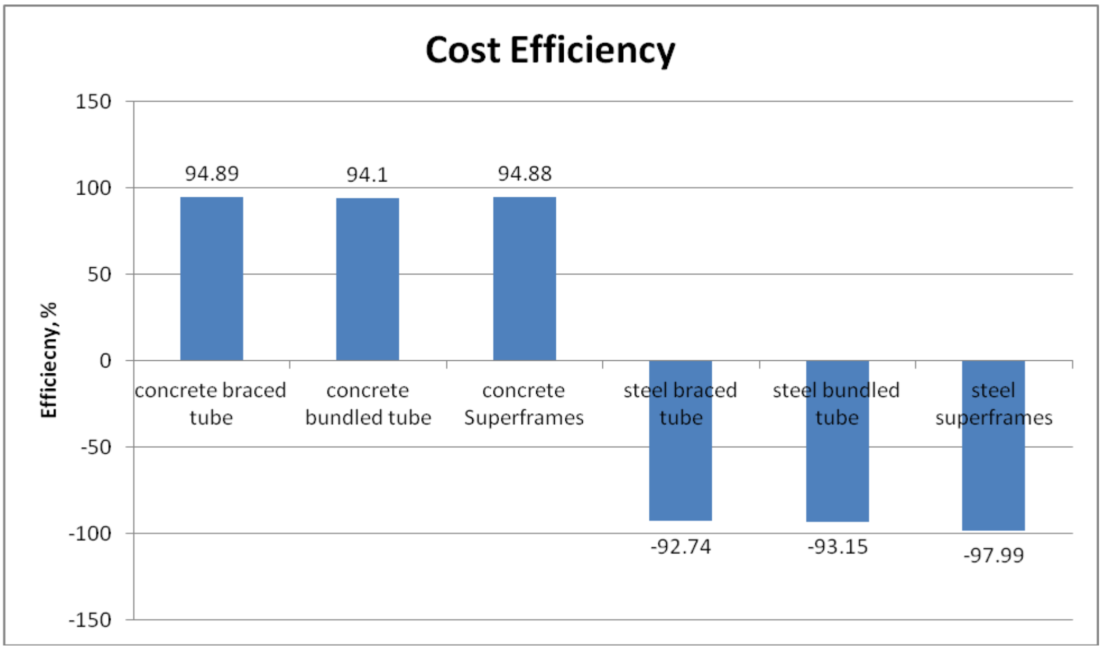


Figure 4.21: Cost efficiency bar chart.

From the evaluation, it can be seen that steel superframes structural system has best satisfies the lateral drift criterion by 44.31%. Nevertheless, the system has failed in satisfying the cost criterion, by costing 97.99% greater than the average cost. On the other hand, by reducing the cost 94.89% from the average cost, widely-spaced braced tube best satisfies the cost criterion, but it totally fails in the lateral drift criterion by -61.1%.

Furthermore, steel structure's maintenance along its life span such as paint, corrosive resistance and fire proofing is very costly, while concrete structure hardly needs any maintenance at all. Concrete is more sustainable since its resources are abundant in Malaysia and it can also be recycled.

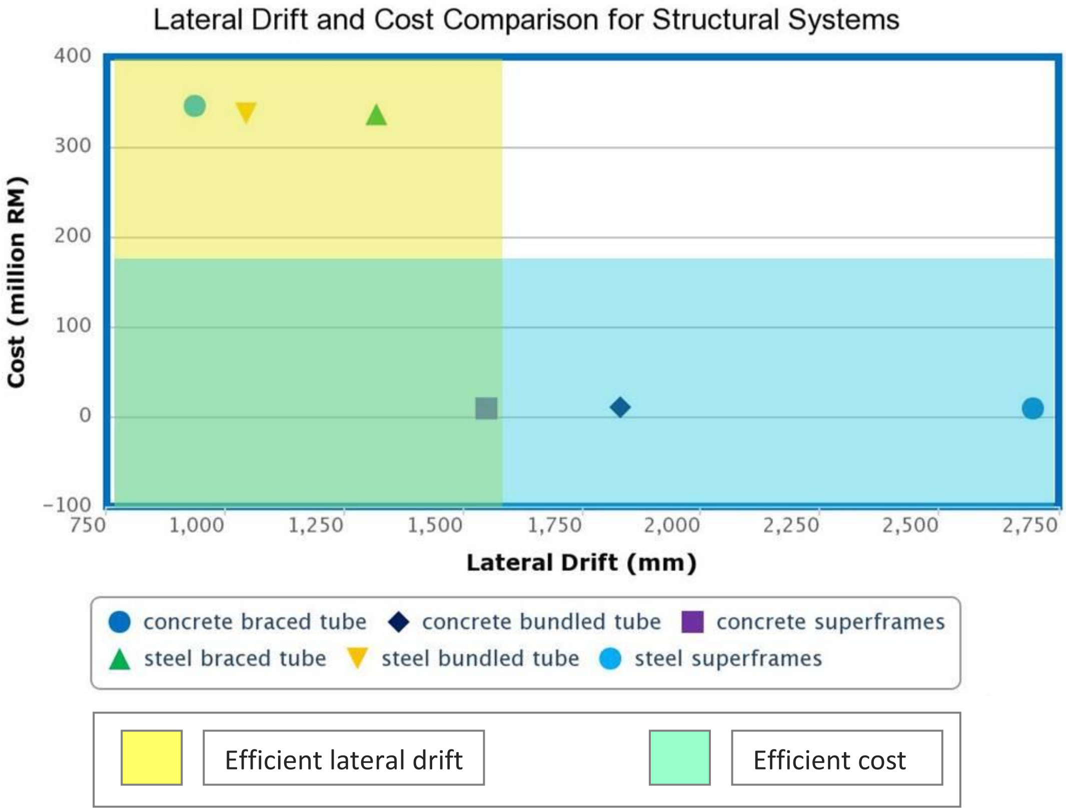


Figure 4.22: All 3 structural systems' lateral drift and cost comparison graph.

After careful research, it is found out that concrete superframes structure gives the best performance as it has efficiently suited both lateral drift and cost criteria by 7.2% and 94.88% respectively. The four super columns at the four corners of the building jointed by trusses at specific floor level provide the stability against wind loading. The super columns also offer resistance against twisting. The system promotes sustainability compared to any steel structural systems. Thus, among the three pre-selected structural systems, concrete superframes is the optimum structural system under static wind loadings without the consideration of dynamic wind effects for super tall buildings in Malaysia.

CHAPTER 5

CONLUSION AND RECOMMENDATION

This research is conducted to assists in fulfilling the demand for vertical spaces in Malaysia, represented by tall buildings. Both the existing interior and exterior structural systems are studied and exterior structure is chosen to be suitable for office building requirements. The factors affecting the selection of structural systems are investigated as well as the site conditions of Malaysia. Three potential pre-selected systems are selected which are widely-spaced braced tube, bundled tube and superframes. The simulations are carried out using ETABS 9.5 software under static wind loading and both concrete and steel are used as the main material respectively. Seismic and dynamic wind effects are ignored in this study.

The simulations' results are analysed and evaluated. The assessment shows that among the three pre-selected structural systems, concrete superframes structure is the most appropriate structural system for super tall buildings in Malaysia under static wind loading without the consideration of dynamic wind effects. Concrete superframes structure efficiently minimized both lateral drift and the cost of the system compared to the other pre-selected systems. Moreover, concrete structure is more sustainable than steel structure for Malaysia's conditions. Hence, the objectives of the research are achieved.

As for the recommendation, wind tunnel simulation is an excellent continuation to the research to analyze the super tall building responses to the dynamic effects of wind. Dynamic wind effects on tall and slender structures are not to be underestimated due to its high uncertainties nature, and need to be approached with suitable architectural design of the building, preferably aerodynamic design.

REFERENCES

Ali, M. M., & Moon, K. (2007). Strutural Development in Tall Buildings: Current Trends and Future Prospects. *Architectural Science Review,* (50.3), 205-223.

American Society of Civil Engineers. (2002). Structural Analysis against Lateral Loads.

Alshamrani, O. S. (2007). Selection of Structural Systems and Materials: Minimizing Lateral Drift and Cost of Tall Buildings in Saudi Arabia. Faculty of the School of Architecture, University of Southern California.

Colaco, J. P. (2005). Structural Systems for Tall Apartment Towers.

Council on Tall Buildings and Urban Habitat. (n.d.). Criteria for Defining and Measuring of Tall Buildings.

D'souza, B. (2013). Admixtures for Tall Structures.

Hackney Tall Building Strategy. (2005). Tall Buildings Design Guidance and Application Checklist. London Borough of Hackney.

Hameed, A., Azeem, I., Qazi, A., Sharif, B., & Khan, N. M. (2013). Drift and Cost Comparison of Different Structural Systems for Tall Buildings. *Pak. J. Engg. & Appl. Sci., (12), 27-38.*

Gunel, M. H., & Ilgin, H. E. (2007). A Proposal for the Classification of Structural Systems of Tall Buildings. *Building and Environment,* (42:7), 2667 – 2675.

Jayachandran, P. (2009). Design of Tall Buildings: Preliminary Design and Optimisation. *Proceedings, National Worksop on High-rise and Tall Buildings, University of Hyderabad,.* Hyderabad, India.

Khan, F. R. (1969). Recent Structural Systems in Steel for High Rise Buildings. In *Proceedings of the British Constructional Steelwork Association Conference on Steel in Architecture*. London: British Constructional Steelwork Association.

KPK Quantity Surveyors. (2012). Materials and Labour Prices. Retrieved from www.kpkqs.com

Liepina, I. (2011). Sustainability of Steel and Concrete.

London Borough of Hackney. (2005). Hackney Tall Buildings Strategy: Tall Building Design Guidance and Application Checklist.

Mendis, P., Ngo, T., Haritos, N., Hira, A., Samali, B., & Cheung, J. (2007). Wind Loading on Tall Buildings.

Moon, K. S. (2008). Sustainable Structural Engineering Strategies for Tall Buildings. *Strucural Design of Tall and Special Buildings,* (17), 895–914.

Quantity Surveyor Online. (2012). Prices of Building Materials. Retrieved June 12, 2014 from www.quantitysurveyoronline.com.my/products

Sev, A., & Özgen, A. (2009). Space Efficiency in High-Rise Office Buildings.

Taranath, B. S. (2005). Wind and Earthquake Resistance Buildings: Structural Analysis and Design.

Zils, J., & Viise, J. (2003). An Introduction to High-Rise Design.