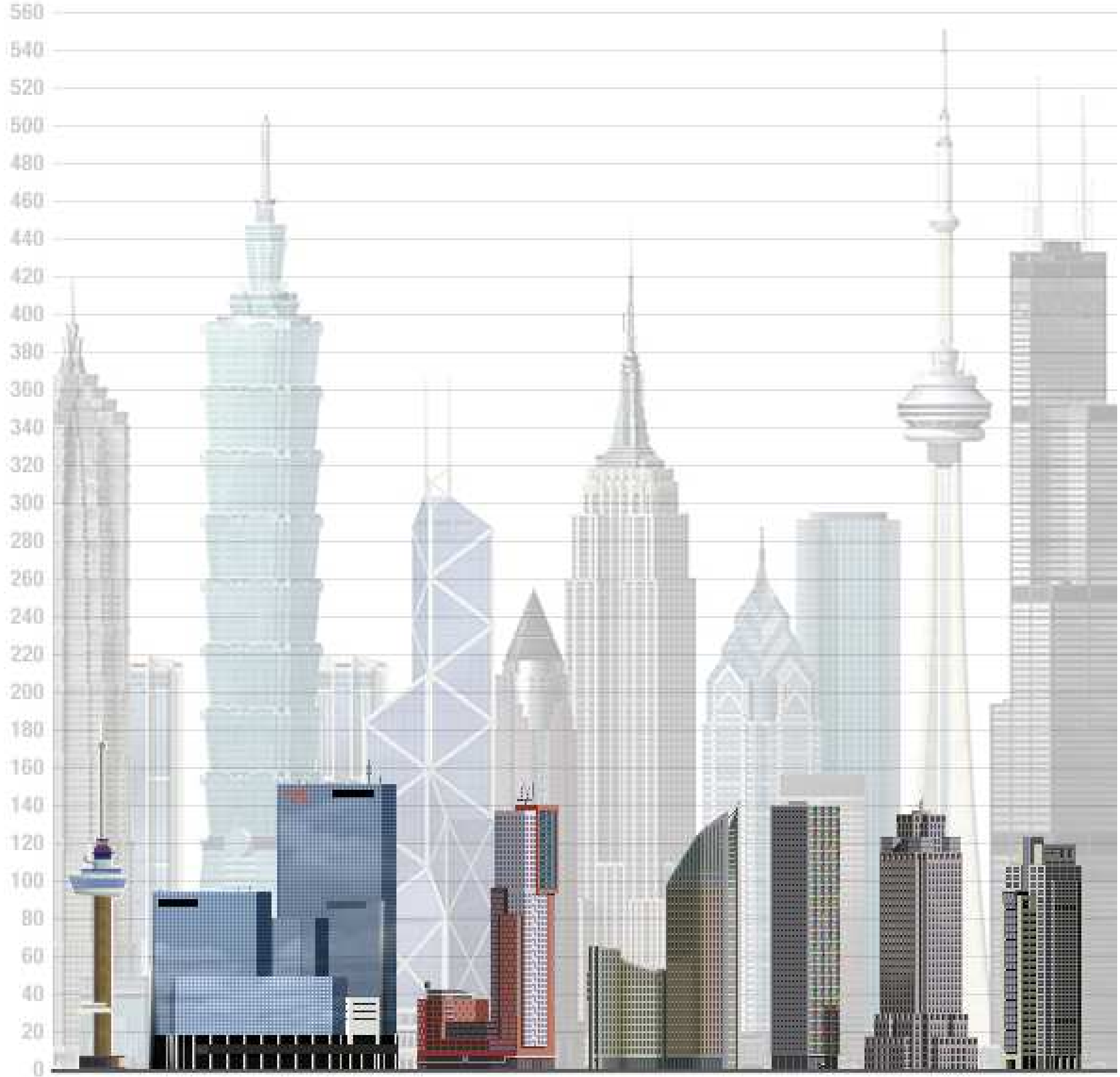
Super high-rise in Rotterdam
Part 1: Literature study



Master's Thesis Report

U.M. Winter

March 2011

Super High-Rise in Rotterdam

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Preface

This Master's Thesis is the final part of my study at the faculty of Civil Engineering at the Delft University of Engineering.
This report describes a structural concept of an 800 meter high building which can be built in the Netherlands. It consists of three parts namely;

- *Part 1: Literature study* consisting of a study in the most important aspects which come into play when designing a high-rise building.
- *Part 2: Structural design* which describes a design of the building's load-bearing structure.
- *Part 3: Appendices*
- *Part 4: Addendum*

I would like to thank the members of my graduation committee who guided me through this graduation process despite their busy agendas.
Also I would like to thank ABT for providing the necessary resources and giving me the opportunity to work on my thesis in a warm environment with many knowledgeable engineers.
Finally, I would like to thank my family; my parents, my brother and sister for their emotional and financial support.

Delft, March 2011

Uriah Winter

Abstract

Introduction

This master's thesis can be considered as a continuation of an earlier thesis done by building engineering student Arne Dijkstra at the Delft University of technology. The main goal of his thesis was finding the ultimate limit to the height of the skyscraper. In the end he found no absolute limit to the height of a skyscraper due to the many boundary conditions which can influence a buildings height. Therefore it was recommended too use a different approach in which the height is predetermined. Based on this height the necessary structural elements and systems are then chosen.

Compared to the rest of the world high-rise in the Netherlands is still in its infancy. The tallest building in the Netherlands is the "Maastoren" with a height of 164.75 meter.
This is a big difference compared to the tallest building in other regions where the buildings are several times higher. The fundamental question of this thesis is: "is it possible to achieve similar heights which are found in supertalls in foreign countries in the Netherlands?".

In order to answer this question the goal of this thesis is to deliver the structural design of a tall building with a predetermined height of 800 meter.

This thesis is divided in 3 parts, namely:

- Part 1: Literature study
- Part 2: Structural Design
- Part 3: Appendices

This is part 1 of the thesis and with no architectural design or even a location this building had to be designed from scratch. Before starting on the structural design of the building a location for the 800 meter building was chosen after which the structural design a literature study was done on supertalls.

Choosing a location

Firstly, a location was chosen for the 800 meter skyscraper. It was decided to place the tower in the Rijnhaven, an unused harbour found in the Kop van Zuid. This area already has several high-rise buildings and by placing our new tower near the existing cluster of high-rise buildings the urban effect of the region is amplified.

Figure 0-1 Final location, Rijnhaven

Literature study

Secondly, a literature study was done on supertall buildings. This literature study includes the different aspects which are important for high-rise such as:

- Foundations and geo-engineering
- Load-bearing structures
- Wind and dynamics
- Vertical transport

Also several reference projects were examined.

Conclusion

After researching the different types of structural materials, elements and systems it was found that the following aspects become more and more important as the height of a building increases:

Mitigation of differential settlements is very important

Unequal settlements result in unwanted stresses in structural members, cracking, an increase of the 2^{nd} order effect and a larger deflection at the top of the building.
A piled raft foundation is suitable for high-rise structures with a high slenderness ratio sensitive to differences in settlements.

Increasing lateral wind load and vertical load

With increasing height the building the forces created by wind loading increase significantly therefore more efficient load bearing structures are necessary for supertall systems.

Susceptibility to dynamic behavior

As the height increases, a supertall becomes more slender and thus more susceptible to dynamic behavior.

Daylight entry problem

Because of the lack of daylight deep interior spaces far from the perimeter are of limited value to the client. Thus a scaled up version of a smaller building results in large proportions unusable areas.

Vertical transportation

With increasing height, the challenge of accessing, exiting and servicing the building floors becomes more complex.

Erection process construction time

Construction time is an important factor in obtaining a return on the large investment made in supertalls. In some cases it even outweighs structural considerations.

Structural concept

It was found that the compound structure described in paragraph (3.3.2) and the pile-and-raft foundation described in paragraph (3.1.3) are very promising solutions for these problems for the following reasons:

The increasing interest in use of underground space in urban areas and technical developments in the area of building excavation have put relatively stiff and load-bearing soil layers within the reach of foundation slab. This makes a piled raft foundation where the loads from the superstructure are transferred partly via the raft and partly via the piles an option.

A compound structure mitigates the wind in both the along-wind and across-wind direction by allowing the wind to flow through the tower.
The openings create a void in the middle which pushes the area to the perimeter within the reach of daylight. Another benefit of a compound structure is that the wind load on the structure is mitigated by means of openings instead of tapering. This allows for a constant footprint along the height of the building resulting in a more prime real estate or leasable area at the top of the building.

Contents

Chapter 1 Introduction

1.1 Introduction

Through the ages tall structure were not only built for functional but also for aesthetic and symbolic reasons.

"A skyscraper is a boast in glass and steel.''
- Mason Cooley

These structures are used to show the dominating position of those who built them. There is a competition going on in the high-rise-construction-world where a building should be taller than its predecessors and remain the tallest for a while. The first tallest building which was the 100 meter high Masonic Temple built in 1892. The Empire State building held the title of tallest building for 40 years (1931-1972). The interval in which one structures height is surpassed by another is getting shorter and shorter and Asia seems to be winning the battle of having the most and tallest buildings.

Figure 1-1 Skyline New York

The council of tall buildings and urban habitat (CTBUH) defines high-rise as follows:

"A building whose height creates different conditions in the design, construction, and use than those that exist in common buildings of a certain region and period."

High-rise is therefore dependant on the location and period of construction.

A building is a supertall when its height exceeds 300 meter (see Figure 1-2). Metropolises such as New York, Chicago, Shanghai and Singapore are known for their impressive skylines. Supertalls are mostly found in the United States and Asian countries like China and Japan. Also Dubai is a city which has recently become home to many supertalls.

In Europe, Rotterdam, Warsaw and Moscow are examples of cities where high-rise has a positive image. A large part of the cities in Western Europe however have traditionally evolved urban areas in which proposals for high-rise can cause considerable resistance.

Table 1-1 and Table 1-2 show the differences in number of high-rise structures between the world and Europe.

Top 10 Skylines Worldwide		
Nr	City	Number> 90 m
1	Hong kong	2939
2	New York	849
3	Tokyo	572
4	Shanghai	549
5	Bangkok	382
6	Chicago	321
7	Singapore	296
8	Sao Paulo	281
9	Seoul	273
10	Dubai	268

Table 1-1 Top Skylines World Wide [1]

Top 10 Skylines European Union		
Nr	City	Number> 90 m
1	Paris	112
2	London	49
3	Frankfurt	38
4	Benidorm	35
5	Rotterdam	29
6	Brussel	22
7	Warschaw	21
8	Wenen	20
9	Madrid	17
10	Berlin	15

Table 1-2 Top Skylines European Union [1]

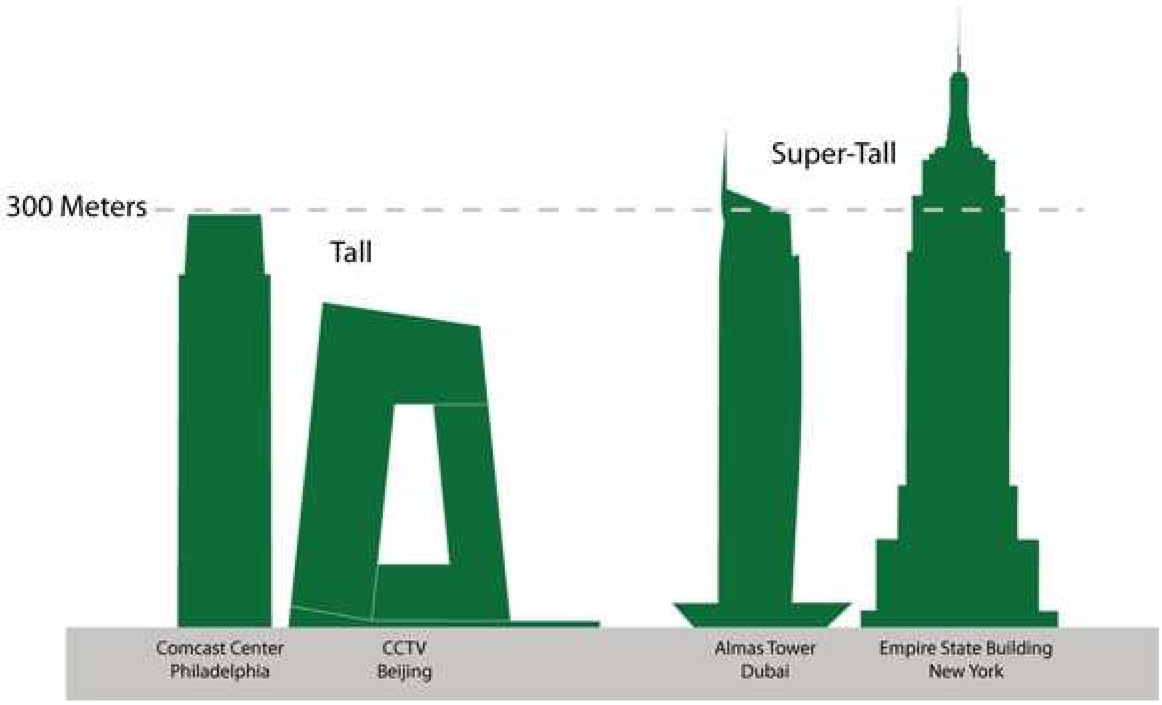

Figure 1-2 Supertall height requirement

1.2 Problem Description

The design of a high-rise building poses several structural, geotechnical and architectural challenges for engineers and architects. The design requires a unique collaboration particularly between the architect and the engineer involving building planning, construction and usage issues. Moreover, because of the scale and complexity of tall buildings, this teamwork often begins at the earliest stages of the design process and continues well into construction. Besides the increased difficulty of designing a good foundation and load-bearing structure several new challenges are encountered which are less important in lower rise building, namely:

- Vertical transport
- Stability
- Comfort
- Fire safety
- Evacuation
- Wind engineering
- Shadow casting

Compared to the rest of the world high-rise in the Netherlands is still in its infancy. The tallest building in the Netherlands is the “Maastoren” with a height of 164.75 meter.
This is a big difference compared to the tallest building in other regions where the buildings are several times higher, namely:

- Dubai the Burj Dubai 800 meter
- Chicago , Wilis Tower 472 meter
- Taiwan, Taipei 101 500 meter

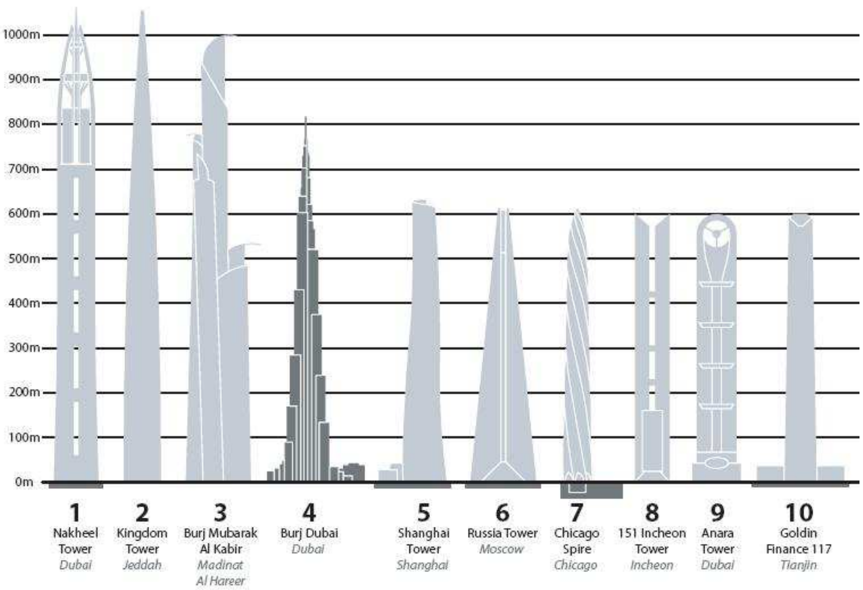

Figure 1-3 10 Tallest in 2020

Each high-rise project is unique and depends on the many location-bound conditions which influence the choices made in the design of a tall building. Because of this the following question is asked: “Is it technically possible to achieve similar heights in the Netherlands?”.

1.3 Goal

The goal of this thesis is to deliver a structural design for a 800 meter high supertall building in the Netherlands. Before we start designing the building (see part 2: Structural design) we will do a literature study to gain insight into the challenges which are encountered when designing a tall building.

Since there are many disagreements on the methods used to measure the height of tall buildings.
For buildings, there have been debates concerning:

- Whether only habitable height should be considered.
- Whether rooftop antennas, viewing platforms or any other architecture that does not form floors, walls and rooms, i.e. not built as an occupiable room, should be considered towards height of building.
- What counts as an official opening.

Many tall buildings have spires and antennas on top. A spire is a decorative, tapering conical or pyramidal structure on the top of a building. The Burj Dubai [20] for example has a spire which is over 200 meter high and the Nakheel Towers spire [27] is the same size as the Eiffel tower.
These spires are almost always unfit for habitation and some believe they should not be used to measure the height of the building.

A large debate occurred when the Petronas twin towers in Kuala Lumpur, Malaysia, laid claim to replacing the Sears tower as the tallest building in the world. Since the Sears tower's 77 meter-tall antennas where not included in the height measurement, the Petronas 452 meter tall towers beat the sears tower by 9.7 meters.
Without their decorative spires however, the Petronas Towers were only 379 meter tall and much shorter than the Sears Tower highest inhabitable floor which is located at 436 meter above the ground. At a meeting in 1996, the council of tall buildings and urban habitat height committee decided that spires should count in measuring the official height of the Petronas towers. Many people, especially Chicagoans disagreed and in response the CTBUH created three categories for determining a buildings height, namely:

1. Height to architectural top
2. Highest occupied floor
3. Height to tip

For this thesis we will use the second criterion to determine the height of our building. This means that we will start measuring from its lowest significant open-air-entrance to the highest occupied floor.

1.4 Approach

Designing a good high-rise structure demands good teamwork from people of different disciplines. The architect, structural engineer, installation engineer and client all have different backgrounds and sometimes different priorities. In this thesis a lot aspects are discussed from a structural point of view. However, aspects which weigh more heavily in other disciplines i.e. architectural considerations and economic feasibility will also be considered when making choices in the design of the tower.

Because of limited time and resources the design of the 800 meter building is mostly depended on existing knowledge from research and reference projects. For example, instead of using a wind tunnel, research on buildings shapes and existing building is used to choose the shape of the building.

1.5 Outline of the literature study

In Chapter *2* a location for the 800 meter building is chosen based on the high-rise policy of Rotterdam.

Chapter *3* is the literature study which covers the most challenging aspects of building a supertall. The goal of the literature study is too gain insight in the important design aspects and thus providing a good basis for the structural design of 800 meter building in *Part 2: Structural design*.

The literature starts off with a paragraph on foundation and geo-engineering which includes the structural systems and elements which can be found in high-rise structures.
This is followed by paragraph *3.2* which offers a brief view on the characteristics and role of materials in tall buildings.
Paragraph *3.3* discusses the structural elements and systems used in tall building. It starts with a categorization of systems with respect to their ability to resist lateral loads and continues by focusing on the structural systems and elements which are suitable for supertalls.
Paragraph *3.4* describes the suitable floor-systems in suspertalls and discusses the aspects which influence its choice.

Wind and dynamics are discussed in paragraph *3.5*. The negative effects such as wind induced vibration and vortex shedding are described as well several aerodynamic shapes which reduce these negative effects.

In paragraph *3.6* several built, proposed and cancelled reference projects are discussed. These projects provide valuable info which can be compared to the theory.

In Chapter *4* the findings from chapter *2* and *3* are used to draw a conclusion on the most important design aspects of an 800 meter building. These design aspects are then used to choose a suitable structural concept for an 800 meter building.

Chapter 2 Choosing a location

2.1 Introduction

The first challenge is to find a suitable location for our skyscraper. Most supertalls have a slenderness ratio of ca 1:8. This means that a 800 meter high skyscraper has a width of 100 meters and we should look for an area where we can place a tower with a 100 by 100 meter footprint.

High-rise structures have a large impact on their environment. They can generate large traffic flows which put a large strain on the existing infrastructure and influence neighbouring structures by blocking daylight from falling on facades and causing increased wind speeds at ground level. It is very important to consider these aspects at an early stage.

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Figure 2-1 High building density in Shenzhen China [5]

Figure 2-2 Wind

A new tower should have a beneficial effect on its environment and it is important to have a clear concept on how a proposed high-rise building can achieve this. An example is portraying the building as an icon and using it to mark special and important places.

The Dutch council on tall buildings gives some recommendations for new high-rise structures, namely:

- Have a clear concept.
- Define the meaning of the tower.
- Realize that high-rise does not miraculously solve urban density.
- Beware of saturated market.
- Prevent a traffic gridlock.

Every city in the Netherlands has a high-rise policy which gives guidelines on where and how high-rise buildings should be built. In the following chapters a location will be chosen by considering the interaction and the effect the building will have on its environment. We will use the recommendations from the “Stichting Hoogbouw” (Dutch council on tall buildings) and the high-rise policy of Rotterdam [1] [12].

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Rotterdam

Rotterdam has a high-rise tradition which started as early as 1898 with the construction of the “Witte Huis”, a 45 meter high building which at that time was the tallest office building in Europe. Because of bombardments in the Second World War the city lacks a large historic centre and offers more possibilities for high-rise than other Dutch cities. In the eighties a lot of new high-rise projects were started and Rotterdam now has the highest concentration of high-rise buildings in the Netherlands.

High-rise policy

In the high-rise policy of Rotterdam, high-rise buildings are concentrated on both sides of the river “de Maas’’. It aims to avoid isolated initiatives in surrounding areas and the stimulation of building high-rise near the city centre. The city’s high-rise policy has helped to create a new identity which was lost during the bombardments in the Second World War.

Figure 2-3 skyline Rotterdam

The shape of the skyline is as follows:

- In the northern direction the buildings have an increasing height starting at the river (ca 70 meter) ending at the Hofplein (where the maximum allowed height is 250 meter).
- At the Statentunnel the buildings can have a height of 100 meter which increases to 250 meter at the Hofplein.
- High-rise around the Coolsingel can have a height of 100- 150 meter at Churchillplein.
- Officially there is no maximum height for high-rise buildings located at the Weena and the Coolsingel.

The high-rise policy of Rotterdam [12] gives the following criteria for high-rise buildings higher than 150 meter, namely:

- A good connection with the public transport system, both local and regional.
- It should have landmark function for the region.
- The size of the location has to be considered as well as the influence of the building on the environment.
- The demand for super high-rise should be market based to prevent the hindrance of Rotterdam local market sector.
- The development cannot have consequences for existing structures.

- There has to be sufficient space to prevent nuisance during construction.
- It has to be able to increase the attraction of the local environment.

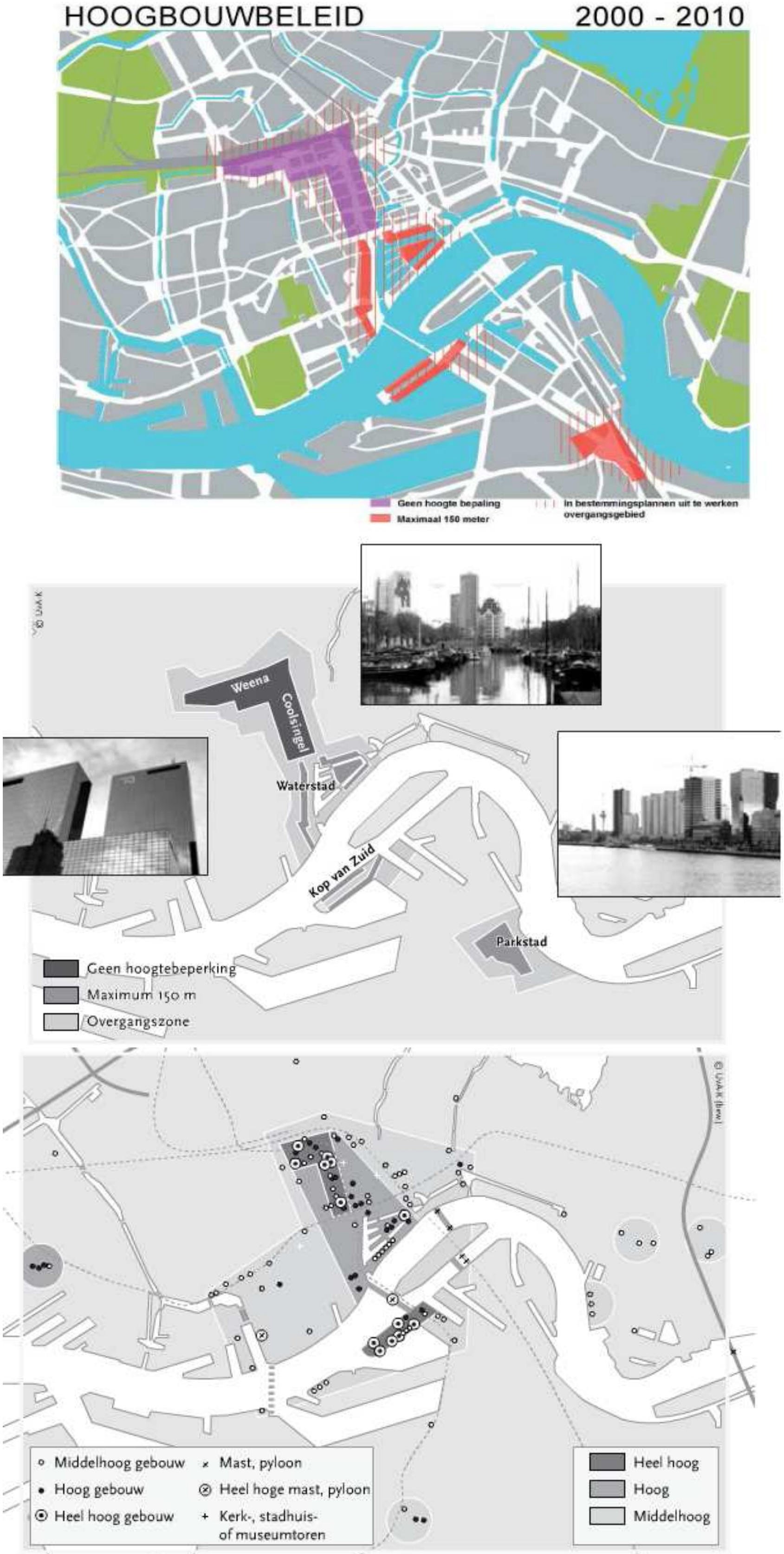

Figure 2-4 High-rise policy of Rotterdam [12]

2.2 Possible locations:

There are several possible locations for our new skyscraper, namely

- Parkhaven
- Kop van Zuid
- High-rise on a manmade island

2.2.1 Parkhaven

Parkhaven is well known for the Euromast, a tall structure which serves as a tourist attraction.

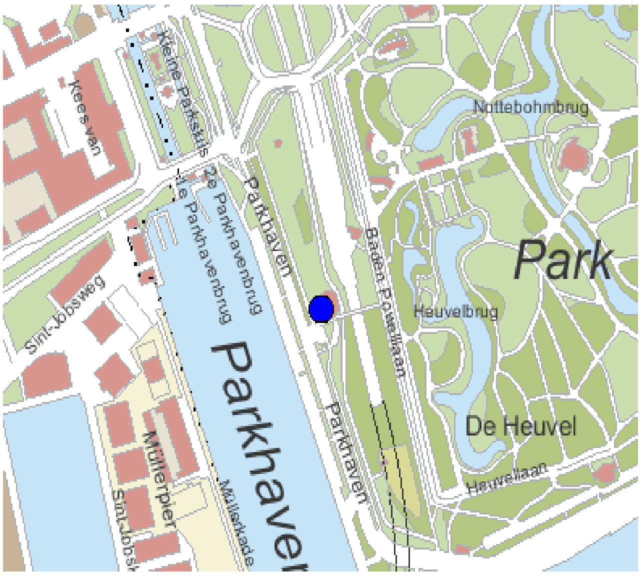

Figure 2-6 Location Parkhaven


Figure 2-5 The Euromast

The Euromast, located in Parkhaven, was completed in 1960 and had a height of 100 meters. In 1970 the height of the tower was increased to 157 meters with the addition of the space tower and since 1995 it has been possible to reach the top of the tower with the help of a shuttle.
For a long time the Euromast was a well known attraction but recently the amount of visitors has been dropping. In its peak years the Euromast attracted 800,000 visitors a year but now this number has dropped to 200,000 visitors.
This dropping in numbers can be attributed to the fact that due to technical innovations buildings in Rotterdam are becoming higher and higher and that the “Park” is not located on current tourist routes. All this has led to a number of plans made by real estate developers to revive the Euromast and Parkhaven by creating a new landmark.

In the first plans the Euromast was replaced by a new tower with a height of more than 350 meter. The idea of removing the Euromast however was not well received by the citizens and municipality of Rotterdam because they felt the structure had become a part of the city.

In 1998 the current owner of the Euromast made a masterplan containing new attractions around the Euromast. This plan was presented in 2001 as the Masterplan Parkhaven and contains the development of new estate such as high-rise building apartments, offices, recreational facilities and the improvement of the current infrastructure. The Euromast would

be brought back to its original state by removing the spacetower and a new tower called “the Amazing tower ” would be build.
This tower would be 330 meter high and have 62 meter high spire making it the tallest building in Europe.
By building a new tower with an urban entertainment centre the Merwede Group and Ballast Nedam Ontwikkelingsmaatschappij hoped to create a new landmark which would attract visitors.

The dS+V (dienst stedenbouw+volkhuisvesting) however rejected the plans with the argument that the masterplan would have a negative impact on the Euromast and put a large strain on the existing infrastructure.

Figure 2-7 Amazing tower

2.2.2 Kop van Zuid

“Kop van Zuid” consists of former unused harbour areas in Rotterdam-South which have been transformed into a new part of the city of Rotterdam. It is located on the southbank of the river “de Maas ”.
As a result of the shifting of port activities westwards, the harbour areas Kop van Zuid lost their function in the second half of the past century. Also the need for urban functions such as housing, offices, and public amenities increased. By turning the unused harbour areas into an urban area the city tried to unite the city centre lying in the north with Rotterdam-South.
The Kop van Zuid is part of the district Rotterdam south and can be subdivided into the following areas:

- Wilhelminapier
- Zuidkade
- Landtong
- Stadstuinen
- Parkstad
- Peperklip
- Entrepot
- Spoortunnelloacties

Figure 2-8 Areas Kop van zuid

Officially the Wilhelminapier is a part of the city centre while the other areas belong to the district Feyenoord.

In the early nineties Riek Bakker and Teun Koolhaas made a masterplan consisting of a new urban area with real estate consisting of a balanced mix of housing, work, retail and leisure in Rotterdam South. The area would be rich in water and contain many high-rises buildings with residential and office functions and would be connected to the city centre by means of the Erasmus bridge and a subway station, Wilhelminaplein. The Kop van Zuid development would create 5,300 new dwellings, 400,000 m^2 of office space, 35,000 m^2 business/working space, 30,000 m^2 of educational and recreational facilities each. Now, the Kop van Zuid is home to a number of high-rise structures including the tallest building in the Netherlands the Maastoren.

Infrastructure

The main infrastructure consists of the “Varkenoordse Viaduct”, “The Erasmus bridge”, The subway station “Wilhelminaplein” and the “laan op zuid”

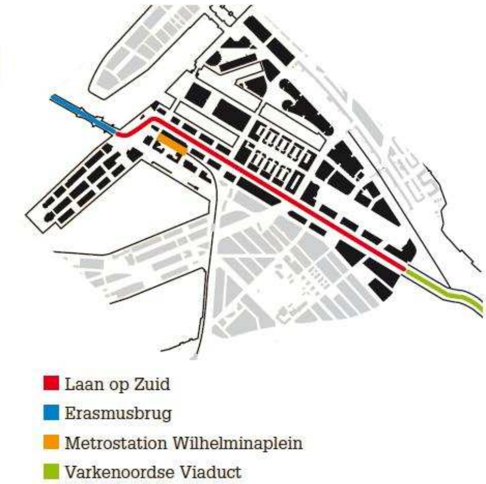

Figure 2-9 Infrastructure Kop van Zuid

The need for good infrastructural connections was recognized in the early stages of planning the Kop van Zuid and was financed by the municipality of Rotterdam and the national government. The Erasmus Bridge connects the Kop van Zuid to a number of important destinations by allowing traffic by tram, car, foot and bicycle. It is however, not only important as a connection between north and south but has also become a landmark and a city icon.

Wilhelminapier

The Wilhelminapier is an urban area in the “Kop van Zuid” in Rotterdam which is officially a part of the city centre. It is located at the foot of the Erasmus Bridge and is home to many high-rise buildings including the Montevideo which is the tallest residential building in the Netherlands. There are plans for several new high-rise buildings on the Wilhelminapier.

Figure 2-10 Render of high rise plans Wilhemlminapier

2.2.3 High-rise on an island

Another possibility is to build the skyscraper on an island. The pictures below show renderings of a visionary study “called harbour island ”done by Groupa Aukett and Urban Bubble Corporation.

Figure 2-11 Harbour Island by Group Aukett and Urban bubble corporation

In this study high-rise structures are located on an island in the “Rijnhaven”. The goal is to stimulate urban integration with an innovative concept. By becoming an international landmark this new urban centre will strengthen the economic growth in Rotterdam-South.

The biggest advantage of this harbour is that there will be plenty of space for the proposed 800 meter skyscraper. The depth of the harbour is 7.65 m and there are almost no waves. Instead of being an isolated initiative the skyscraper will be part of a cluster of high-rise.

Figure 2-13 Harbour Island render

Figure 2-12 Harbour island render

2.3 Final location

As seen in the figure below **Parkhaven** does not offer enough space to accommodate a skyscraper of 800 meter.

Figure 2-14 Parkhaven

If we consider a slenderness of 1:8 - 1:10 we will need an area of 80 by 80 m - 100 by 100 m for a height of 800 meter. For these values the room necessary for infrastructure has not yet been taken into account. Also the building will cause settlements which will be problematic for important neighbouring structures such as “Erasmus Medisch Centrum” and the “Maastunnel”

The **Kop van Zuid** has become home to many new high-rise buildings but there isn’t much space left. Most of the empty spaces on the Wilhelminapier for example will be taken up by proposed high-rise buildings such as Zalmhaven, New Orleans, de Rotterdam, Baltimore, San Francisco, Boston, Philadelphia and Havana.


Figure 2-15 Renders showing future plans for the Kop van Zuid

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Building the skyscraper on an island like the visionary study " **Harbour Island**" would solve a lot of the aforementioned issues

Figure 2-16 Final location, Rijnhaven

The building would have more than enough space for itself and possibly a plinth. Also it stands on its own but is still a part of the skyline (close to the Wilhelminapier and Erasmus Bridge). Placing the tower near a cluster of high-rise buildings amplifies the urban effect the city municipality is hoping to achieve. Existing infrastructure of the Kop van Zuid can be used and if necessary improved.

Henceforth the project shall be called the Rijnhaven Tower because the skyscraper is located in the Rijnhaven.

Chapter 3 Literature Study

3.1 Foundation and geo-engineering

3.1.1 Introduction

A good foundation is an important part of a high-rise structure because its function is to safely transfer the structural loads from the building to the ground. Successful geotechnical engineering remains hidden underground and the importance of a good foundation only becomes visible when errors are made. The results are settlements, tilting and building damage. Poor planning, wrong ground subsoil assessment and bad design can result in serious construction delays and additional building costs.
To prevent this, a foundation must be properly designed and constructed taking into account the soil characteristics and the nature and strength of the materials used for the foundation.

3.1.2 Settlements

A high-rise building causes large loads on a relatively small area. This will undoubtedly result in settlements. Problems however, arise not so much because of the settlements but because of the unequal settlements. Such differences create stresses in the building structure and may require the addition of extra measures such as dilatation joints.

According to [71] differential settlements can be caused by :

- Differences in foundation pressure
- Differences in geometry foundation
- Differences in stiffness of the sub soil
- Differences in stiffness of the foundation elements

Differences in foundation pressure are the result of the fact that the loads on a structure are not always applied uniformly and some parts of the structure are more heavily loaded than others. The core for example is a heavily loaded part of the structure because it contains heavy installations and transmits most of the horizontal and vertical loads.
These differences cause more settlements beneath the core than other parts and result in tilting of the building. Settlements can also occur because a combination of high wind loads and the vertical loads lead to an asymmetric stress profile at the foundation.

There are several measures which can be taken to control settlements and tilting, namely:

- Adjust the design of the foundation to the difference in loading. More piles where there are more loads. Adjust the length of the piles.
- Make the structural element which is heavily loaded stiffer for example by making the floor thicker. This will help spread the loads and decrease the difference in deformation.
- Add a dilatation which separates the heavily loaded structural part from the other structural components.

High-rise buildings can also have consequences for their direct environment. A high-rise building delivers a large pressure on the soil causing settlements that influence surrounding (lower rise) buildings. This can cause differences in settlements.

3.1.3 Foundation types

The foundation has to transfer the large loads from acting on the high-rise building to the ground with as little deformation as possible. The chosen foundation type depends on the ground conditions. We distinguish three different foundation types, namely:

- Shallow foundation
- Deep or pile foundation
- Pile and raft foundation

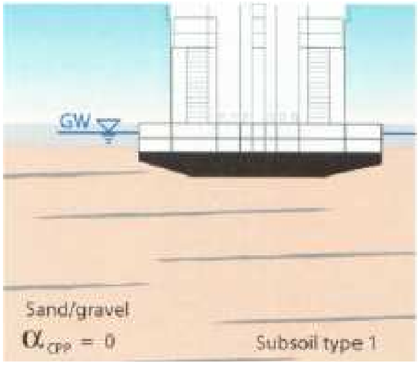

Figure 3-2 Raft foundation [5]

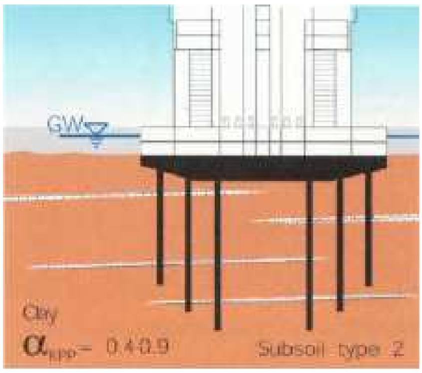

Figure 3-3 Pile and raft [5]

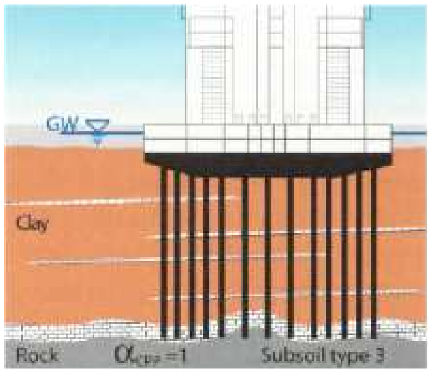

Figure 3-1 Pile foundation [5]

Shallow foundation

A shallow foundation is the most economic option when there is subsoil with good load-bearing capacity present. It is however less suited for the transfer of large point loads and asymmetric load distributions and can undergo significant settlements. Because of these reasons it is useful to calculate if a pile and raft foundation is a more economic option, even if there is a good load bearing layer present.
There are three types of shallow foundations: a pad a, strip and raft foundation.

Pad foundations are used to support an individual point load such as those due to a structural column. They may be circular, square or rectangular. They usually consist of a block or slab of uniform thickness, but they may be stepped or haunched if they are required to spread the load from a heavy column. Pad foundations are usually shallow, but deep pad foundations can also be used.

Strip foundations are used to support a line of loads caused by either a load-bearing wall or when a line of closely spaced columns need supporting and applying individual pad foundations would be inappropriate.

A **raft foundation which is** basically a large slab which distributes the vertical forces from the building over a large area which is usually the entire footprint of the building. The raft helps prevent unequal settlements between the different load bearing elements which transfer vertical loads to the foundation. A raft is used when the load-bearing elements from the super structure are spaced close together and individual pad foundations would interact.

A raft foundation can also transform into a floating foundation by excavating soil and using the uplift water pressure to counteract the vertical loads of the building.

Deep foundation

A deep foundation is used when there is no adequate soil capacity available close to the surfaces so loads must be transferred to firm layers substantially below the ground surfaces. These layers can be very deep .The piles of the Petronas Towers in Malaysia for example reach a depth of 120 meters.
In a deep foundation load transfer to a deeper load bearing layer takes place via foundation piles or a slurry wall and the task of the foundation slab is to spread the loads from the building.

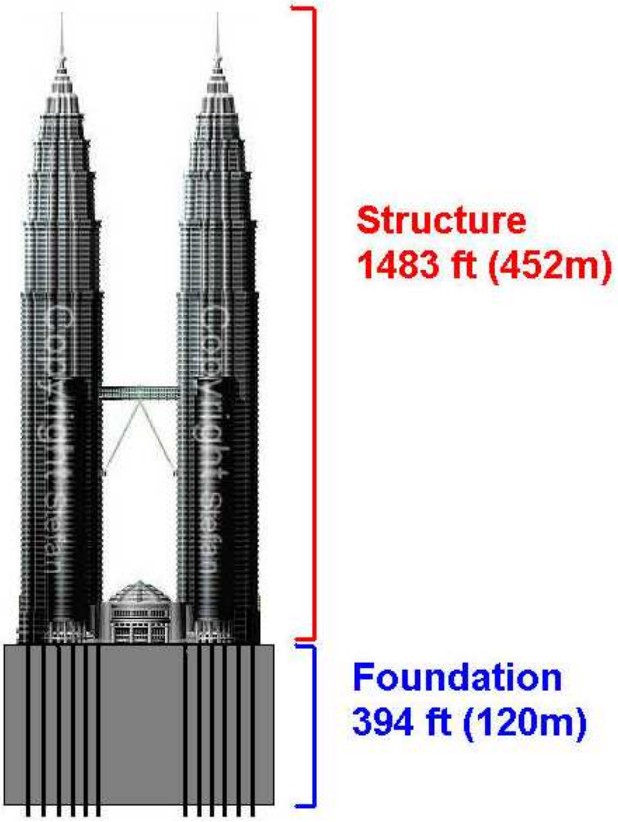

Figure 3-4 Foundation Petronas Tower

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Pile and Raft foundation

A pile-and-raft foundation system is a recent development in geo engineering. It is used when the subsoil has a limited load-bearing capacity and is composed of three elements.

1. Piles
2. Pad/raft
3. Ground

However, unlike a deep foundation, the vertical loads are transferred partly via the foundation piles and partly via the foundation raft.

$$R_{total} = R_{raft} + \sum_{j=1}^{n} R_{pile,j}$$

The following interactions take place.

- Transfer of loads from the superstructure to soil layers with better load bearing capacity through foundation piles via end bearing and skin friction.
- Mutual interaction between the foundation piles (group effect).
- Area load transfer from the raft to the subsoil.
- Increased axial stress on the pile jacket and hence skin friction as a result of surface pressure of the raft.

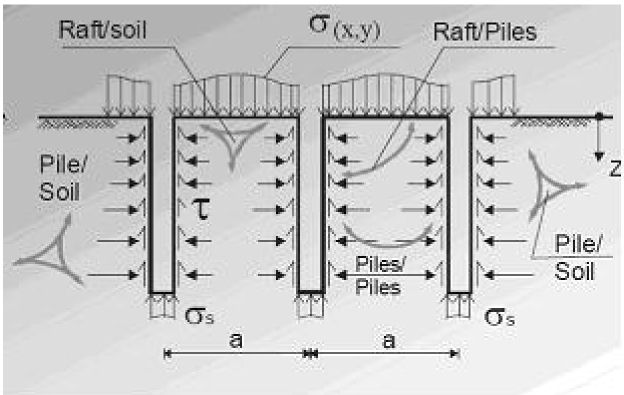

Figure 3-6 Interaction Pile and raft

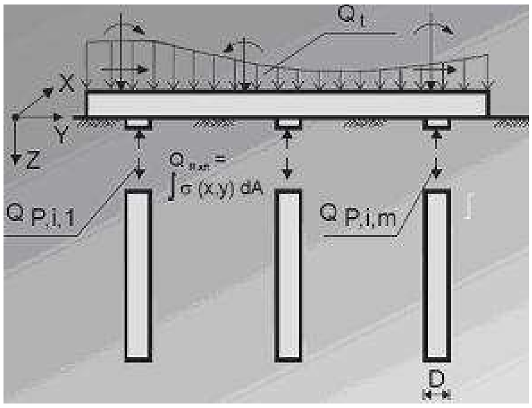

Figure 3-5 interaction pile and raft

The main idea is that controlled settlements are not a problem as long as the differences in settlements are kept to a minimum (tilting).

Despite it being new, this system has already been used in a number of projects. These projects are mostly high-rise and industrial buildings in areas like London, Frankfurt and Goteborg with homogeneous subsoil and stiff over consolidated clay, but also in sand layers with loose to mediocre density, like Perth and Berlin.
It is also used for smaller buildings in areas with a more layered subsoil such as Tokyo and Sao Paulo. [72][73]

Advantages of the pile and raft foundation are

- A limited increasing settlement and stresses in the foundation slab can lead to a considerable reduction in piles.
- Controlling the settlement differences is possible by optimizing the position and the number of piles.

Piled raft foundations were originally meant as an improvement for shallow foundations. In the Netherlands deep foundations are used for high-rise buildings. However, with increasing heights, higher loads are leading to denser piling and larger pile diameters. The increasing interest in use of underground space in urban areas and technical developments in the area of building excavation have put relatively stiff and load-bearing soil layers within the reach of foundation slab. Besides a reduction of the upward forces caused by groundwater, the possibility of applying multiple basement layers can also ensure that the foundation slab transfers loads directly to the load-bearing soil layer. This enables the foundation to reduce settlements in deep and weak soil layer compared to the conventional deep foundation. [72][73]

A pile and raft foundation is recommended for:

- Foundations subjected to eccentric loads from the superstructure.
- High-rise structures with a high slenderness ratio and other structures sensitive to differences in settlements.
- Buildings with large load jumps which, for a shallow foundation, require dilatation joints beneath groundwater levels.
- Buildings on inhomogeneous subsoil.

Randolph (1994) has defined three different design philosophies with respect to piled rafts, namely:

- The “conventional approach”, in which the piles are designed as a group to carry the major part of the load, while making some allowance for the contribution of the raft, primarily to ultimate load capacity.
- “Creep Piling” in which the piles are designed to operate at a working load at which significant creep starts to occur, typically 70-80% of the ultimate load capacity. Sufficient piles are included to reduce the net contact pressure between the raft and the soil to below the preconsolidation pressure of the soil.
- Differential settlement control, in which the piles are located strategically in order to reduce the differential settlements, rather than to substantially reduce the overall average settlement.

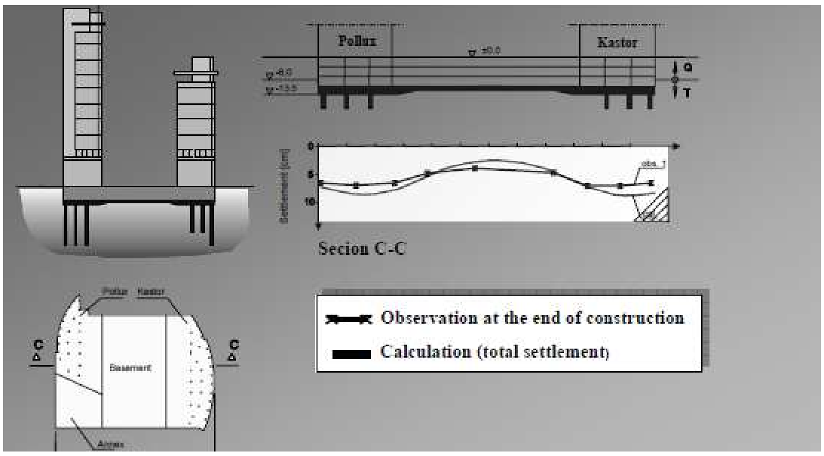

Figure 3-7 Kastor and pollux pile and raft foundation

3.1.4 Piles

Piles are relatively slender columns which are inserted into the ground. They are used when soil layers directly beneath the building have insufficient load bearing capacity and the loads need to be transferred to bearing strata beyond the reach of shallow foundations. Piles are supported by their end bearings and skin friction.
In addition to supporting the building they can also be used as anchors against uplift forces and resisting lateral and overturning forces. The first piles were made of wood and now there are a wide variety of pile types available on the market.

The most important design aspects which influence the choice for a pile type are:

- The degree to which the environment (surrounding structures) is affected by vibrations and sound
- The soil deformation caused by the installation of the pile.
- The size and type of load on the piles (compression, tension or bending).
- The load displacement behaviour
- The sustainability of the piles
- Feasibility
- Costs

There are two different pile types, namely:

- Displacement piles
- Non-displacement piles

Displacement piles can be subdivided into large and small displacement piles. They are driven into the ground and displace soil. Driven piles can be performed partially preformed or cast in place. Small displacement piles are steel profiles and steel tubes. Since these piles are twice as expensive as prefab piles they are used in urgent situations for example when large tensile loads or bending moments are present.

Non displacement piles are made by forming a void trough boring or excavation of the subsoil after which concrete is casted. Bored piles can have large diameter and can be very long.

In the Netherlands prefab concrete piles are common. These piles can reach a load-bearing capacity of 4000-5400 kN. Occasionally bored piles which can have a load-bearing capacity of 10000-20000 kN are used [58]

3.1.5 Basements

Basements are usually used in tall buildings as parking spaces, storage of services or underground shopping centers. Besides providing additional space they can also play a structural role by acting as a form of buoyancy raft or reducing net bearing pressure by removing soil.
During construction it is important to provide adequate support for the excavation and to control the ground water.

3.2 Materials and supertall buildings

3.2.1 Steel and concrete in high-rise structures

Introduction

Since the focus of this thesis is on supertall buildings we will not cover basic material aspects in great detail. Table 3-1 gives a summary of some of the material aspects of the materials steel and concrete.

Summary material properties		
	Steel	**Concrete**
E-Modulus	Ca 210000 N/mm^2	31000 N/mm^2 (C20/25) -44000 N/mm^2 (C90/105)
Strength	• 235 N/mm^2 to 355 N/mm^2	• Compressive stress ranging from N/mm^2 (C20/25) to N/mm^2 (C90/105) • Tensile stresses 1,6 - 5,0 N/mm^2 • Tensile stresses require reinforcement + prestressing
Material behavior	Yielding is not brittle. Steel is able to redistribute stresses and can give warnings before failure occurs.	Creep and shrinkage are time dependent deformations which should be accounted for in the design.
Weight density	Ca 78.5 kN/m^3	Ca 25 kN/m^3
Fire safety	Steel strength decrease rapidly at high temperatures (>600 C)	Concrete can resist high temperatures longer than steel.
Construction time	• Cranes are used to place the structural elements. • Prefab can be mounted on the construction site.	• With modern technology concrete can be pumped up to great heights making cranes unnecessary • Longer when formwork and steel reinforcement are used
Connections	Preferably hinges, moment resistant connections are expensive and time consuming.	Usually moment resistant
Damping	lower	Higher

Table 3-1 summary material properties.

In supertall buildings floor slabs and beams can be made of light weight concrete which reduce the structures self-weight. The columns are normal or high strength concrete because they have to carry loads of all upper floors whereas the floor and beam only have to support the load of their floor.

High strength concrete

High strength concrete can offer many possibilities for high-rise buildings. According to the European Norm EN 206-1 high strength concrete is concrete with a strength class above C55

	Strength class → High strentgh concrete													
F_{ck} characteristic cylinder strength	12	16	20	25	30	35	40	45	50	55	60	70	80	90
F_{ck} characteristic	15	20	25	30	37	45	50	55	60	67	75	85	95	105
Average compressive strength	20	24	28	33	38	43	48	53	58	63	68	78	88	98
Average direct tensile strength	1,6	1,9	2,2	2,6	2,9	3,2	3,5	3,8	4,1	4,2	4,4	4,6	4,8	5,0
Secans E-Modulus	27	29	30	31	33	34	35	36	37	38	39	42	42	44

Table 3-2 strength and deformation characteristics according to EN 1992-1-1:2004

High strength concrete mix requires good quality control on site and is very expensive due to the requirement of high cement content which greatly increases the material costs. It is able to carry larger loads but has the following disadvantages:

- It deteriorates more quickly under extreme high temperatures (fire).
- It tends to become brittle more abruptly than normal strength concrete resulting in cracks and breaks in the material.

Another advantage important for high-rise buildings is that high strength concrete mixture is a very easily pumped, highly fluid mixture. High strength concrete typically will move through the pump lines using less pressure than typical heavier grout mixes.

Differential column shortening

The effect of column shortening is a major consideration in the design and construction of tall buildings, especially in concrete and composite structural systems.
Long-term axial shortening of the vertical elements of tall buildings results in differential movements between two vertical elements and may lead to the additional moments of connection beam and slab elements, and other secondary effects, such as cracks of partitions or curtain walls. Thus, accurate prediction of time-dependent column shortening is essential for tall buildings from both strength and serviceability aspects, especially for medium to high-rise buildings. Extensive research has been conducted to investigate this phenomenon. It has been shown that differential column shortening is affected by the relative axial stiffness and the tributary area of columns and walls. Moreover, the ratio between beam and column stiffness and the construction sequence also have significant influence on the axial force redistribution.

3.3 Load-bearing Structures

Besides transferring the gravity loads to the foundation an important goal of the structural system in a tall building is resisting the lateral loads caused by wind. Therefore the hierarchy of structural systems is mostly categorized with respect to their relative effectiveness in resisting lateral loads. The aim of this paragraph is to describe the various structural systems used in supertall buildings together with their economies, relative efficiencies and advantages. This will be done by discussing each system and in some cases illustrating them by examples of actual application.

Several attempts have been made to classify the efficiency of structural systems for different heights or storeys. A classification by [8] is shown in Figure 3-8 and Figure 3-9.

In [8] Structural systems of tall buildings are divided into two broad categories, namely:

- Interior structures
- Exterior structures

This classification is based on the distribution of the components of the primary lateral load-resisting system over the building. A system is categorized as an interior structure when the major part of the lateral load resisting system is located within the interior of the building. Likewise, if the major part of the lateral load-resisting system is located at the building perimeter, a system is categorized as an exterior structure. It should be noted, however, that any interior structure is likely to have some minor components of the lateral load-resisting system at the building perimeter, and any exterior structure may have some minor components within the interior of the building.

The author of [8] also notes the following:

"This classification of structural systems is presented more as a guideline and should be treated as such. It is imperative that each system has a wide range of height applications depending upon other design and service criteria related to building shape, aspect ratio, architectural functions, load conditions, building stability and site constraints. The height limits shown are therefore presumptive based on experience and the authors' prediction "

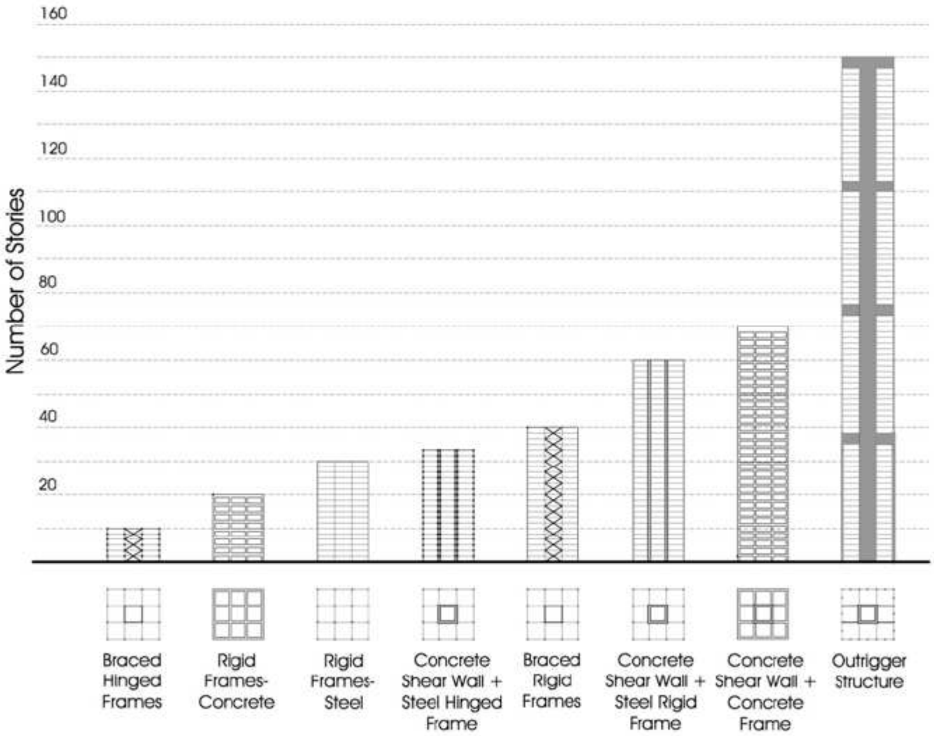

Figure 3-8 Interior structures [8]

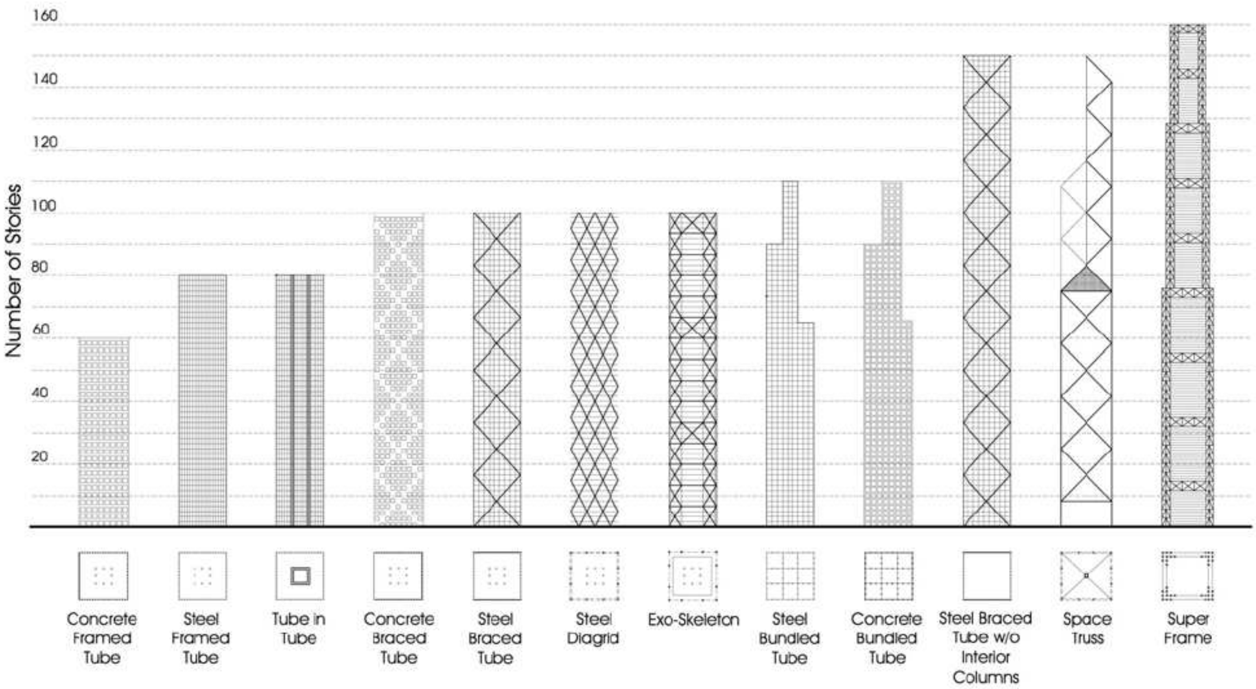

Figure 3-9 Exterior structure [8]

3.3.1 Structural components in supertall buildings

Before discussing the loadbearing structures of tall buildings we will take a look at some common structural components used in supertalls, namely:

- cores
- megacolumns
- perimeter tubes

Floors will be discussed in paragraph (3.4).

Cores

High-rise requires vertical transport such as lifts and stairs. Concrete walls in elevator shafts, stairwells and partition walls are often necessary to ensure fire insulation and satisfy acoustic or architectural demands. These walls have a very high in-plane stiffness making them perfect for providing bracing to a tall building. Existing wall slabs and access cores are thus often used to carry gravity and lateral loads.

For a stable building at least three linear elements or a torsionally stiff box are necessary in every horizontal plane. The lines of action of these elements may not intersect in one point. The first condition counteracts the deflection of the building along the x and y axes and the second condition counteracts rotation of the building.

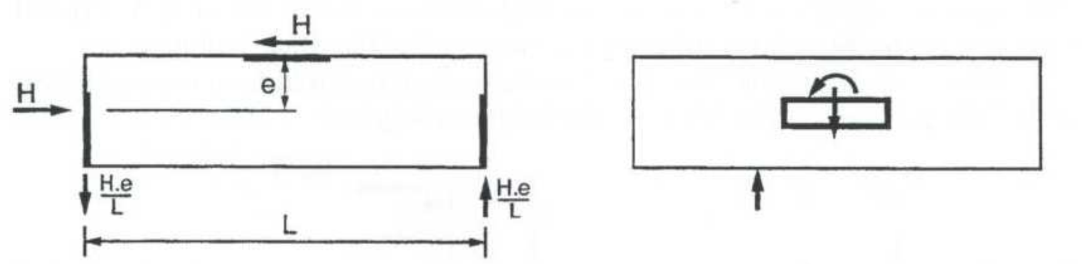

Figure 3-10 Shear walls and core

Megacolumns

Megacolumns are large often composite columns used in core-outrigger and megastructures structures. These columns are used to increase the internal lever arm which allows the structure to create a larger counteracting moment (see Figure 3-24). The advantage of megacolumns is that they cause limited architectural obstruction in the façade as opposed to tube structures which require closely spaced columns or diagonals.

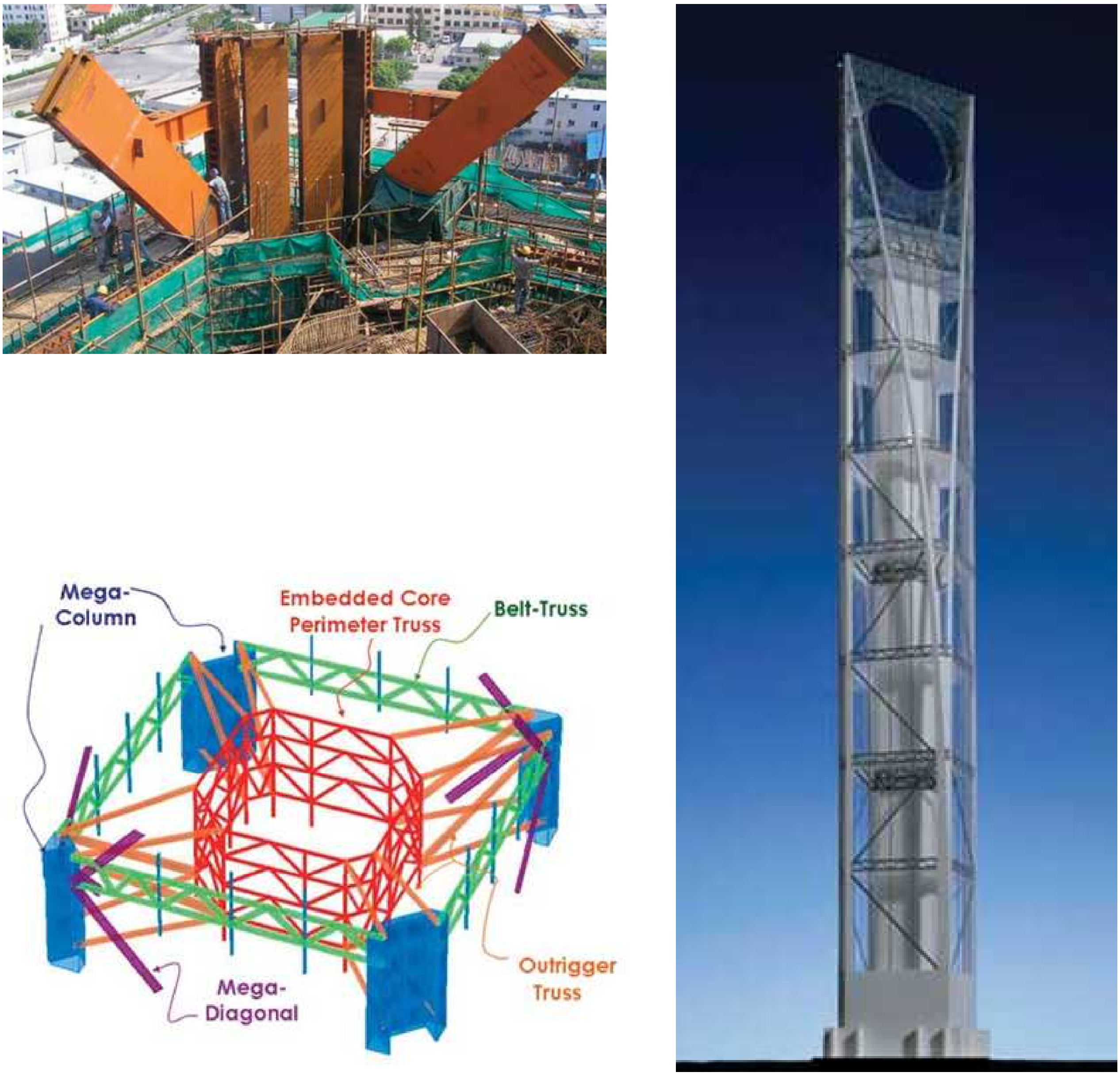

Figure 3-11 Megacolumn (top left) and structural system Shanghai World Financial (down left) and(right)

Perimeter tubes

By ensuring the rigidity of the facade across the width and depth of the entire building, the façade is transformed into a rigid body called a tube structure.
Due to their slenderness, which means greater vulnerability to lateral forces, the nature of a building's perimeter has more structural significance in tall buildings than in any other building type. Therefore it is in tall building, like in a beam, structurally efficient to concentrate as much lateral load-resisting system components as possible near the buildings perimeter. This increases their structural depth, and in turn, their resistance to lateral loads. Greater heights can be achieved by transferring not only a part of the vertical load but a part of the horizontal loads via the facade.

The rigid connections in the façade can be achieved by using:

- frame structures
- jointed walls
- diagonals

A framed tube structure resists lateral forces with a strong, tightly connected perimeter framework, requiring closely spaced columns at the edge of the structure. This allows for large open spaces within the building plan, even in a very tall structure.
These tube structures improve the overall stability of the building and behave like giant flange frames and perpendicular web frames carrying axial loads and shear.

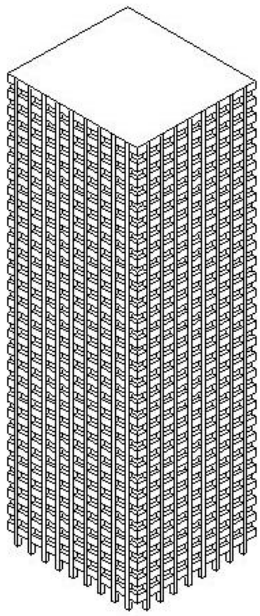

Figure 3-12 Perforated facade

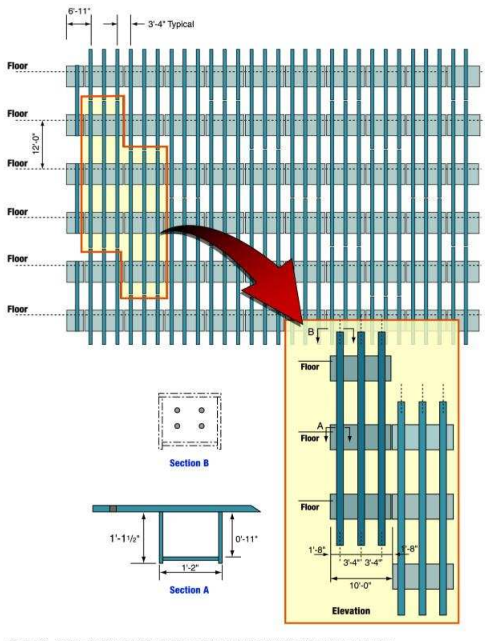

Figure 3-13 Façade WTC, USA

Exterior concrete tube

An exterior concrete tube can be created by perforating the reinforced concrete shear walls of the façade with window openings. This tube structure does not have the same degree of stiffness as an inner core but the large lever arm compensates for this. An example of such a structure can be seen in Figure 3-12.

Steel rigid frame tubes

A steel rigid frame structure consists of columns and girders joined by moment resistant connections. As mentioned earlier the lateral stiffness of a rigid frame is provided by the bending stiffness of the columns girders and the connection in the bending plane.
In the USA rigid frame tubes are designed almost exclusively in steel. A well-known example of the application of such a steel rigid frame was the World Trade Centre (Figure 3-13 and Figure 3-15) located in New York. In this building the exterior tubes provided most of the necessary rigidity for the towers. The building had an above average steel consumption and this is one of the reasons why it did not collapse immediately after the impact of the planes on September 11. A large part of the horizontal load was removed by the exterior tubes. Even though 50 percent of the façade columns were destroyed on the impact side, the buildings robust design gave people some time to flee the building.

Trussed frame tubes

Rigid frame tube can be turned into trussed tube by adding diagonal members to the frame. This type of tube system results in considerable saving of building materials because loads working on the building are transferred as normal forces in the diagonals. Since the lateral loads are resisted primarily through the axial stiffness of the frame members and the material is used more efficient. Examples of braced frame tubes are the John Hancock centre see figure (Figure 3-14) and the Citicorp centre (Figure 3-16). A disadvantage of a braced frame tube is that it obstructs the architectural planning of windows and doors.

Figure 3-16 Citycorp

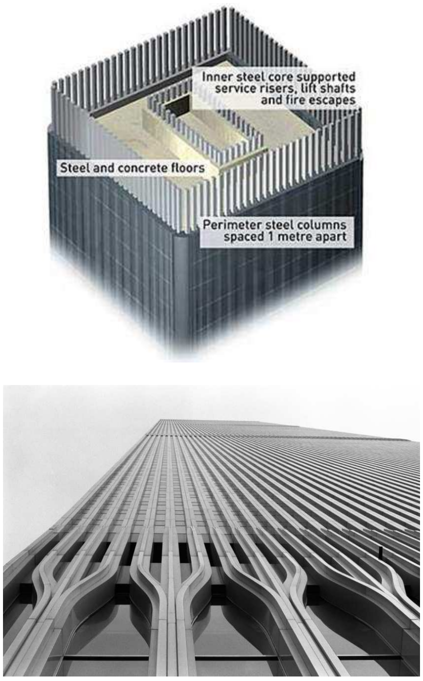

Figure 3-15 World trade center

Figure 3-14 John Hancock

Shear lag

The difference between a tube structure used in high-rise buildings and regular tubes is the result of a loss in rigidity caused by the openings. In an ordinary tube the moment caused by wind load causes a tensile force in the flange on the windward side and a compression force in the flange on the leeward side. The result is a constant stress in the flanges and linear stresses in the webs.
In a perforated tube however, the openings make the tube structure less rigid enabling the columns in the middle areas to evade the stresses. This results in higher stress at the corner columns and is known as the Shear-lag effect.

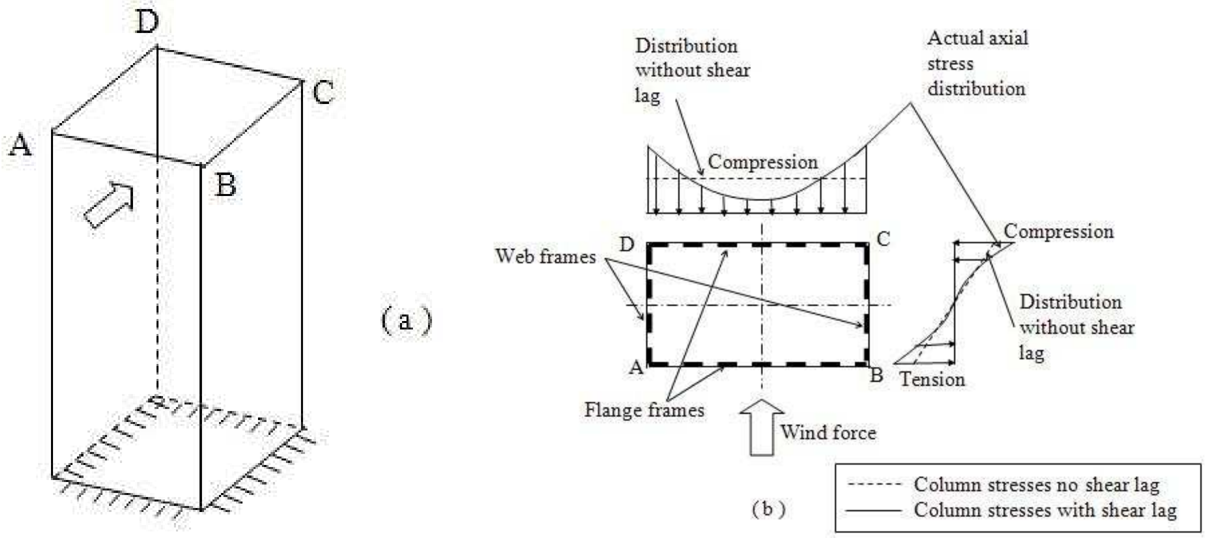

Figure 3-17 Shear-lag phenomenon

3.3.2 Supertall loadbearing systems

Supertall are described as high-rise buildings with a height of over 300 meters (1000 feet). Now that we have taken a look at the structural elements which are used in supertall buildings we will examine several structural systems.

The following structural systems are suitable for supertalls:

- tube-in tube structures
- bundled tube structures
- core-outrigger structures
- compound structures

Tube in tube structures

When both the tube system and the inner core are coupled by means of floor slabs we speak of a tube in tube structure. In this system both the inner core and the outer tube act jointly in resisting both the gravity and lateral loads.

A trussed tube with a braced module or diagrid module is the most efficient perimeter tube system for supertall tube-in-tube buildings.
Diagonal members or shear walls are added to create the braced frame structure where the members are no longer subjected to bending.
Braced frames consist of vertical and diagonal members or shear walls which resist lateral loads primarily through axial stiffness. Because the members are subjected to axial loads the system is laterally very stiff for a minimum addition of material. This makes a braced frame an economical structure.

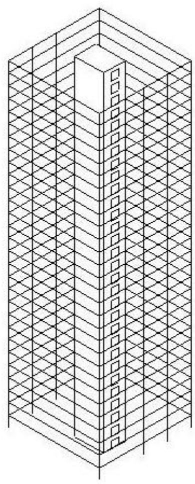

Figure 3-18 Tube in tube

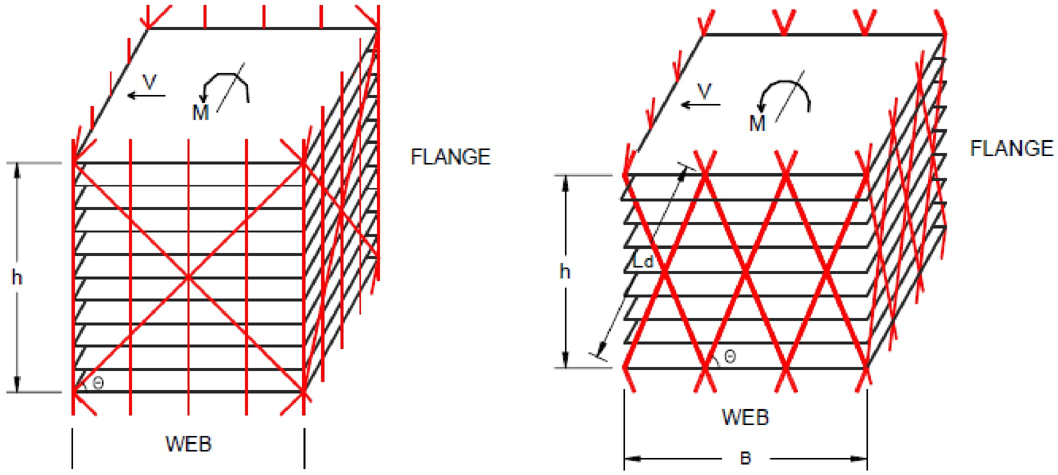

Figure 3-19 Braced module(left) , diagrid module (right)

Ideally the lines of action of the members in a diagonally braced frame should intersect in a single point. In reality this is often not the case because complex connections have eccentricities. The result are secondary stresses which should be taking into account in the structural design. The shortening of columns caused by vertical loading can cause loosening of the tensile bracings. The result is that these braces can only carry tensile forces caused by lateral loads under high deformations.
A disadvantage of a braced frame structure is the obstruction of internal planning and the locations of windows and doors.

Figure 3-21 Guangzhou East Tower

Figure 3-20 Lotte - early design by SOM

Bundled tubes

A bundled tube system consists of more than one framed or trussed tube, bundled together in order to resist lateral forces. This adds strength to a structure, in the same manner that a bundle of straws is harder to bend than a single straw.
The structural behaviour is improved by subdividing the main tube into smaller tubes which introduce additional shear-resistant webs. This way shear lag is compensated because the additional stiffeners make sure that the flange planes contribute more to the removal of bending stresses and that the web planes have more frames available for the removal of shear forces.

The Sears tower reached a height of 443 meters and held the title of tallest building for quite a while. It is the prime example of the bundled tube concept. Its super structure is built up out of nine interlocking square tubes which terminate at different heights giving the building a tapered shape. The bundled tube concept was created by Fazlur R. Khan of Skidmore Owings and Merrill and was very revolutionary. Each tube is rigid steel frame which counteracts the vertical and lateral loads together with the surrounding tubes. This system allowed for large open office spaces of 23 meters on the lower levels and smaller floor plates on the upper levels. At every mechanical level belt trusses improve the comfort and help reduce the lateral wind loads even further.

Figure 3-22 Sears Towers

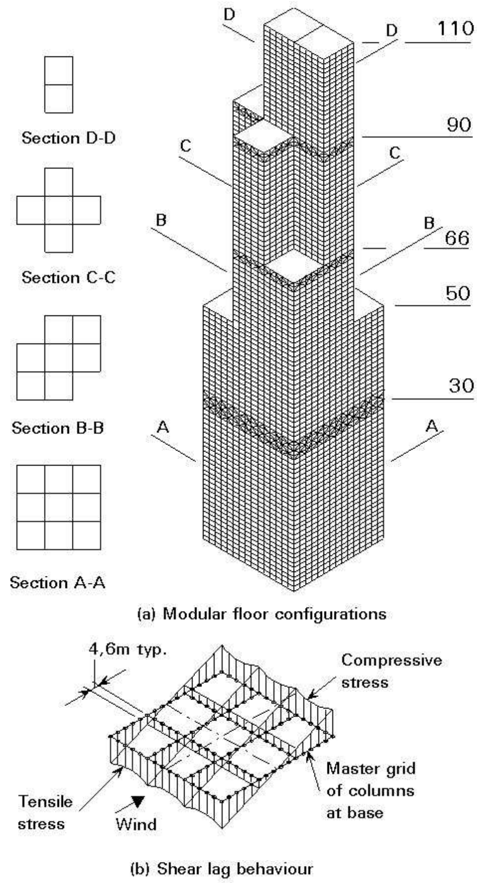

Figure 3-23 Bundled tube concept

Core-outrigger structures

A core-outrigger system consists of a rigid core which is tied to the perimeter by very strong horizontal connections.
The core is coupled to another core or facade column using outriggers girders. The coupling however is not continuous over the height of the building but only present at individual stories.

Outrigger systems have been historically used by sailing ships to help resist the wind forces in their sails, making the tall and slender masts stable and strong. The core in a tall building is analogous to the mast of the ship, with outriggers acting as the spreaders and the exterior columns like the stays. As for the sailing ships, outriggers serve to reduce the overturning moment in the core that would otherwise act as pure cantilever, and to transfer the reduced moment to the outer columns through the outriggers connecting the core to these columns (Figure 3-24). This same concept can also be found in sailing canoes
The core may be centrally located with outriggers extending on both sides or in some cases it may be located on one side of the building with outriggers extending to the building columns on the other side [9].

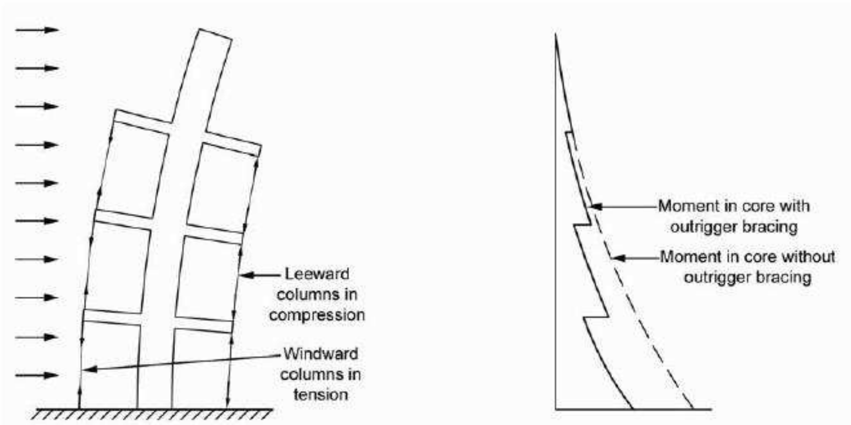

Figure 3-24 Core-outrigger system

The effect of adding outriggers can be seen in Figure 3-24. Instead of acting like a pure cantilever the core is now subjected to a resisting moment caused by the outrigger and outer columns. Advantage is taken of the moment caused by the large lever arm between the columns. The lateral load on the building causes a tension in the columns on the windward side and compression on the leeward side. In this way the horizontal deformation of the building is reduced.

One advantage the core-outrigger system has over tube systems which requires diagonals or closely spaced columns is that the exterior column spacing can easily meet aesthetic and functional requirements, and the buildings perimeter framing system may consist of simple beam-column framing without the need for rigid-frame-type connections. For supertall buildings, connecting the outriggers with exterior megacolumns opens up the facade system for flexible aesthetic and architectural articulation. In addition, outrigger systems have a great height potential up to 150 stories and possibly more.

This systems disadvantage is that the outriggers can interfere with the occupiable or rentable space and the lack of repetitive nature of the structural framing which can have a negative impact on the erection process. These drawbacks however can be overcome by careful architectural and structural planning which includes placing outriggers in mechanical floors and development of clear erection guidelines.

The outrigger systems may be formed in any combination of steel, concrete and composite construction. A very early example of outrigger structure can be found in the Place Victoria Office Tower of 1965 in Montreal designed by Nervi and Moretti. It was also used by Fazlur Khan in the 42-story First Wisconsin Center of 1973 in Milwaukee, Wisconsin.
Now the core outrigger system is very popular for supertall buildings an the application of this structural system can be seen in many supertall buildings such as Jin Mao Building, the Taipei 101, Petronas towers and International Finance Center.

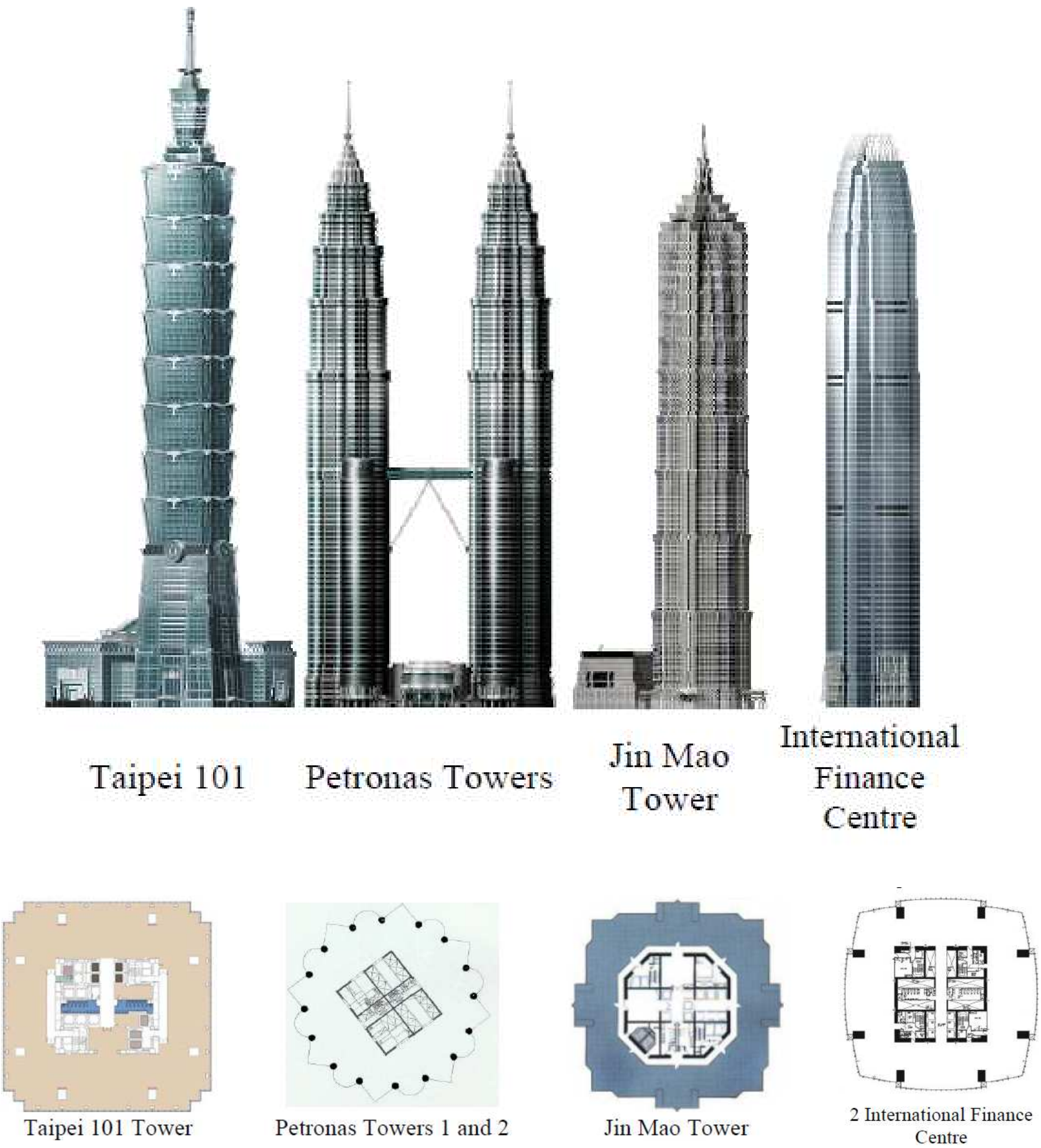

Figure 3-25 Core outrigger cross-sections of supertall buildings

In [7, Lame Ali] the optimum location and number of outriggers is examined.
The characteristics of the building are described by the parameters alpha, beta and omega

- α represents the rigidity of the core with respect to the rigidity of the column
- β represents the rigidity of the core with respect to the rigidity of the outrigge.
- ω is the characteristic structural parameter which combines the previously mentioned α and β

$$\alpha = \frac{EI}{(EA)_c \left(\frac{d^2}{2} \right)}$$

$$\beta = \frac{EI}{(EI)_0} \cdot \frac{d}{H}$$

$$\omega = \frac{\beta}{12(1+\alpha)}$$

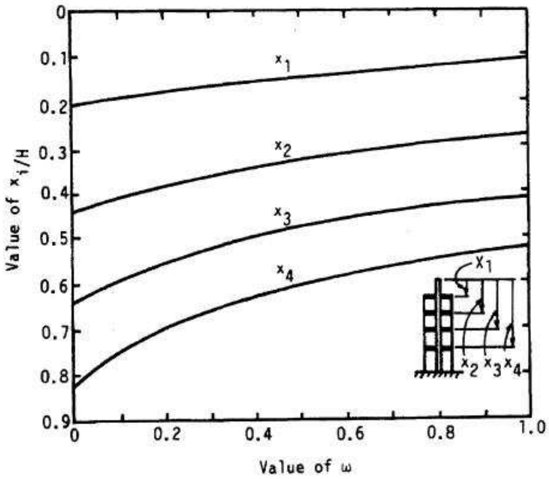

Figure 3-26 Optimal outrigger location [7]

where:

h is the height of the building
d the width/depth of the building
EI is the stiffness of the core
EI_0 is the stiffness of the outrigger
EA is the stiffness of the megacolumn

Note ω =∞ means that the outriggers are rigid.

Figure 3-28 and Figure 3-27 show that the increase from 3 to 4 outrigger has a smaller impact on the reduction of the drift and the base moment than the earlier jump from 1 to 2 and 2 two 3 outriggers. Therefore [7] recommends to use a maximum of 4 outriggers.

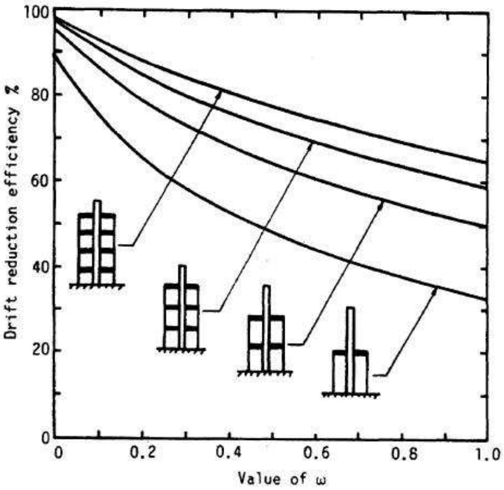

Figure 3-28 Drift reduction [7]

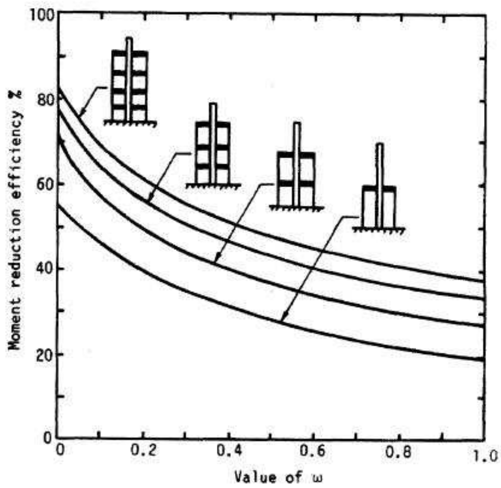

Figure 3-27 Moment reduction [7]

Compound structures

It is common to have outriggers in one building where their job is to connect the core to another core or perimeter columns. Outriggers however can also connect multiple buildings. By connecting individual towers a compound structure with voids and slots is created.
In such a compound structure, the individual towers each have their own load-bearing system and are connected with outriggers to form one structural entity. These outriggers are usually located in the skybridges and mechanical floors. However, unlike Petronas Towers where the skybridge (Figure 3-29) rests on a sliding joint they are used to structurally link multiple towers thus combining the strength of the two towers. In addition to their new structural characteristics their social function is also increased because they act as transportation hubs and public squares for the sky neighborhoods.

Figure 3-29 Petronas Towers and skybridge (no structural link)

The outriggers greatly increase the new compound or linked structures internal lever arm and create a very laterally stiff structure. Also the openings between the towers help mitigate the wind loads by allowing the wind to pass through the building.

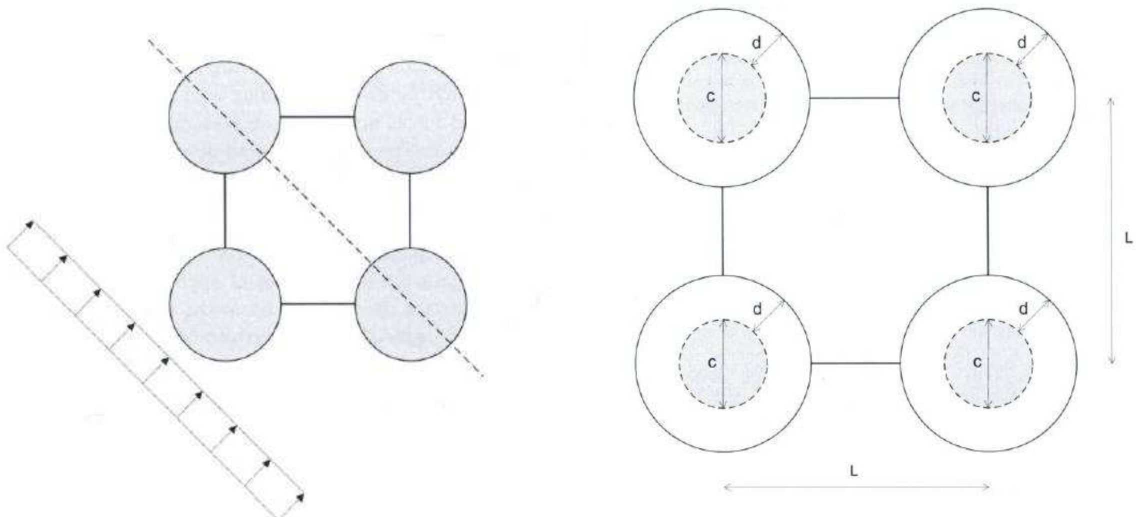

Figure 3-30 Schematic representation of a compound structure [4]

In [34] a wind model study was carried out at BTWTL to demonstrate how openings or gaps through a building (360 m) can reduce the across-wind response. A square cross-section with an aspect ratio of 9:1 without any changes such as tapering setbacks and changes in cross-section was chosen.
The cross-section had the following aerodynamic modifications:

- Along wind gaps (width D/6) located through the model centreline in plan.
- Across wind gaps (width D/6) located through the model centreline in plan.

The effects of these modifications can be summarized as follows;

- Introducing gaps results in a pronounced reduction of the vortex shedding induced forces and hence the across wind dynamic deflection of the building.
- A major reduction in the excitation and response occurs in the presence of the along-wind gaps which vent the wake to the positive pressure on the building's front face. The addition of identical gaps in the across-wind direction results in a further smaller response. Results indicated that across-wind gaps, if used alone, are not as effective as comparable along-wind gaps.
- Introducing the gaps shifts the spectral peak to a somewhat higher reduced velocity. This implies that the vortex shedding frequency is reduced below that of the unmodified geometry and resonant vibrations of the building are postponed to a somewhat higher wind speed.

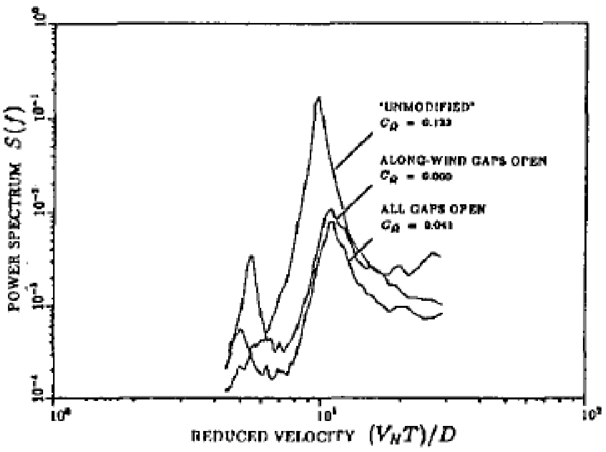

Fig. 1 Across-Wind Base Bending Moment Spectra From Balance Tests

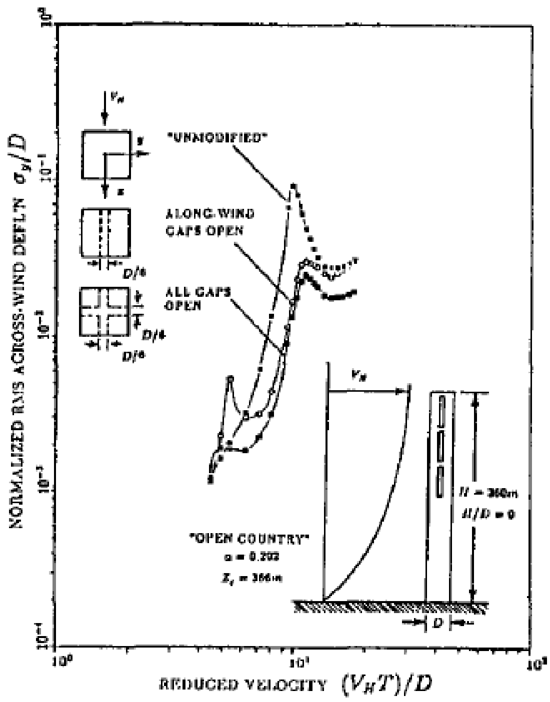

Fig. 2 Across-Wind RMS Tip Deflections From Force Balance Tests

Figure 3-31 Reductions due the addition of gaps in the building.

In [57] the effectiveness of aerodynamic response control for mitigating the across wind aerodynamic responses is described.

The conclusions are:

- It is evident that the presence of the gap reduces the across-wind response by disrupting the regularity of the vortex shedding process.
- For sectional configuration with along wind open passage the across wind response is surpressed since incoming air flow through open passage controls negative pressure region near the leeward wall.
- For sectional configuration with across-wind open passage the across wind aerodynamic response is less than without open passage but the aerodynamic damping effect tends to be weakened since air flow from the side wall prevents separated flow from reattaching and the width of the wake is widened.

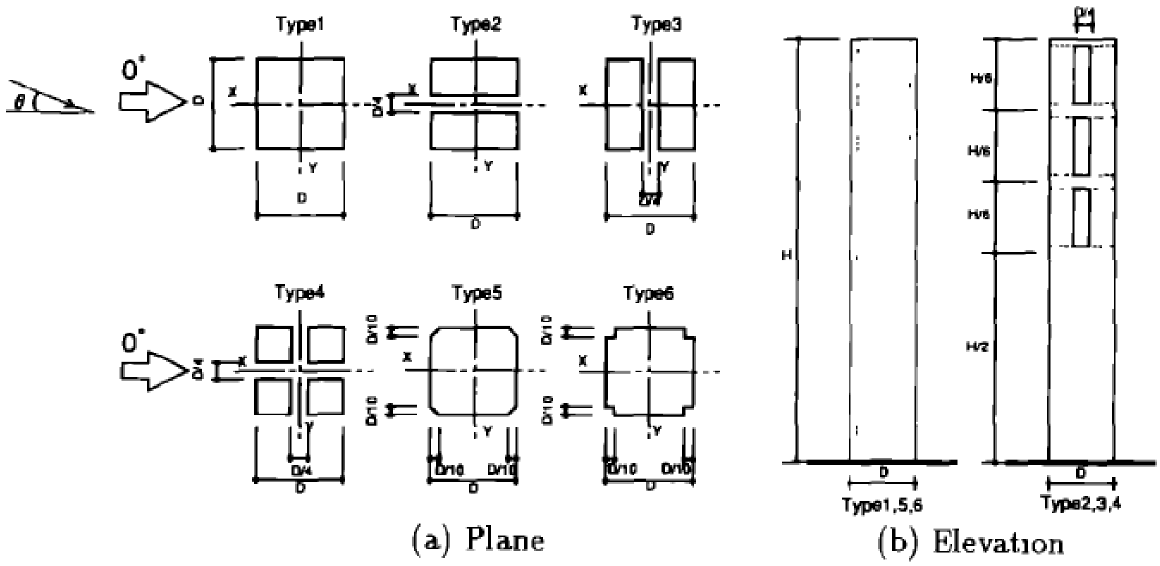

Figure 3-32 Tested cross sections and elevation

Besides increased lateral loads another problem arises as buildings get higher. Slender structures have smaller internal lever arms and are more susceptible to dynamic excitation. Therefore it makes sense to strife for a lower slenderness for higher buildings since a more robust structure is able to resist larger lateral loads and has better dynamic behaviour. This however is not feasible because a large part of the floor area will not be reached by natural daylight and therefore not lettable.
The World Trade Centre in USA (Figure 3-35) for example was a very robust high-rise structure. The floor print was 63.4 by 63.4 meter and with a height of 417 and 415 meters the slenderness was 1:6.6. Because of their large floor areas, the twin towers had office spaces which were never reached by natural daylight. Such a structure is not possible in Holland because the slenderness is limited by the fact that Arbo laws forbid office spaces which lack the entry of natural daylight.

Figure 3-35 WTC New York

Figure 3-34 Nakheel Tower

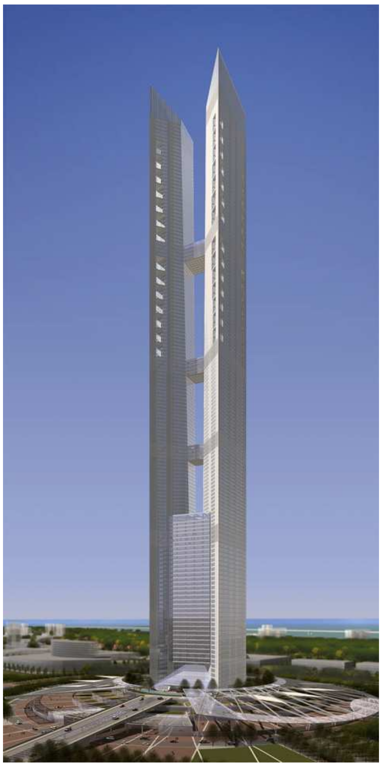

Figure 3-33 Incheon Tower

Because of this non-structural limiting factor in the design most supertalls have a slenderness ratio between 1:6 -1:8.

A possible solution is to taper the building which unfortunately results in loss of the most valuable floor area which is located near the top. A compound structure tries to solve this problem by adding voids which push the floor area of the structure to its perimeter.
In a compound structure the individual towers can be very slender allowing natural daylight to reach (most) of the floor area but at the same time the combined structure is very strong and robust which makes it possible to reach large heights and still comply with architectural demands.

Currently there are no completed supertall compound structures. But there are plans for a 600 meter high tower in Korea (Incheon tower, Figure 3-33) and a 1000 meter high tower in Dubai (Nakheel Tower , Figure 3-34).

Conclusion

The most suitable load-bearing structures are the ones which have a maximum internal lever arm. This can be seen in both the tube structures and core-outrigger systems where the buildings perimeter is used to transfer (part of) the lateral loads. However, unless they are tapered, these load bearings systems do not reduce the lateral loads on the building like a compound structure does by allowing the wind to flow through the building.

The compound structure is a very promising structural system as it provides a solution for the conflict between a maximum internal lever arm and the entrance of daylight.

It should be noted that even though most literature prefers trussed tube structures over core-outrigger systems, there are relatively few tube structures being built in practice.
At the time of writing this thesis there is only one tube structure in the top 10 tallest buildings listed in Table 3-1 namely, Willis Tower. Willis tower was built in 1972 and uses a unique bundled tube system with no diagonals. The other 9 buildings are all a form of the core-outrigger system.
This can be attributed to the fact that the architect often wants no obstruction (diagonals or closely spaced columns) in the façade. Thus the choice for a load bearing system is not only dependant on its structural behaviour.

nr.	Building	City	Height (m)	Height (m)
1.	Burj Khalifa	Dubai	828	Butressed core
2.	Taipei 101	Taipei	508	Core-outrigger
3.	Shanghai World Financial Center	Shanghai	492	Core –outrigger/ trussed tube
4.	International Commerce Centre	Hong Kong	484	Core-outrigger
5.	Petronas Tower 1	Kuala Lumpur	452	Core-outrigger
5.	Petronas Tower 2	Kuala Lumpur	452	Core-outrigger
7.	Nanjing Greenland Financial Center	Nanjing	450	Core outrigger
8.	Willis Tower	Chicago	442	Bundled tube
9.	Trump International Hotel & Tower	Chicago	423	Core -outrigger
10.	Jin Mao Building	Shanghai	421	Core-outrigger

Table 3-3 Top 10 tallest buildings 2009-2010

3.4 Floors

Introduction

A floor system primary goal is to carry the gravity loads during and after construction and acting as a diaphragm which transfers horizontal loads to the buildings core.

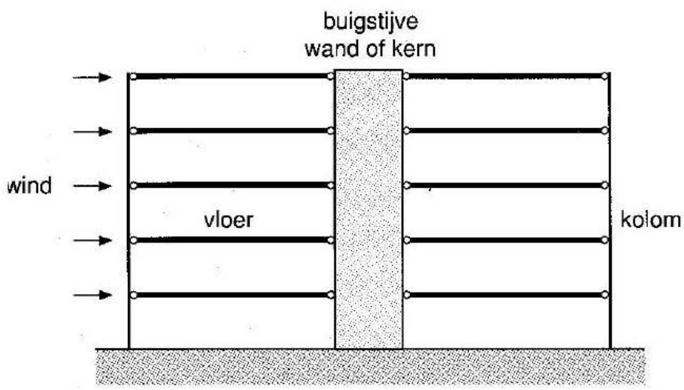

Figure 3-36 Wind load transferred to core

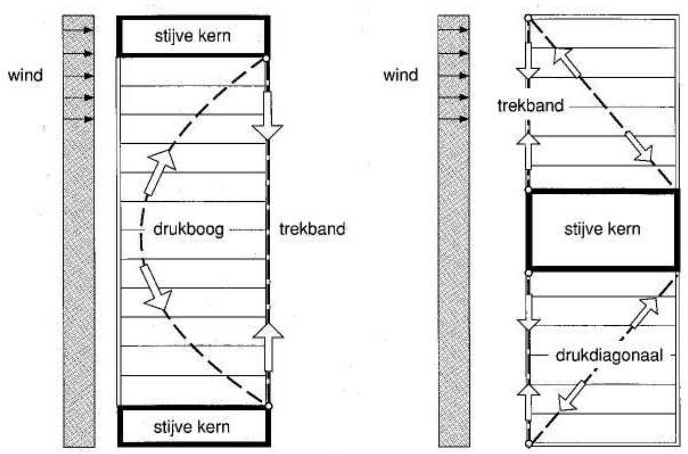

Figure 3-37 Diaphragm action floor elements

Secondly the floor system separates the vertical spaces so it should have fire-resistant and acoustic properties. The floor system also accommodates installations such as the heating, ventilating and air conditioning systems.

Important design aspects for floors are:

- Floor thickness
- Material use
- Costs
- Construction speed
- Flexibility (shape)
- Flexibility (installations)
- Fire safety
- Acoustics
- Vibrations

Because of their large share in a high-rise structure self weight, floors can take up a large part of the structural costs. It is therefore very important to choose the correct floor system since a reduction of the buildings ***dead load*** can have a considerable impact on the design of other structural members in the foundation and the superstructure. In very tall buildings a reduction in the floor thickness and storey height can even result in more floors for the same building height allowing for more rentable space.

Another consideration is the effect a floor system has on the ***erection process***

"The primary difference between a super-tall tower and two towers half its size is not the cost per square meter – it is the time it takes to build the tall one versus the two shorter ones, and

the loss of revenue through lost rent. This makes most super-tall buildings financially unfeasible." Adrian Smith, Principal, Adrian Smith & Gordon gill Architecture

Construction speed is an important factor for tall buildings and is heavily influenced by a choice of a floor system. The choice for prefab or cast in place concrete floors for example has a big influence on the planning of the erection process and the number of crane movements.

Cast-in-place floors are created by pumping concrete to great heights. Pumping is a very efficient and reliable means of placing concrete, which makes it a very economical method as well. Sometimes a pump is the only way of placing concrete in a certain location. Such as a high-rise building or large slabs where the chutes of the concrete truck can't reach where the concrete is needed.
Other times the ease and speed of pumping concrete makes it the most economical method of concrete placement which uses a concrete pump and pipelines to transport concrete, with great transmission capacity, high speed, high efficiency, savings in manpower and continuous operation. Because of these reasons pumping technology has become the most important method in super high-rise building construction.
Prefab concrete floors require a large amount of crane movement and become uneconomical for supertalls.

A new high-rise building means that in a short amount of time a large amount of floor area becomes available on the real estate market. Selling and renting such a huge amount of square meters is not easy. And when all the square meters are rented or sold changes in the populations living habits and financial market can cause the real estate market to change.
In order to cope with such changes the client often wants a certain ***flexibility*** which enables him to adapt the building to these changes.
Flexibility can be obtained by designing certain stories of a building to have interchangeable functions. The ability to remove walls and turning offices spaces into residential areas and vice versa for example can offer the client solutions for future changes.
Different functions in a mixed used building however all have their own optimal spans, grids and different demands regarding sound insulation, storey height and live loads. Each function characteristics are all influenced by or related to the chosen floor system.
A choice in floor system also has a direct relation to the flexibility of building plans because the architectural lay-out i.e. the positioning of walls and columns or plan shape is influenced by its floor system.

The floor system should also have sufficient ***fire resistance*** and ***acoustic*** properties which can require a certain mass or multilayered system.

3.4.1 Cast in place

Flat slab floor

A flat-slab floor (Figure 3-38 d) can have a span of 8.5-9.5 m and is usually 280-320 mm thick. The concrete in these flat slabs significantly increases the total weight of the structure. The smooth girder free underside provides optimal arrangement of necessary installations. Also a suspended ceiling can be left out so that installations are directly fixed to the slab underside. Because of this the floor can be used to help stabilize the buildings heat flow

Floors with reinforced concrete joists

The use of joist can reduce the thickness and total weight of the floor. This type of floor however, requires a longer time to mount and cast concrete because of the addition of a beam which make extra formwork and additional reinforcement cages are necessary.
Figure 3-38 a and b show a one way an two way joists floor system

Floors with reinforced concrete suspender beams

A reinforced concrete floor with suspender beams is shown in Figure 3-38 e. This system combines the advantages of a smooth (slab floor) underside with a reduction of thickness (joists)
Installations can be placed between the beams and at the beam ends (lengthwise)

Prestressed concrete floors

Prestressing can be used in order to achieve longer spans than 9 meter. Prestressed floors can have a slenderness of L/40 so a 12 meter span with 300 mm thickness is possible.

These conventional cast-in-place floor systems are relatively heavy and thick. Because of this composite and prefab floor systems where developed with the aim of reducing the storey height and self-weight.
These reduction are achieved by integrating installations in the floor and adding of voids to concrete slabs

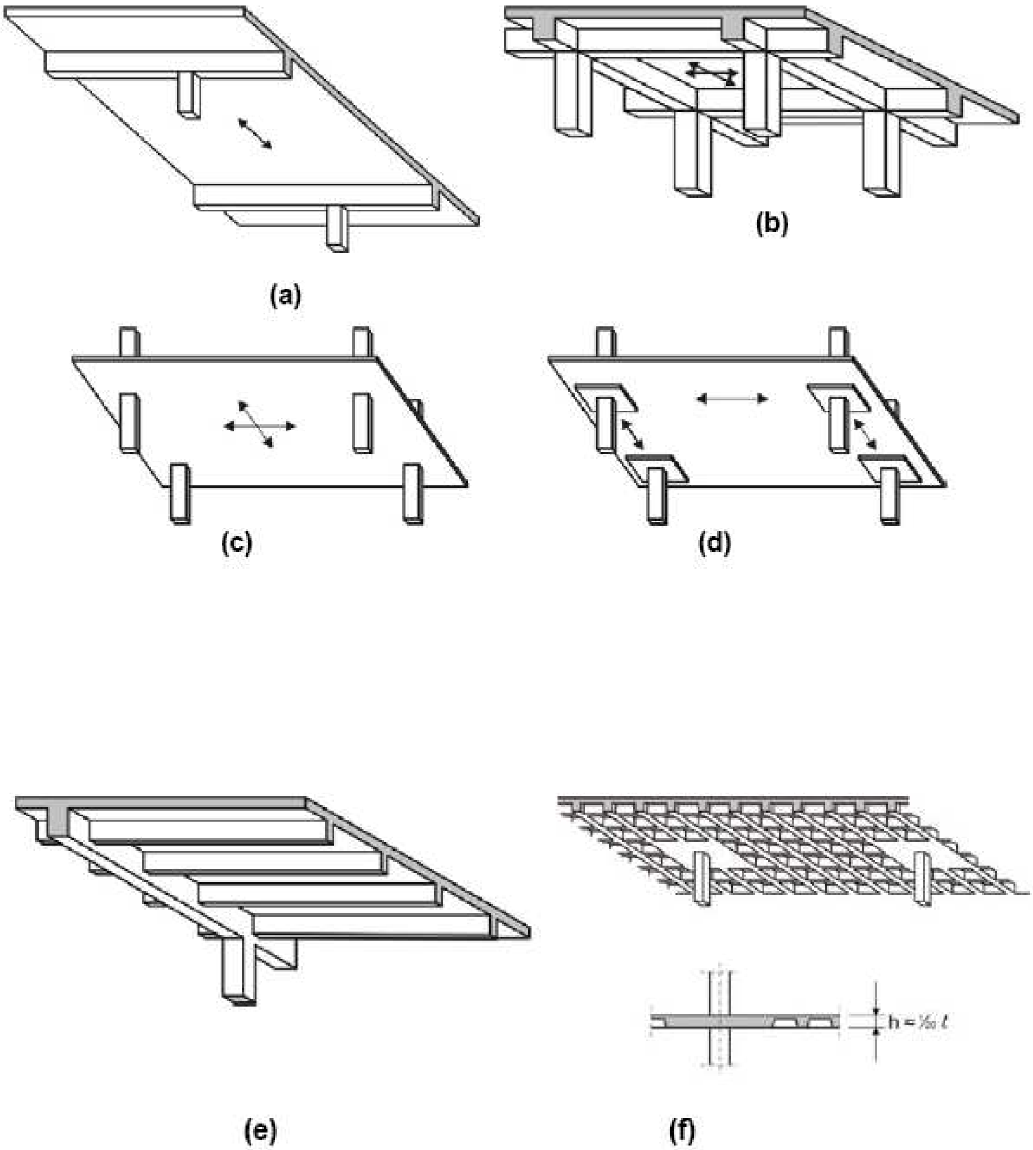

Figure 3-38 Floor-systems

3.4.2 Composite floors

Composite floors combine the structural advantages of different materials. Steel and concrete composite floors are most common but composite floors consisting of cast concrete and precast concrete are also possible.
Composite action is normally achieved by welding shear studs through the steel decking and onto the top of the beams before pouring the concrete. The shear connectors provide sufficient longitudinal shear connection between the beam and the cured concrete so that they act together compositely. Together composite slabs and beams produce structurally and resource efficient flooring systems for a range of applications.

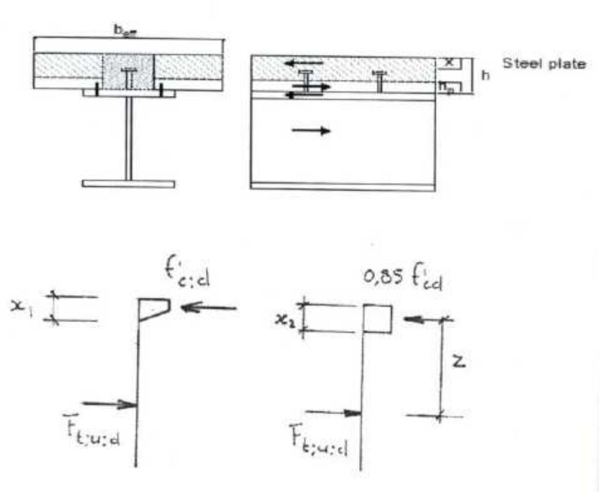

Figure 3-39 composite floor

Steel-concrete floor

Traditional steel-concrete composite floors consist of rolled or built-up structural steel beams and cast in-situ concrete floors connected together using shear connectors in such a way that they would act monolithically. The principal merit of steel-concrete composite construction lies in the utilization of the compressive strength of concrete slabs in conjunction with steel beams in order to enhance the strength and stiffness of the steel girder.
Fast erection is possible due to the steel deck which can serve as a working platform. The disadvantage for this type of floor is that cost are higher.

Figure 3-41 composite floor

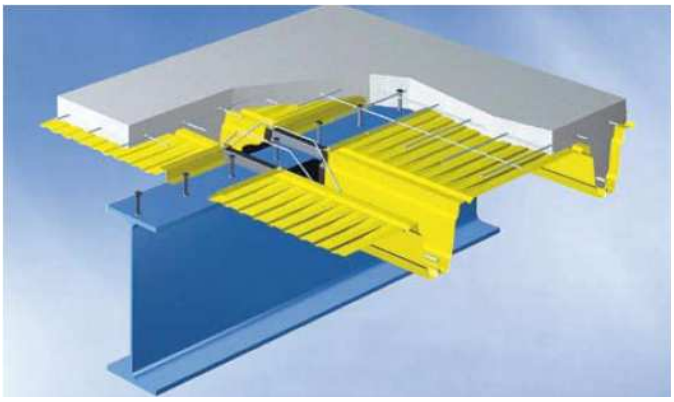

Figure 3-40 composite floor

Conclusion

The choice in floor system is heavily influenced by non-structural considerations such as their effect on the erection process fire-resistance and acoustic demands.

As mentioned earlier the erection process is an important factor in the design of a supertall building. The faster the erection the sooner the client can start renting and selling square meters on the real estate market. Floor systems such as hollow core slabs, bubbledeck and slimline which require many crane movements are therefore not suited for supertalls. Cast in situ concrete floors are heavier but much more feasible since concrete can be pumped up to great heights. Composite floor systems consisting of steel beams and steel profiled sheets connected to concrete by means of shear studs uses less crane movements than precast concrete floor systems.
Steel decks and steel beams can be lifted to great heights in bulks using a crane where the steel deck can be used as a working platform. After assembly the concrete is poured using pumps. Thus a composite floor is able to reduce the dead load and ensure a feasible erection method.

3.5 Dynamics and wind-induced behavior

3.5.1 Introduction

Besides gravity loads buildings are also subjected to time varying dynamic loads such as wind and earthquakes. Static loads like self-weight and snow are applied relatively slow and do not change direction or size. Dynamic loads however change size and direction and can be applied very quick.
Because of their complexity it is often hard to determine the exact nature of dynamic loads and how the structure will behave under its influence. The frequency of earthquakes lies between 1 and 10 Hz and frequency of the wind lies between 0.01 and 1 Hz. Because tall buildings usually have an eigenfrequency below 1 Hz they are more susceptible to wind loads. Since the building will not be located in an earthquake-prone region the dynamic effects off earthquakes will not be discussed in this thesis.

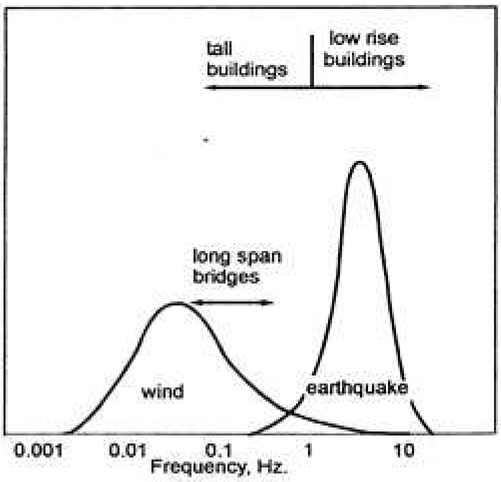

Figure 3-42 Eigenfrequency tall buildings

3.5.2 The Wind loading-chain

Wind plays a dominant role in the structural design of a high-rise structure. Vertical loads caused by the structure self weight and live loads increase almost linearly with the buildings height. The wind moment at the base of the structure increases exponentially along the height of the building $\left(M = \frac{1}{2}qh^2\right)$. The Horizontal displacement of a building $\left(u = \frac{qh^4}{8EI}\right)$ is related to its height to the fourth power.
Therefore a non-linear increase of material use is needed in order to comply with ultimate and serviceability limit states. In order to design an efficient and economic structure, knowledge of the nature and effects of wind loads, the influence of the buildings parameters and structural system is necessary.

The wind loading chain gives an overall picture of the aspects which play a role when designing a high-rise building.

Global wind climate: ***Wind speed in the open field.***
Local wind climate: ***Topographic terrain roughness neighbouring buildings.***
Aerodynamic response: ***Wind flow around the building and the resulting pressure suction and friction.***
Structural response: ***Stresses deformations accelerations acting on the building.***
Criteria: ***Allowable stresses deformations accelerations.***

*The global and local wind climate*s define the wind environment and are dependent on the buildings location.
The aerodynamic response describes how the wind is transformed into loads acting on the building. The most important parameters are the shape and size of the building
The way the structure behaves under the dynamic wind loads is called the *structural response* and gives the stresses, deformations and accelerations acting on the building. These can be calculated with structural mechanics and should comply with the *criteria* found in the national building codes.

3.5.3 Global and local wind climate

Wind is a very complex phenomenon and is a result of the movement of air caused by thermal and pressure conditions in the atmosphere. The wind-motion is turbulent making a concise mathematical definition difficult. Wind has a very low viscosity (1/16th of water) which causes particles of air to move in all directions at speeds greater than 0,9 -1.3 m/s.

For structural engineering purposes we consider the wind vector in one point the sum of two vectors, namely:

- A static component(mean wind)
- A dynamic component (turbulence)

<u>Mean wind speed</u>

The wind velocity at a certain height above the ground is constant. This is the gradient wind speed Ug where frictional forces are negligibly small. Near the ground the wind speed is varies because of friction caused by the terrain. The height of this boundary layer is called the gradient height and depends on the terrain roughness.

Turbulence

Strong wind contains turbulent fluctuations and wind gusts. Turbulence is the result of wind blowing over obstacles the generated eddies.

3.5.4 Aerodynamic Response

The motion of tall buildings occurs primarily in three components, namely :

- along-wind motion
- across-wind motion
- torsional motion

Along-wind motion

Along-wind is the term used to refer to drag forces where a structure experiences an aerodynamic force which has the same direction the wind (Figure 3-43). The structural response induced by the wind drag is referred to as the along-wind response. The along-wind motion is the result of pressure fluctuations on windward and leeward face.

Across-wind motion

The term across-wind (Figure 3-43) is used to refer to transverse wind or wind forces in the plane perpendicular to the direction of wind. In the design of most modern tall buildings, the across wind response is the governing design aspect. Supertalls with high slenderness and flexibility can undergo large across-wind responses.
[9] states that while the maximum lateral wind loading and deflection are usually observed in the along wind direction, the maximum acceleration of a building loading to possible human perception of motion or even discomfort may occur in across wind direction.

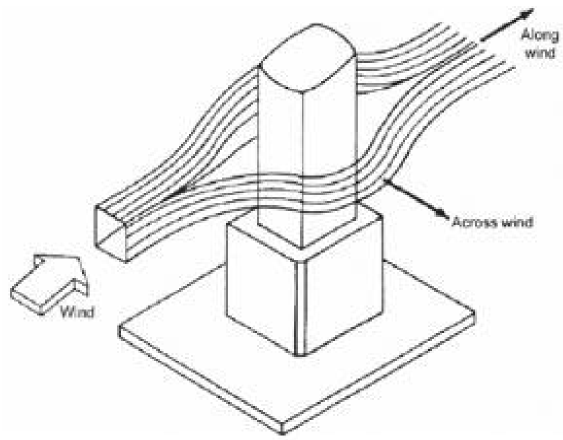

Figure 3-43 Along and Across-Wind

Vortex shedding

Vortex shedding is caused when a fluid flows past a blunt object. The fluid flow past the object creates alternating low-pressure vortices on the downstream side of the object. The object will tend to move toward the low-pressure zone.

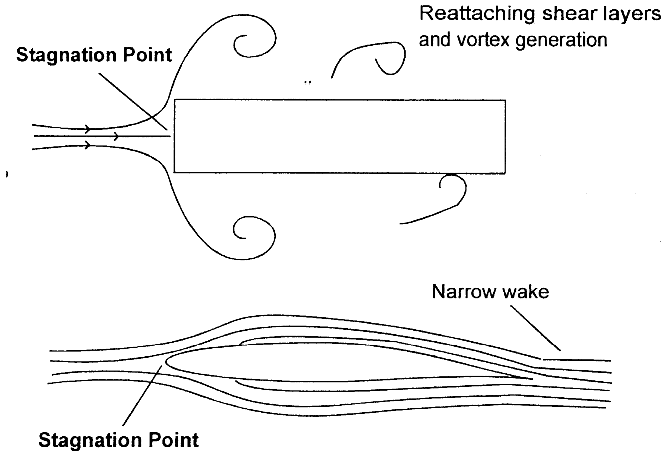

Figure 3-44 Bluff and streamlined body aerodynamics.

Vortex excitation is one of the critical phenomena that affects tall slender towers by causing strong fluctuation forces in the crosswind direction. It is probably the main behaviour that distinguishes tall towers from mid-rise buildings. Equation (1) gives the frequency *N* at which vortices are shed from the side of the building, causing oscillatory across-wind forces.

$$N = S \cdot \frac{U}{B} \qquad (1)$$

Where:

U is the wind speed.
S is the Strouhal number.
B is the buildings width.

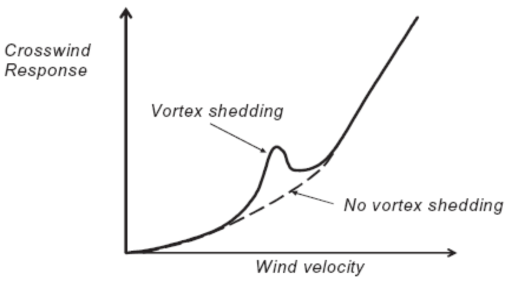

Figure 3-45 Across-wind Response

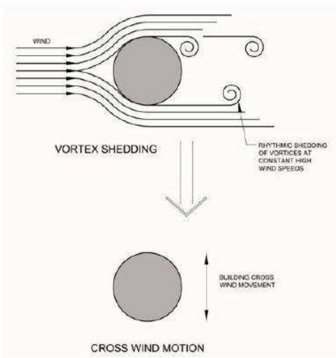

Figure 3-46 Vortex Shedding

The Strouhal number is a constant with a value typically in the range 0.1–0.3 and depends on the towers shape and on the Reynolds number.
For a square cross-section, it is around 0.14 and for a rough circular cylinder it is about 0.20. When *N* matches one of the natural frequencies N_r of the building, resonance occurs which results in amplified crosswind response, as illustrated in Figure 3-45. From Equation (1) it becomes clear that this will happen when the wind speed is given by:

$$U = \frac{N_t \cdot B}{S} \quad (2)$$

The peak in the response in Figure 3-45 can be moved to the right on this plot if the building's natural frequency is increased, and if it can be moved far enough to the right the wind speed where the peak occurs will be high enough that it is not a concern. This is the traditional approach of adding stiffness, but this approach can become extremely expensive if the peak has to be moved a long way to the right.
However, the height of the peak is sensitive to the building shape and, with clever aerodynamic shaping, the peak can be substantially reduced or even eliminated. Possible measures which can be used are discussed in the following paragraph.

At low wind speeds, the vortices are shed symmetrically (at the same instant) on either transverse side of the building and building does not vibrate in the across wind direction. On the other hand, at higher wind speeds, the vortices are shed alternately first from one and then from the other side. When this occurs, there is an impulse both in the along wind and across wind directions. The across wind impulses are, however, applied alternatively to the left and then to the right.

Other dynamic excitations are buffeting, flutter and torsion. Torsion occurs when the building is loaded asymmetrically. However not only the torsion stiffness of the building is important but also the torsion frequency which should not resonate with the frequency of the wind loading. Turbulence buffeting arises from fluctuations in wind speed and directions.

Influencing the dynamic behaviour of the building

Since the governing lateral load on supertall is wind, the aerodynamics of a tall building have a huge influence on its structural behaviour. The lateral loads on a building do not only require a need for structural integrity but also involve the challenge of keeping the structures deformation and acceleration within the limits. Making sure that the motions of the tower are within acceptable limits is often a bigger challenge than meeting strength requirements. Because of this it is recommended to consider aerodynamics early in the design.

There are four ways which allow the engineer and architect to control the dynamic response of a building, namely:

- changing its mass
- changing its stiffness
- increasing its damping
- choosing its shape

Changing the Mass and stiffness.

Stiffening the building sufficiently can force the resonant speed in eq (2) above the top end of the design range. This is however a very costly and impractical solution for super tall buildings.

Another approach is to increase the buildings mass. The buildings amplitude of motion tends to vary with inversely with the Scruton number :

$$Sc = \frac{2m\delta}{\rho\beta^2} \qquad (3)$$

where,

m = the generalized mass per unit
δ =logarithmic decrement of damping
ρ = air density
B = building width

Increasing the mass of the building can reduce the displacement of the building. For the same building stiffness this solution can yield a longer sway period. However, this solution which is straightforward can also be very costly when significant improvements are necessary. Also fundamental dynamics prove that increasing in stiffness will provide reductions in the amplitude of motion, but will not affect accelerations which comprise the stimulus for motion perception. Furthermore by stiffening the structure, the jerk component, another contributing factor to motion stimulus, may increase.

Increasing the structures damping

A tall tower under the action of wind tends to act as an energy storage device. The fluctuating wind forces cause the tower to move and the motions gradually build up, alternately exchanging kinetic energy with stored elastic energy as the building sways. A supertalls ability to resist these motions is determined by the ability of the tower to dissipate energy faster than the rate at which the wind feeds energy in. A measure of the tower's energy dissipation ability is its damping ratio and the higher the damping ratio, the better the a supertall is at dissipating energy.
The evolution of the structures of tall buildings has been towards efficiency. Nowadays high strength materials are often used in supertalls. High strength steel for example has (nearly) the same modus of elasticity regardless of the strength of the steel and while the modus of elasticity does increase for high strength concrete, the increase is relatively smaller than the increase in strength. Thus tall buildings are now lighter than earlier ones causing structural motion problems due to wind.

From the scruton relationship in equation (3) it can be seen that another way to decrease the amplitude of the wind exited motion is to increase δ. This leaves the vortex shedding within the design range but can suppress the sway motion of the building to a more acceptable level. The increase in damping causes the building to bleed energy out of the motion fast enough to counteract the energy caused by vortex shedding.
There are two ways to increase damping of a supertall, namely:

- Distributed damping
- Mass damping

Distributed damping is applying many energy dissipating devices throughout the building reducing the buildings response to dynamic excitation. Viscous dampers which can be placed in the structural frame of the building have proven to be very effective for distributed damping.

Mass damping systems concentrate the damping in one or two locations. The most effective location for a mass damping system is close to the area of peak amplitude of vibration, which is typically near the top of the building. There are two types of mass damping systems, namely:

- Tuned Mass Damper (TMD)
- Tuned Liquid column Damper (TLCD)

A ***Tuned Mass Damper*** is connected to the building through a suspension system allowing it to move freely. It is also connected to the building by large shock absorbers (dashpots). When the building undergoes wind-induced oscillation the TMD moves out of phase with the buildings swaying motion. This causes the dashpots to convert part of the buildings kinetic energy into heat, reducing the buildings oscillation. In order for this system to be effective both the TMD and the building need to start oscillating simultaneously. This means that the eigenfrequency of the damper should be close to the eigenfrequency of the building.

When designing a TMD it is necessary to limit its motions so that it mass does not damage the building structure when exposed to very high wind loading. This is done by installing nonlinear hydraulic dampers and hydraulic buffers around the mass block.

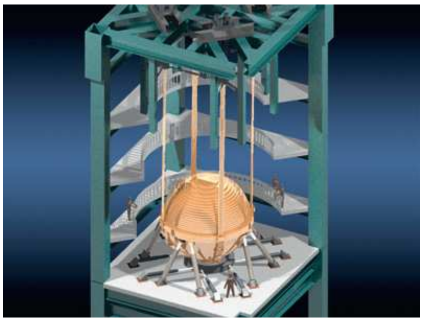

Figure 3-48 TMD Taipei 101

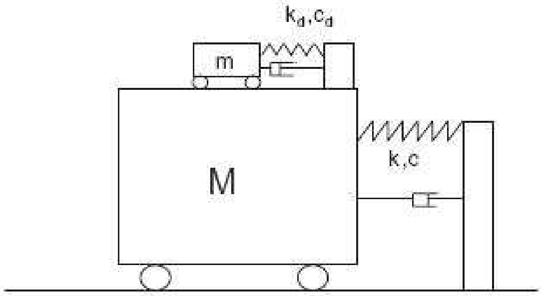

Figure 3-47 Tuned mass damper

The tuned mass damper principle is illustrated in Figure 3-47, where:

M is the mass off the building.
K is the buildings stiffness.
C is the viscous damping of the building.
m_d is the mass dampers mass.
k_d *and* c_d are the stiffness and the damping of the suspensions system which connect the TMD to the building.

At the time of writing this thesis the Taipei 101 in Taiwan is the second tallest building in the world and has a height of 508 meter. The building is located close to major fault line in Taiwan meaning the tower could be subjected to earthquakes, fierce winds and also typhoons. For these reasons a 730-ton tuned mass damper (Figure 3-48) was installed to counteract the buildings movement. By acting like a giant pendulum, the building's movements due to wind are reduced by 30 to 40 percent.

Tuned Liquid column dampers use water or other liquids. The system consists of two vertical columns and a horizontal connection. The columns contain water and have their own natural period of oscillation depending on their geometry. When the water passes through the horizontal connection which contains a screen sluice gates energy is dissipated which reduces the lateral movements of the building.
An advantage of this system is that the TLCD system can be combined with the water supply for fire suppression. Water tanks are usually already incorporated in the design for fire extinguishing. In such cases choosing a TLCD over a TMD is beneficial because there will be no increase in vertical loads because the loads from the water tanks are already incorporated in the design. The Comcast Center in Philadelphia contains the largest tuned liquid column damper in the world at 1,300 tons. (Figure 3-49)

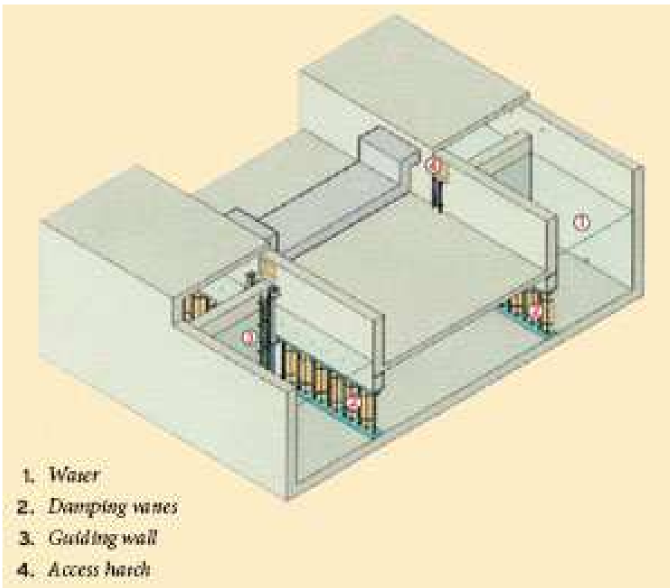

Figure 3-49 Worlds largest TLCD in Comcast Center

Changing the buildings' shape

The shape of supertall is usually determined by the architect and has a large influence on the behaviour of a tall building. It is therefore highly recommended to consider the influence the shape has on static and dynamic behaviour of the building early in the design. However if the shape has been fixed there are still ways to improve the wind induced behaviour of the building.

Possible improvements are:

- corner modifications
- tapering and setbacks
- varying the cross section
- applying spoilers
- porosity and openings
- rotating or adding twists

Corner modifications

Buildings often have a square and rectangular shape which experience relatively strong vortex-shedding. By modifying the corners through chamfering stepping and rounding this effect can be reduced. The stepping of corners in the Taipei 101 (Figure 3-52) for example, resulted in a reduction of 25% of the base moment. Several corner modifications are shown in Figure 3-50.

Tapering and setbacks

For a certain wind speed the vortex shedding varies according to the Strouhal number and the width of the building "b". If the shape of the building can be varied along its height through tapering or setbacks the vortices will become confused and incoherent as a result of trying to shed at different frequencies at different heights.
An example of a tapered structure is the Millennium Tower (Figure 3-53b). Setbacks were used in the Burj Dubai (Figure 3-53a).

Varying cross section

This is the same concept as tapering and setbacks. The vortices become confused at different heights with different frequencies.

Spoilers

This principal is used in chimneys to reduce the vortex shedding. The most well-known spoilers are so called spiral scruton strakes seen in Figure 3-51. These are not very practical for most buildings but vertical fins are a more practical alternative.

Porosity and openings

By allowing the air to flow through the structure the wind load is reduced and the effects of vortex shedding are weakened. Examples are the Shanghai Financial Centre (Figure 3-53c) and Incheon Tower (Figure 3-53d).

Rotate, ad twist

An interesting trend in modern tall building design is twisted forms. This twisted form can be found again in today's tall building designs such as the Turning Torso in Sweden and the proposed Chicago Spire Project in Chicago designed by Santiago Calatrava (Figure 3-53f).
A twisted or rotated structure can prevent the wind load from prevailing in one direction and avoid simultaneous vortex shedding along the height. This principle is also applied in the design of the Shanghai Centre (Figure 3-53e).
In terms of static response, twisted forms are not beneficial.

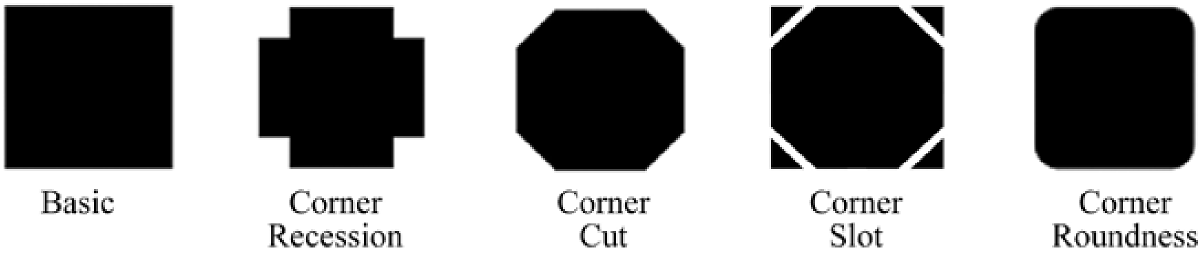

Figure 3-50 Examples of corner modifications

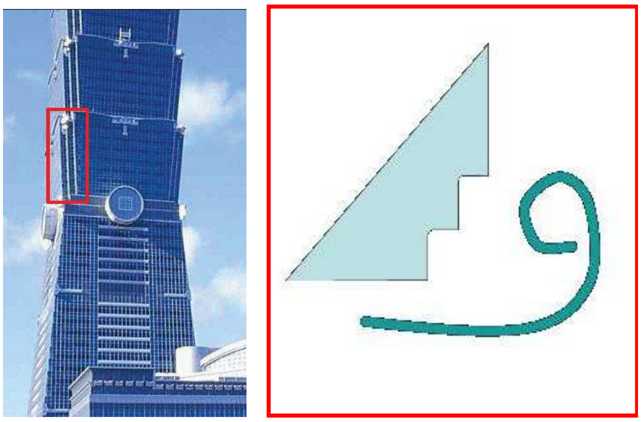

Figure 3-52 Taipei 101 corner modification

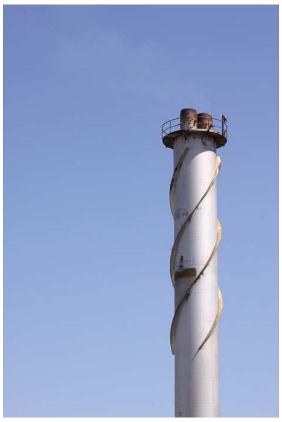

Figure 3-51 chimney spoilers

(a) **(b)** **(c)** **(d)** **(e)** **(f)**

Figure 3-53 Examples of wind-reducing building shapes

3.5.5 Structural response and Criteria

Wind loads on the structure

Design loads caused by the wind needed to design the structural system. The basic design criteria stability, strength and serviceability should be satisfied.
Stability means that the building can resist overturning uplift and/or sliding
The strength criterion is satisfied when all the structural components are able to withstand the imposed wind loads without failure during the life time of the structure. The deflection and motions of the building have to remain in acceptable limits. The serviceability criteria make sure that there is limited damage to the structure crack and that the human comfort criteria are not exceeded.

In the international community the negative experience due to wind-induced motion is tested using two criteria for acceleration, namely:

- Peak acceleration
- RMS acceleration (root mean square)

In the RMS method it is assumed that the negative experience due to the buildings movement is the result of sustained or ongoing motion which is described by an average effect over a period of time. The peak acceleration assumes that the negative experience due to the buildings movement is the result of large events (peaks). The RMS index is often favored due to its easy measurability and predictability. It offers a more accurate means of combining response in different directions based on their respective correlations. Advocates of peak acceleration argue that the peak resultant accelerations are difficult to estimate using RMS criteria (Isyumov 1993).
In the Netherlands there are two regulations which can be used for the comfort criterion, namely: NEN 6702 and ISO 6897.

NEN 6702 shows the limiting peak in a graph with two curves. Curve 1 applies to floors with industrial, office or educational function. Curve 2 applies to floors with a residential, gathering, health care, hotel sport or commercial function. This standard uses the peak acceleration as the limiting criteria.

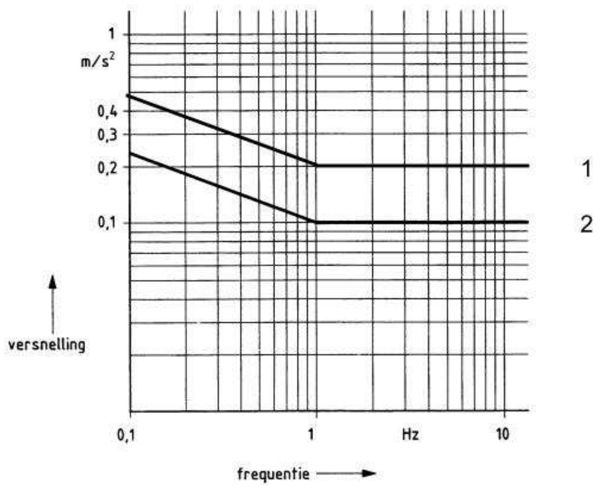

Figure 3-54 Peak acceleration according to NEN 6702

ISO 6897 is the international standard which uses the RMS index as the limiting criteria. Acceleration limits are given for natural frequencies between 0,063 and 1 Hz.

Along-wind accelerations

A calculation of the buildings acceleration is usually done by testing a scale model in a wind tunnel. NEN 6702 gives a simplified equation to determine the along-wind accelerations.

$$\alpha = 1,6 \cdot \frac{(\rho_2 \cdot p_{w1} \cdot C_t \cdot b_m)}{\rho_l} \tag{5}$$

Where

ρ_2 factor dependant on the eigenfrequency and damping of the building
$p_{w,1}$ variation in thrust on the building in N/m
C_t summation of the wind factors for thrust and suction 1.2
b_m the average width of the building
ρ_l mass of the building per metre building height

$p_{w,1}$ is given by

$$p_{w1} = 100 \cdot Ln(\frac{h}{0,2}) \tag{6}$$

where

h is height of the building
ρ_2 is given by equation below

$$\rho_2 = \sqrt{\frac{0,0344 \cdot f_e^{-2/3}}{D(1+0,12 \cdot f_e \cdot h)(1+0,2 \cdot f_e \cdot b_m)}} \tag{7}$$

Where

f_e eigenfrequency of the building in Hz
D damping factor
h height of the building
b_m average width of the building

To calculate the natural frequency of the building NEN 6702 gives the following formula

$$f_e = \sqrt{\frac{a}{\delta}} \tag{8}$$

a is a value dependant on the distribution of the mass of the building 0.384 m/s^2.

Across-wind accelerations

The complex nature of the across wind loading which results from an interaction of incident turbulence, unsteady wake effects and building motion makes predicting the across wind vibrations of a tall building very difficult. For this reason the across-wind accelerations are usually determined using a wind tunnel. The NBCC (National Building Code Canada gives a formula based on a wide range of turbulent boundary layer studies which can be used to determine the peak acceleration at the top of supertall.

$$a_w = f_e^2 g_p \sqrt{WD} \left(\frac{a_r}{\rho_B g \sqrt{\beta_W}} \right) \tag{9}$$

Where:

f_e is eigenfrequency of the building Hz
g_p is peak factor
W is the average width of the building in m
D is the average Depth of the building in m
P is average density in kg/m^3
g is acceleration due to gravity
β is the structural damping

$$a_r = 78,5 \cdot 10^{-3} \left(\frac{V_H}{n_w \sqrt{WD}} \right)^{3.3} \tag{10}$$

Where:

f_e is eigenfrequency of the building in Hz
b_m is the average width of the building in m
v_h is the mean wind speed at the top of the building

Wind loads on the facade

Determining the wind pressures on the surface are of the building in order to design the cladding system. Wind tunnel test have become the standard for designing the facade with the aim of reducing the initial capital cost and avoiding expensive maintenance cost later on

Environmental wind studies.

Investigating the wind effects on the surrounding structure pedestrians and motor vehicles

3.6 Vertical transportation

Tall buildings are possible because of elevators and the core which contains the vertical transportation functions as the buildings artery and is also it structural backbone.

In a tall building a compromise has to made between ensuring a functional building and keeping the area lost by vertical transport to a minimum. Therefore a special vertical transport expert is often part in the initial design phase.
Important aspects to be considered when the designing the vertical transport for a supertall are:

- Population (inhabitants /employees)
- Population density
- Peak (which traffic peak is governing)
- Height of the building
- Distribution of the functions in the building
- Distribution of the population in the building
- Distribution of the population in different elevator groups

Usually in elevator planning for a new building, the up-peak traffic is used to define the number of elevators, their sizes and speeds. Recommendations for the handling capacity and interval vary according to building type.
For the up-peak analysis, the number of floors and entrance floors, floor heights, and the population on each floor are defined. Elevator round trip time (RTT) is calculated according to the number of probable stops during an up peak.

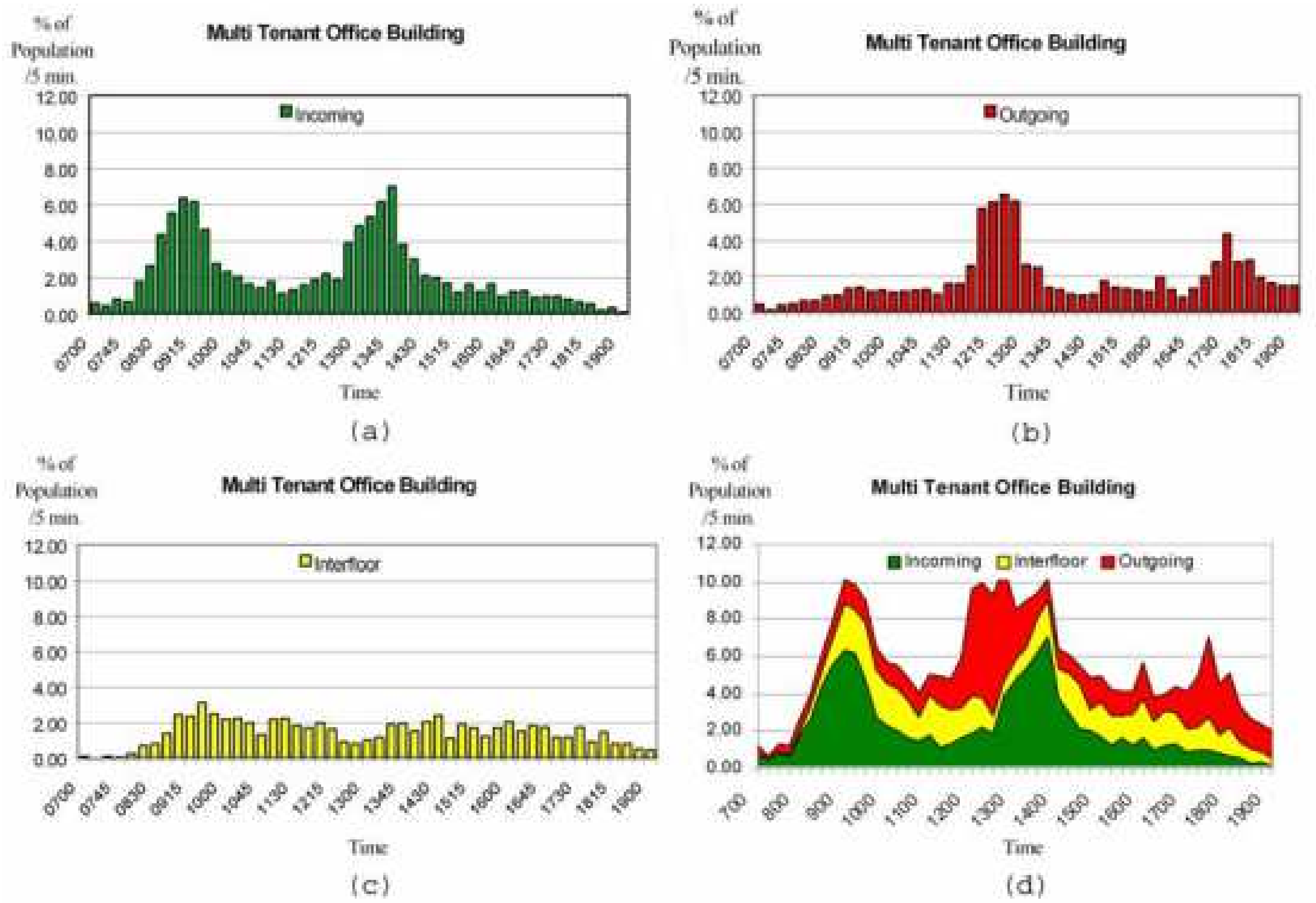

Figure 3-55 Up peak graphs for an office building

A 200-story tower will most likely be designed multiple sky lobbies that are to be serviced by double-deck shuttle lifts. Utilizing sky lobbies and their shuttles, multiple local zones of lifts may be stacked on top of one another, significantly reducing the number of lift shafts that penetrate the building's lower floors(see Figure 3-58).

Figure 3-56 double decker lift Midland square, Nagoya

Figure 3-57 double decker lift- Midland square,Nagoya

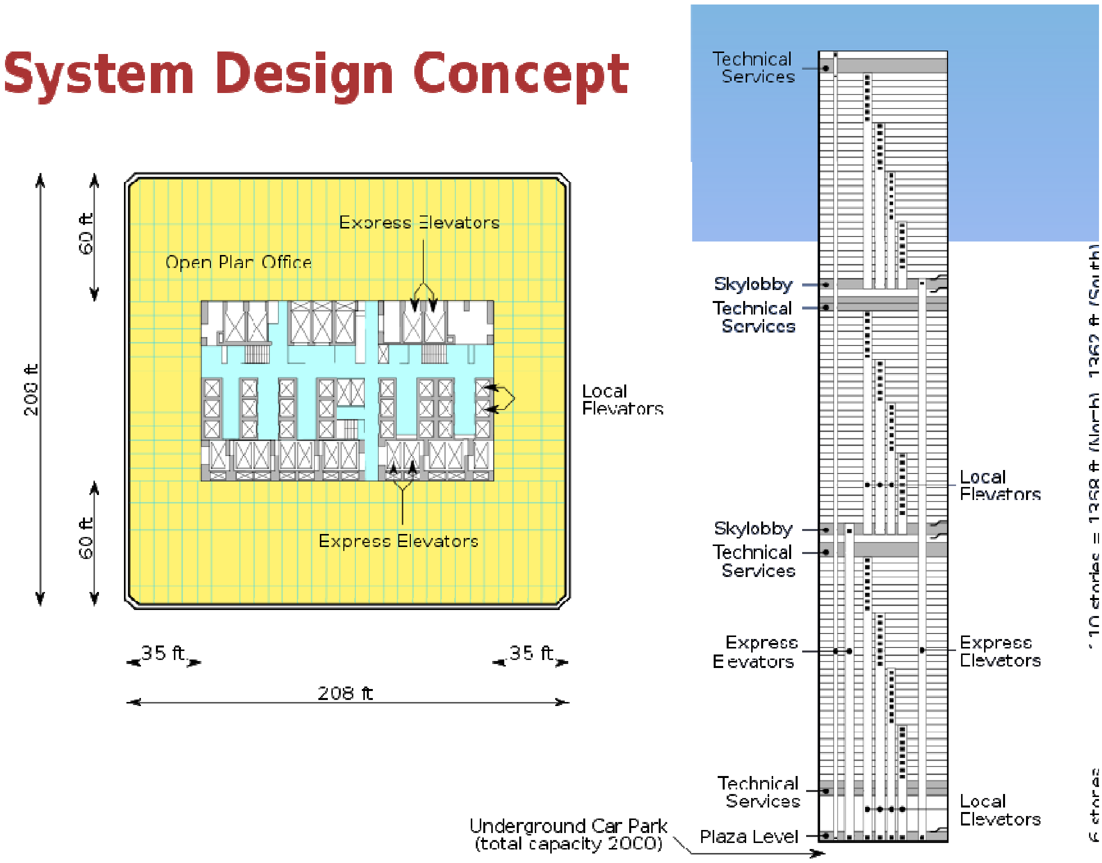

Figure 3-58 WTC Stacked lifts system

3.7 Reference projects

3.7.1 Introduction

High-rise was originally built so that a large number of living or office spaces can exist on a smaller piece of land. In populated dense cities, land can be expensive and scarce therefore it might be better to build up rather than outward on the ground. In the birth place of high-rise, Chicago, building vertically was not for show but a necessity due to lack of available land.

Lacks of available land, dense cities and increasing population have led to the concept of the vertical city. In this concept people can live, work and recreate in a tall building. This concept has inspired great architects such as Le Corbusier and Frank Lloyd Wright.The Burj Dubai was actually inspired by Frank Lloyd Wright's mile high tower (the Illinois). This tower was a theoretical building which he designed in 1920s consisting of five vertical zones of 100 stories each. It was designed to be 1,609 meters tall with 528 stories, a gross area of 1.71 million square meter and aimed to provide a solution to the ever-sprawling city of Chicago. Le Corbusier also designed a "Vertical City"(1946-52) in Marseille, which was 340 villas with shops raised above the ground on pilots and a roof garden gymnasium.

Other visions are the Bionic Tower in Shanghai designed by Celaya, Pioz & Cevera Architects, Sky City 1000 in Tokyo and Holonic Tower developed by Takenaka Corporation, X-Seed 4000 in Tokyo designed by Taisei Construction Corporation and Millennium Tower in Tokyo designed by Norman Foster.

The range of the heights of these visonary megastructures are from about 600 m tall Holonic tower to 4000 m tall X-Seed 4000.

At the time of writing this thesis the height of most supertall buildings lies between 300-500 meters. Only the Burj Dubai has reached a height of over 800 meters and can be considered as the first attempt at the realization of a vertical city. There are however several visionary, proposed and canceled projects with similar or greater heights.
In the following paragraphs one completed and a few proposed, canceled and visionary ultra tall buildings will be discussed.
First for each building facts like the location architect structural engineer height will be summed up followed by a discussion of the structural system and the wind engineering.

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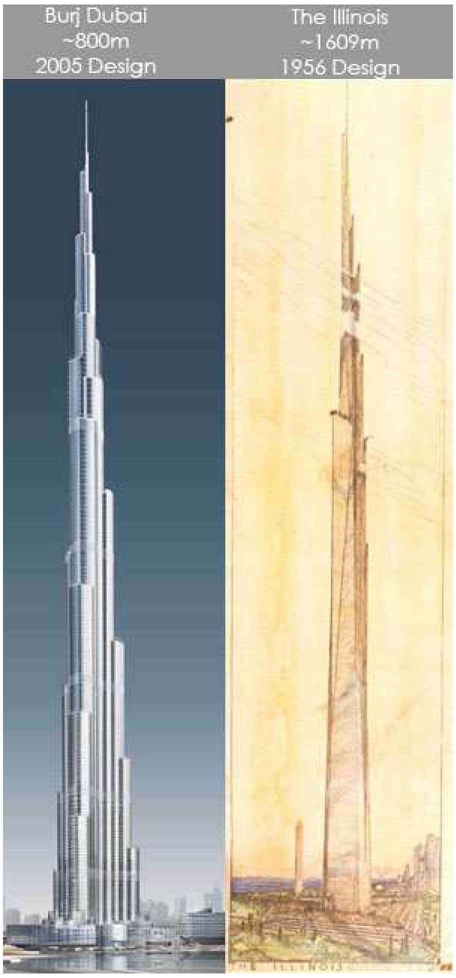

Figure 3-59 burj khalifa and the Illinois

3.7.2 Completed

Burj Dubai/ Burj Khalifa

Location :	UAE, Dubai
Completion date	2 januari 2010
Client:	Emaar properties
Architect :	Adrian smith (SOM)
Structural engineer:	Skidmore Owings and merill
Mechanical Engineer:	Skidmore Owings and merill
Contractor:	Samsung, Besix ,Turner, Arabtec
Height:	828 m
Stories:	162
Use:	mixed use
Principle Structural material:	Concrete

Introduction

Over the years the actual height of the Burj Dubai has been kept secret by the people involved in the construction and development. This was done to keep competitors guessing.
The final height is now known to be 828 meter.

The architects of the Burj Dubai attempted to incorporated cultural and historical influence of the region into the building.
The ground plan of the Burj Dubai has a Y-shape which resembles the hymenocallis , a desert flower found in the region surrounding Dubai. This Y shaped plan is ideally suited for residential and hotel usage because of the maximum outward views and entry of daylight.

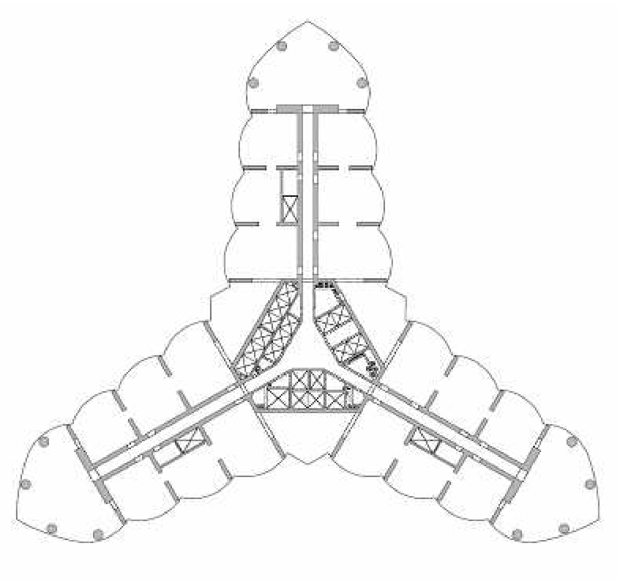

Figure 3-60 Buttressed core Burj Khalifa

Interesting facts

- Tallest structure ever built: 818 m (previously Warsaw radio mast - 646.38 m).
- Tallest structure: 818 m (previously KVLY-TV mast - 628.8 m).
- Tallest freestanding structure: 818 m (previously CN Tower - 553.3 m).
- Building with most floors: 160 (*previously both 1 & 2 World Trade Center - 110*).
- World's highest elevator installation.
- World’s fastest elevators at speed of 64 km/h or 18 m/s (previously Taipei 101 – 16.83 m/s).
- Highest vertical concrete pumping (for a building): 601 m (previously Taipei 101 - 449.2 m).
- Highest vertical concrete pumping (for any construction): 601 m (previously Riva del Garda Hydroelectric Power Plant - 532 m).
- The first world's tallest structure in history to include residential space.

level	**Function**		
160-206	Mechanical		
156-159	Transmission		
155	Mechanical		
139-154	Office		
136-138	Mechanical		
125-135	Office		
124	Observatory		
111-123	Office		
109-110	Mechanical		
76-108	Residential		
73-75	Mechanical		
43-72	Residential		
40-42	Mechanical		
19-39	Hotel		
17-18	Mechanical		
5-16	Hotel		
4	Hotel		Mechanical
3	Hotel		Restaurant
2	Hotel		Lobby
1	Hotel	Lobby	Restaurant
Concourse	Restaurant		Lobby
B2-B1	Parking		Mechanical

Table 3-4 Levels and function in the Burj Khalifa

Structural system

Burj Khalifa uses a buttressed core in which a rigid core is further supported by attached walls which flare out toward the lower levels. This structural system consists of a hexagonal core buttressed by high performance concrete walls connected to hammer walls and perimeter columns.

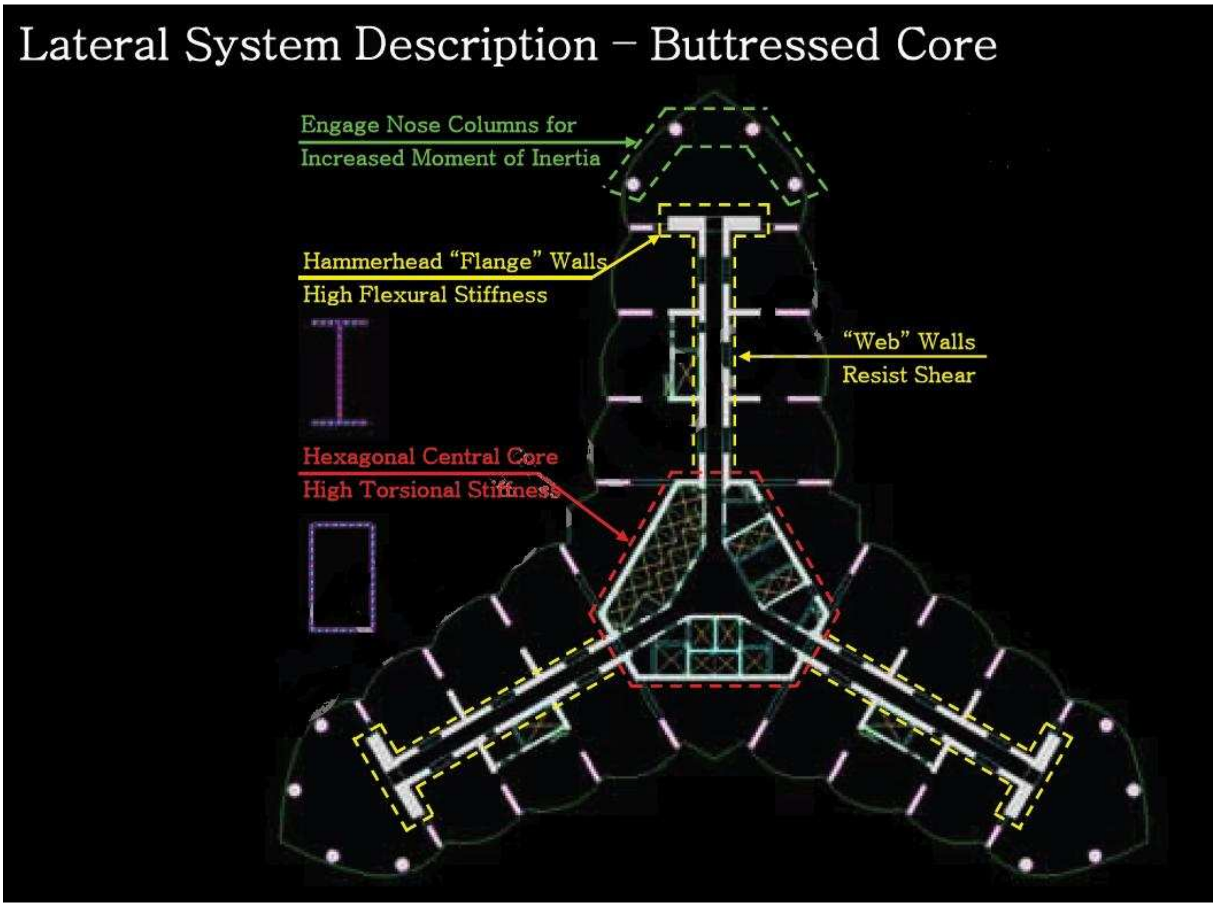

Figure 3-61 Buttressed core

The result is a laterally and torsionally very stiff tower. At mechanical floors outriggers increase the internal lever arm of the building by allowing the perimeter columns to participate in the lateral load transmission. By tying everything together at mechanical levels the strength of the structural system is increased.

The building has about 30 setbacks along its height which help confuse the wind and control vortex shedding. Its top section consists of a structural steel spire utilizing a diagonally braced lateral system. The structural steel spire was designed for gravity, wind, seismic and fatigue in accordance with the requirements of AISC Load and Resistance Factor Design Specification for Structural Steel Buildings (1999). The exterior exposed steel is protected with a flame applied aluminum finish.

Concrete

Impressive concrete technology was used in the design of The Burj Khalifa. In order to ensure a fast erection process the design of the concrete for the vertical elements required a compressive strength of 10 MPa at 10 hours to permit the construction cycle and a design strength/modulus of 80MPa /44 GPa.
The concrete strength tests indicated the actual concrete utilized had much higher compressive strength than the specified strength requirements.
The wall concrete specified strengths ranged from C80 to C60 cube strength. The C80 concrete for the lower portion of the structure had a specified Young's Elastic Modulus of 43,800 N/mm^2 at 90 days.

Besides the strength the pumpability and workability of the concrete was very important. Because of the high summer temperatures ensuring pumpability to reach the world record heights was a probably the most difficult concrete design issue.
Four separate basic mixes were developed to enable reduced pumping pressure as the building gets higher and a test was done which simulated the pressure loss when pumping to a height of 600 meter. The Putzmeister pumps which were used on site include two of the largest in the world and are capable of concrete pumping pressure up to a massive 350 bars through a high pressure 150 mm pipeline.
Also a special concrete mix was made to resist attack from the ground water and the concrete was designed as a fully self-consolidating concrete.

Foundation

The Burj Dubai has a 6 storey garage and is founded on a 3,7 meter solid reinforced concrete raft which was poured utilizing C50 self-consolidating concrete. The raft is supported by 194 cast in place borepiles. The piles are approximately 43 meter long and have diameter of 1,5 meter diameters. Each pile has a design capacity of 3000 tonnes

A detailed 3D foundation settlement analysis was carried out by Hyder Consulting Ltd. Based on the results of the geotechnical investigation and the pile load test result it was determined the maximum long-term settlement over time would be about a maximum of 80mm This settlement would be a gradual curvature of the top of grade over the entire large site. When the construction was at Level 135, the average foundation settlement was 30mm .

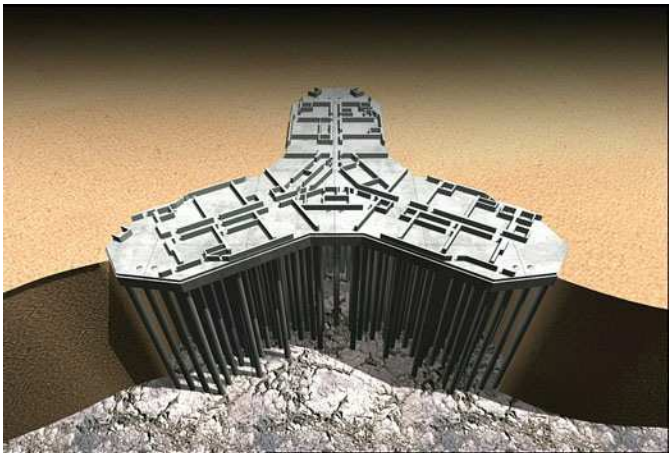

Figure 3-62 Foundation Burj Khalifa

Wind engineering

The Burj Khalifa was practically designed using the wind tunnel. The buildings setbacks are used to confuse the wind. The building rises to the heavens in several separate stalks, which top out unevenly around the central spire. This somewhat odd-looking design deflects the wind around the structure and prevents it from forming organized whirlpools of air current, or vortices, that would rock the tower from side to side and could even damage the building.

An extensive program of wind tunnel tests and other studies were undertaken under the direction of Dr. Peter Irwin of Rowan Williams Davies and Irwin Inc.'s (RWDI) boundary layer wind tunnels in Guelph, Ontario

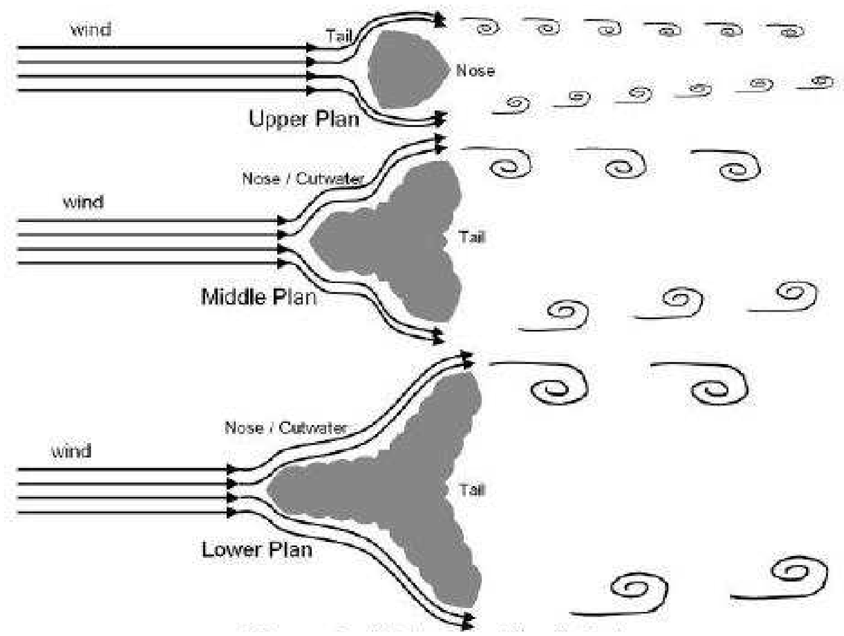

Figure 3-63 disorganized vortex shedding

Several rounds of force balance tests were done as the geometry of the tower evolved and being refined. The three wings set back in a clockwise sequence with the A wing setting back first. After each round of wind tunnel testing, the data was analyzed and the building was reshaped to minimize wind effects and accommodate unrelated changes in the Client's program.

During the design of the building the number and spacing of the setbacks changed as did the shape of wings. This process resulted in a substantial reduction in wind forces on the tower by "confusing" the wind (Figure 3-63) by encouraging disorganized vortex shedding over the height of the tower.

Cladding pressure studies

For a building of this height and shape wind forces acting in the cladding cannot be accurately predicted using standard code tables or formulas. The codes recognize this and permit the determination of loads by means of specialized Wind tunnel testing. The testing takes into account specific of building geometry local climate and surrounding detail.

Pedestrian wind level studies

The comfort of pedestrians at ground level and on the terrace levels was evaluated by combining wind speed measurements on wind tunnel models with the local wind statistics and other climatic information.
Two aspects of pedestrian comfort were considered; the effect of the mechanical force of the wind and the thermal comfort bearing in mind air temperature relative humidity solar radiation and wind speed.

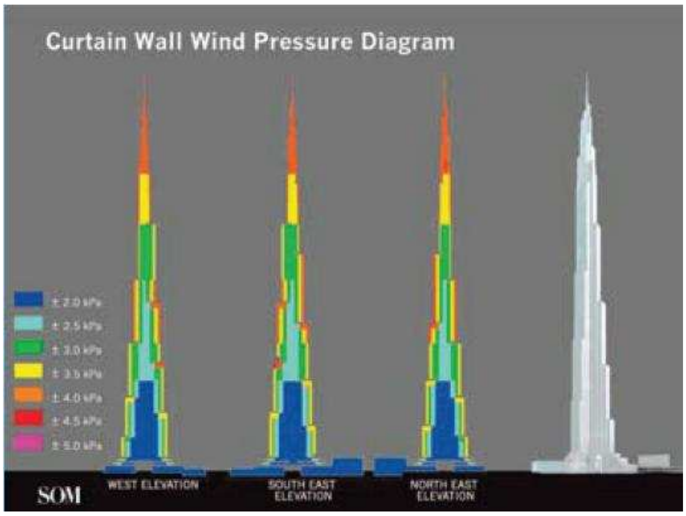

Figure 3-65 Curtain wall wind pressure Burj Khalifa

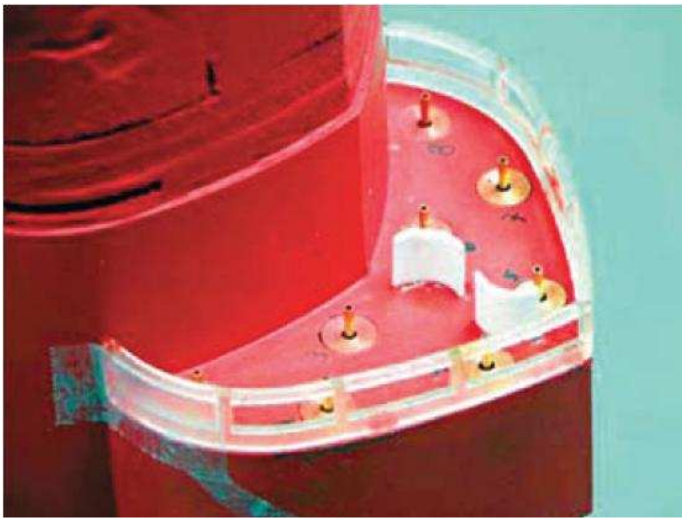
Figure 3-64 wind study; comfort on terrace

[20] Baker W.F. Novak L.C.(2008), *Engineering the world's tallest The Burj Dubai* , CTBUH World congress 2008

[21] Baker,B. *Supertalls the next generation* (pdf), CTBUH 2010 world conference India

3.7.3 Proposed

Incheon Tower

Location:	Korea, Incheon
Completion date:	2014
Client:	Consortioum led by Portman holdings
Architect:	John Portman Associates
Structural engineer:	Thornton Tomasetti
Height:	601 meter
Stories:	151
Use:	mixed use
Principle Structural material:	Concrete

Figure 3-66 Incheon Tower - Songdo landmark city

Introduction

Incheon tower will be the centerpiece of an 11 billion dollar development project called Songdo landmark city. For this project 1500 acres of land will be re-claimed from the Yellow Sea in the Incheon free economic zone, which is located 30 km from Seoul, the nation's capital.
Preliminary plans envision a total development of more than 2 million square meters that will be constructed on a phased basis at an estimated cost of more than 11 billion dollars.

Architecture

The towers have a trapezoidal shape and are designed to maximize natural light and view for its users.

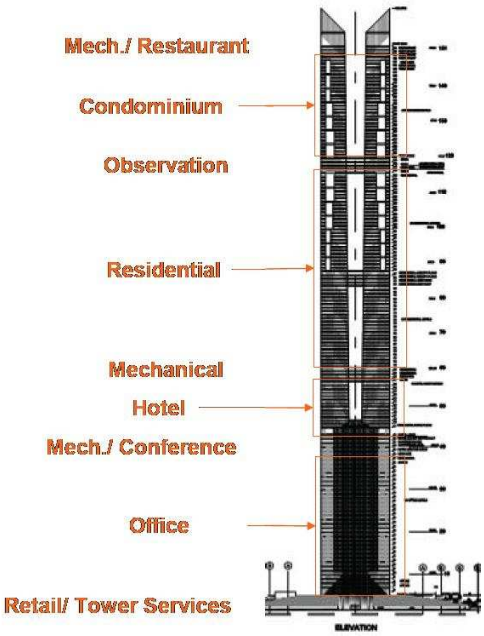

Figure 3-68 Functions Incheon tower

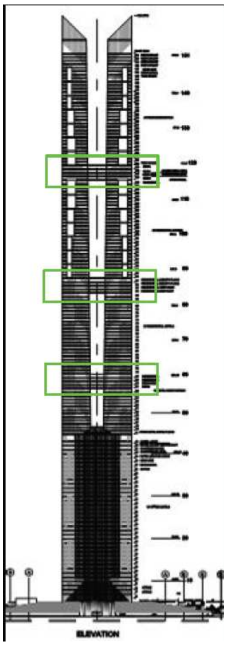

Figure 3-67 skybridges Incheon Tower

The building will offer the following functions:

- 30 floors of commercial use.
- A 300 room hotel.
- Residential apartments.
- Condominiums.
- Observation areas.
- A restaurant at the top.
- A five-storey retail and parking podium with two basement levels.

Structural

The Incheon tower is a split tower design. It consists of two towers connected by three four-storey bridges containing rigid outrigger trusses. These skybridges are essential because they tie the individual towers together.
Independently these slender towers are not structurally efficient but by linking the two towers together they act as a single structural entity where the increased internal lever arm of the new combined structure is able to resist more lateral loads.

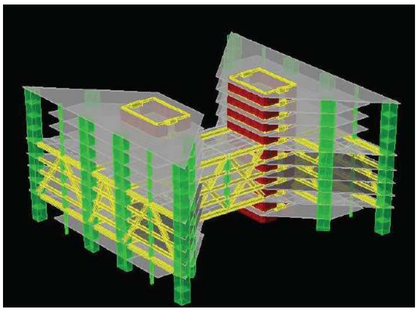

Figure 3-69 Skybridge structure

Four outrigger trusses connect the two towers.
Three of these form 25 meter long skybridges at levels 57-60, 84 -87 and 116-119
The fourth truss is located at levels 31-34 and seperates the office spaces from the hotel below.

The skybridges are 25 meter long and are located between the short edges of the trapezoidal plans.
Each trapezoidal plan consists of a 10 by 15 meter core and six megacolumns, 4 on the

longest edge and 1 on each inclined side. All the megacolumns taper along the height of the building and are linked to the core at the roofline with a hat truss.
At the mechanical levels outriggers connect the two tower cores and the megacolumns by means of four storey high trusses. By connecting all the structural elements over the entire width of the building the structure is able to resist larger lateral loads.
In order to increase the comfort level at the top floors a passive tuned mass damper will be installed to reduce the buildings acceleration.

Wind engineering

Reducing the wind load was an important aspect in the design of the building but the aerodynamic behavior had to be studied as well. The architectural design of Incheon tower includes a trapezoidal plan with very sharp corners.
With the help of slots the wind load and aerodynamics effects such as vortex shedding are reduced

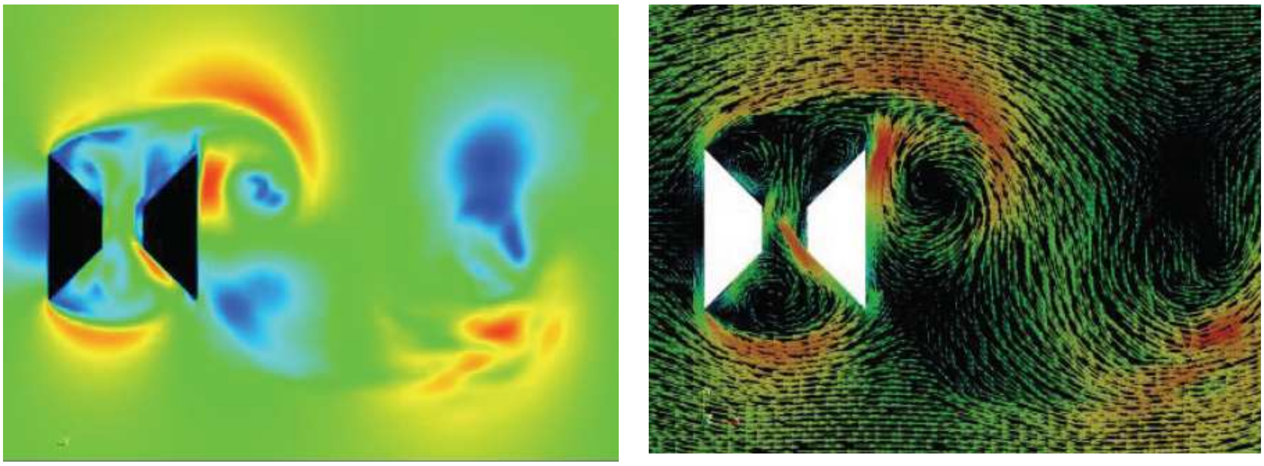

Figure 3-70 wind studies incheon tower

[22] Cory K., 151 *Incheon Tower Incheon, south korea(pdf),* presentation. Thornton tomasettie

[23] Fostner B. (2008), *Outriggers lend strength to tallest superstructure in South Korea* , december 2008 Civil Engineering

[24] Hi Sun Choi, *Super tall building design approach (pdf),* March 6 2009

Nakheel tower

Location :	UAE, Dubai
Completion :	on hold
Client:	Nakheel
Architect:	Woods Bagot
Structural engineer :	WSP Group
Height:	1000 m
Storeys:	200 storeys
Use:	mixed use
Principle Structural material:	concrete

Figure 3-72 Nakheel Tower

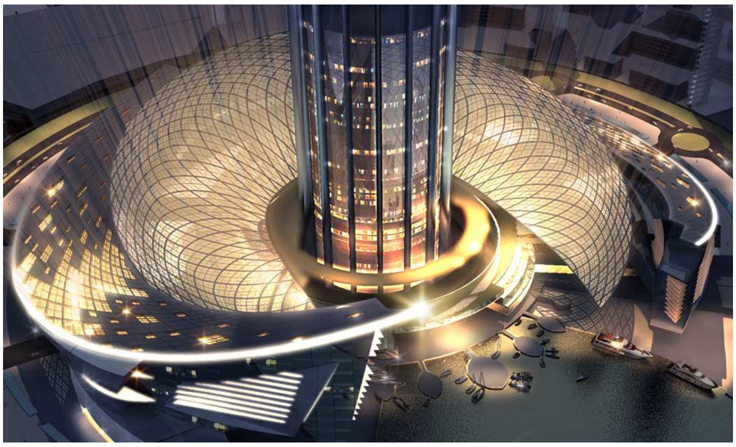

Figure 3-71 Nakheel Tower plinth

Introduction

This mixed use residential, commercial, and office structure is part of the Nakheel Habour & Tower development. If built, the Nakheel tower will be the first realization of a vertical city. It will be inhabited by 15000 people who will live work and socialize within the building.
The Nakheel Tower will be more than a kilometer high

Structural engineering

Commonly tall buildings consist of a single core and taper towards the top in order to reduce the lateral loads. Architecturally nakheel tower consists of several groups of 25 floors but structurally it functions as a single entity. In order to reach the height of 1000 meters Nakheel tower is divided into 4 separate parts, each with his own core. Every 25 floors these 4 parts are linked by means of skybridges containing belt trusses.
The 4 towers increase the internal lever arm of the structure and reduce the overturning wind forces on the structure.
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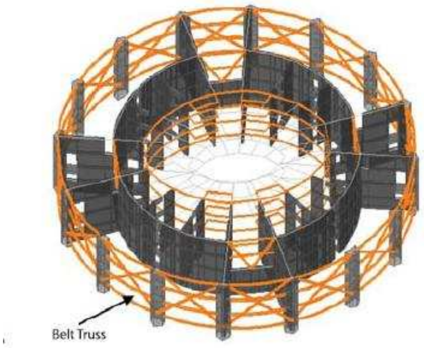


Figure 3-73 Structural connections at mechanical levels

Some interesting facts about the tower are:

• It will have over 200 floors.

• It will have approximately 150 lifts.

• The design structure of four separate elements allows for structural rigidity while also allowing the wind to pass freely in the spaces between the skybridges reducing the overall wind load.

• Total volume of concrete will be 500,000 cubic meters.

• All of the reinforcing bars laid end to end could stretch from Dubai to New York (1/4 of the way around the world).

• The tower will have 20 km of barrettes – (almost 400 barrettes). Barrettes are a form of pile used to make the foundation. A single foundation barrette has the capacity to support a 50 storey building.

• The building has enough cooling capacity to air-condition over 14,000 modern homes or to service 14 luxury resort hotels each with 2,000 rooms and all the public areas and amenities.

• The building is so tall that it experiences five different microclimatic conditions over its height, each with individual design features.

• The temperature in the atmosphere at the top of the building can be as much as 10 degrees cooler than the bottom.

• Due to the high speed shuttle lifts one may be able to see the sunset twice from the bottom and again from the top of the building.

• There will be approximately 10,000 car parking spaces in Nakheel Tower.

• Nakheel Tower and podium combined will be in excess of 2 million square meter.

Figure 3-74 Nakheel Tower

Architecture

The plan for the Nakheel tower is inspired from a 16 pointed star often seen in regional design. This geometric shape symbolizes equal radiation in all directions from a single point.

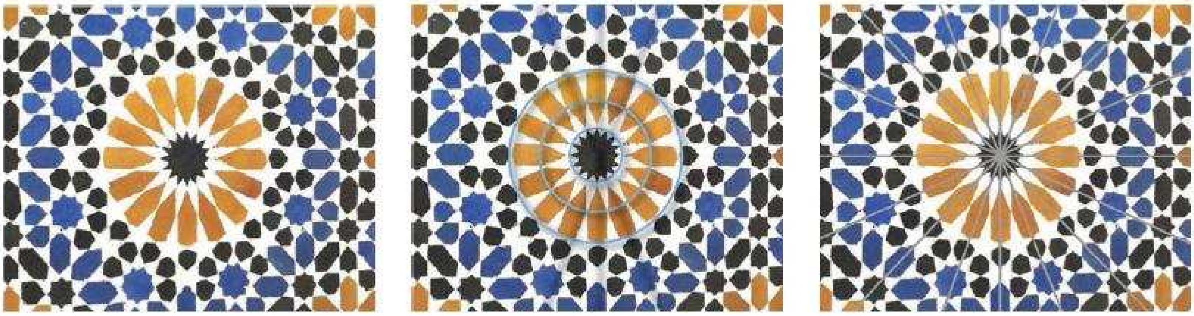


Figure 3-75 Arabic pattern

When designing a high-rise structure it is common to have a broad floor plan at ground level which tapers as the structure gets higher. This is done because of the favorable effect this has on the lateral loads caused by wind and earthquakes. The downside is that it also reduces the buildings most valuable real estate, the top of the building. The Nakheel Tower has a diameter of 100 meter which gives the tower a slenderness ratio of 10:1.

Even with this high slenderness, the central area of the tower cannot be used as a lettable area because the distance to the facade prevents the entrance of natural light.
By creating a void in the centre the usable area is located at the perimeter. This also allows wind to pass through the structure by means of wind slots which reduce the wind load.
Because tapering is not necessary the form can be almost constant from top to bottom.

The skybridges offer public spaces where the inhabitants can interact, socialize. It also functions as transfer point between lifts a refuge zone for emergencies and is the structurally links the four towers using belt trusses.
In such a tall structure safety is a very important factor. The four legs of the tower ensure and in-built redundancy because if one of the tower cores is disabled due to an emergency it is possible to flee to an unaffected neighboring tower.

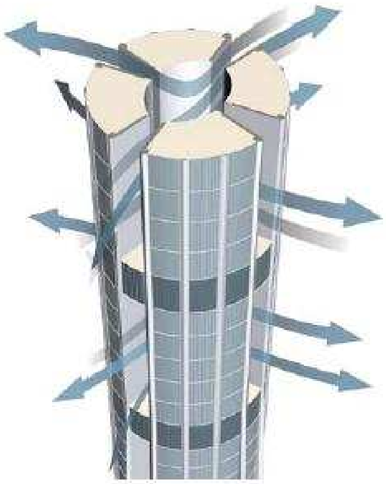


Figure 3-76 Voids and slots

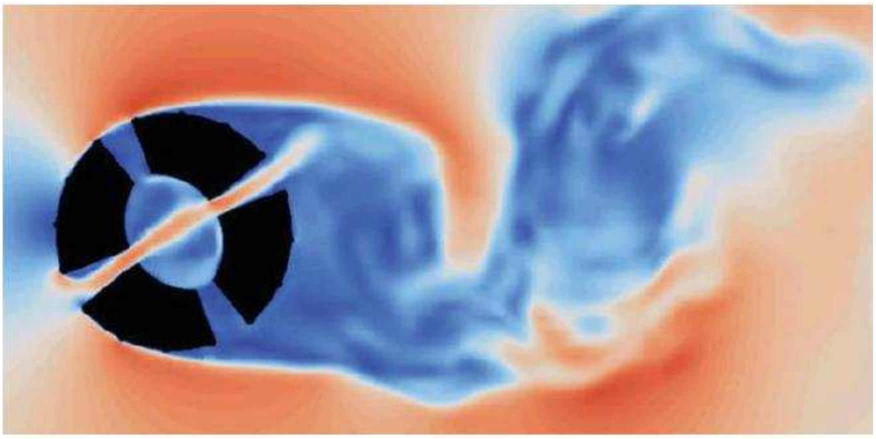


Figure 3-77 CFD analysis

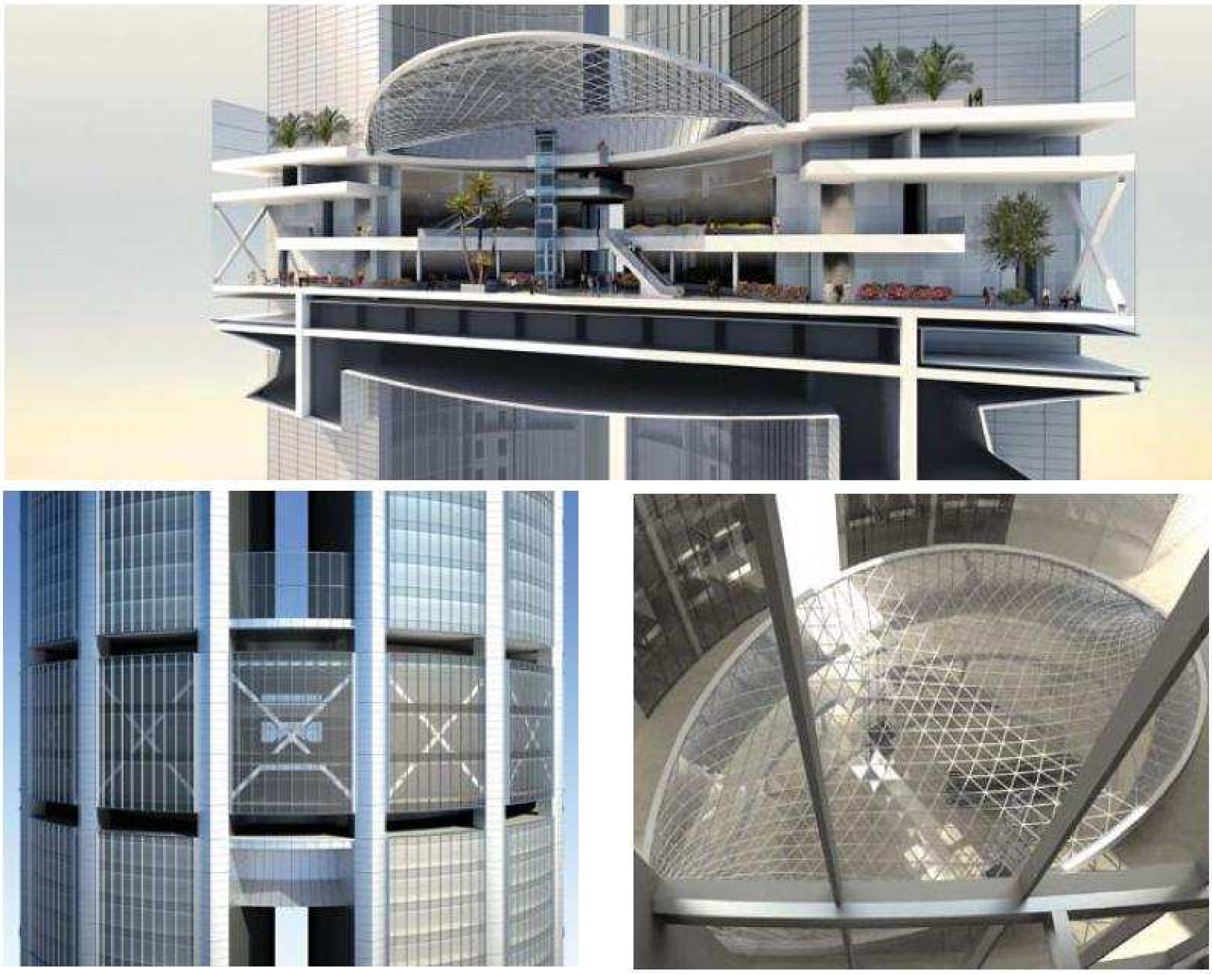


Figure 3-78 skybridge Nakheel Tower

The nakheel towers vertical transport system consist of 156 lifts using the latest of doubledeck technology and express lifts. The express lifts are able to reach the skylobby at 56m and transfer floors. From the skybridges residents, guests and tenants can use a local lift to travel within the 25 floors levels above.

For such a huge structure minimizing the construction time is very important. The aim of the developers is to maximize the repetition of facade elements to reduce construction time

Figure 3-79 Nakheel Tower subdivisions

Wind engineering

The cylindrical tower is 95m in diameter, but in actuality is four towers encircling an internal

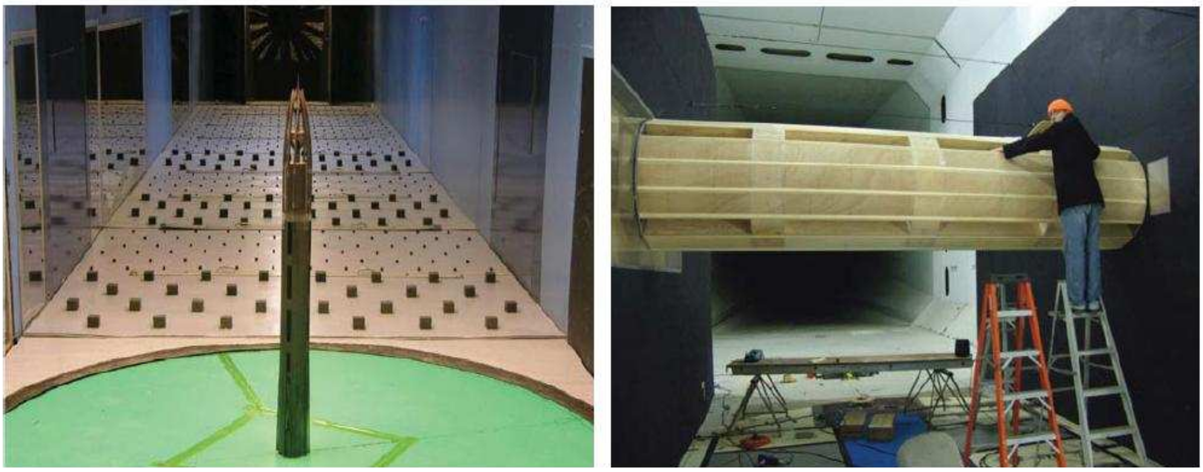


Figure 3-80 Wind tunnel tests

void, linked at intervals by sky bridges. This design mitigates the effects of the wind load, allowing the air to pass freely through the building. The slots in the building have been proven to reduce the wind load by three-fold. An added benefit of this design is to allow large floor plates at high levels, as the building does not have to taper to counter the wind effect.

[27] Mitcheson-Low Mark , Rahimian Ahmad, O'Brien Dennis *,Case study Nakheel tower the vertical city* ,CTBUH journal 2009 issue 2

[28] M.Mitcheson-Low, *Kilometer high tower: fact or fiction*, CTBUH 2009 chicago conference

Kingdom tower

Location :	Jeddah Saudi Arabia
Completion :	on hold
Client:	Kingdom Holding Company
Architect:	Omrania and Associates and Pickard Chilton
Structural engineer :	Hyder consulting, Arup
Contractor:	Bechtel
Height:	1600 m
Principle Structural material:	concrete

The Mile-High Tower is a skyscraper proposed for construction in Jeddah, Saudi Arabia. At 1600 m it could be the tallest building ever built. The US$13.6 billion project, the centerpiece of a planned community near the coast, is being proposed by Al-Waleed bin Talal’s Riyadh-based Kingdom Holding Company. This community will include including residential units, commercial space, office area, education vicinity, entertainment facilities and hotels.
The first renders show the building with the shape of a Rocket, would have 2 supporting flying-buttress towers, more than 244 meter high, to help it standing up. It will need an advanced damping system to stop the swaying at high floors and the ability to withstand huge different of freezing wind at the top and desert heat at the bottom.
Recent reports suggest that the project had been put on hold due to the global economic crisis Kingdom Holdings Company quickly however says that the project has not been shelved.
In May 2008, after soil testing in the area cast doubt over whether the proposed location could support a skyscraper of significant height, MEED reported that the project has been scaled back, making it "up to 500 meters shorter".

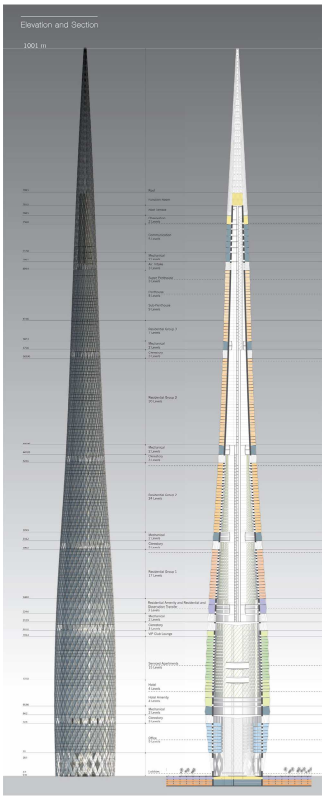


Figure 3-81 Kingdom Towerr

Burj Mubarak al kabir

Location : Kuwait
Completion : 2016
Architect: Erik Kuhne
Height: 1001 m

This vertical metropolis will be the centrepiece of Kuwait's new city of silk. The Kuwaiti skyscraper will measure 1001 meters. Burj Mubarak al Kabir was envisioned by London-based architect Eric Kuhne and it will have to withstand winds up to 150 mph.

The Mubarak's size is intended to accommodate Kuwait's explosive population growth, with seven 30-story neighbourhoods stacked atop one another, each with apartments, offices and hotels, and four-story "town squares" linking them. The buildings height has a cultural significance. One thousand and one meters for the classic Arabian fairy tale "One Thousand and One Nights".

Instead of building one shaky tower the Architect Eric Kuhne designed three interlocking towers which rotate 45 degrees from top to bottom, for better stabilization.
The buildings' inside edges will meet in the center in order to mold a triangular shaft-like structure. This technique will help the building to withstand heavy winds, and no matter which way the wind blows, the skyscraper will be braced by two of its three towers. Although the three-pronged design keeps the high-rise from swaying, it doesn't counter the choppy winds that whip around the uppermost stories, which can cause damaging vibrations

Vertical ailerons which control rolling motions, are used to redirect the changing wind around the tower. These are normally used as horizontal trailing edges on airplane wings. In this case they help disorganizes the vortex shedding and reduces vibration due to wind.
Three blades that will be built near the top of the tower will carry a mosque, a church and a synagogue to signify the unity of the three monotheistic religions.

Figure 3-82 Burj Mubarak

[32] Burj Mubarak extreme engineering the tallest skyscraper, Popular science p 36-37

3.7.4 Visions

Dubai city tower

The Dubai city tower also known as Dubai's vertical city is a supertall design created by an unknown architect. This proposal or vision began circulating in emails and skyscraper forums on 25 august 2008.
The tower is proposed to be sited along the Persian gulf where part of the building could push into the ocean creating a marina and a destination for cruise ships and tourism and is designed to be 2400 meters tall and will have 400 habitable stories and a 400 meter high wind-energy-producing spire.
At first it was unsure whether this building is a vision or proposal. It was however not included in the CTBUH tallest in 2020 list. With its 2400 meters it is the second tallest building ever fully envisioned after the X-Seed 4000. If ever constructed, the Dubai City Tower will be much taller than any other current man-made structure. The Dubai City Tower will be almost seven times taller than the Empire State Building. The design has a central core with 6 outer buildings that are connected to the central core every 100 floors. This design both stabilizes the structure and spreads out its mass. A 200 km/h vertical bullet train will act as the main elevator. The design is inspired by the Eiffel Tower to better deal with the massive wind forces pushing on it. It The Dubai City Tower is estimated to consume 37,000 MWh of electricity per year, with a 15 MW peak usage. The power will be mostly supplied by its 400 meter energy producing spire.

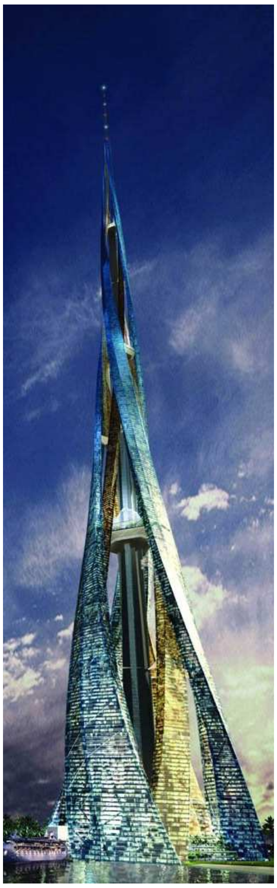
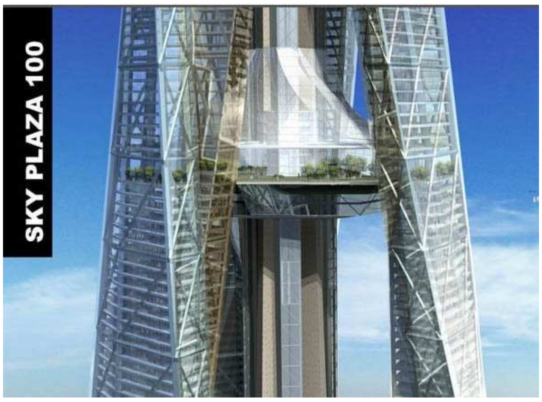


Figure 3-83 Dubai vertical city

Carol Willis, the director of the Skyscraper Museum in New York and a professor of urban studies at Columbia University, said the project appeared "buildable in technical terms" but economically difficult to justify.

Alastair Collins, of the international Council on Tall Buildings and Urban Habitat, said that height was the easy part with skyscrapers.

"The hardest part is the servicing of the height: the transportation, power, water and waste disposal," he said, adding that such a tower would also produce swarms of traffic.



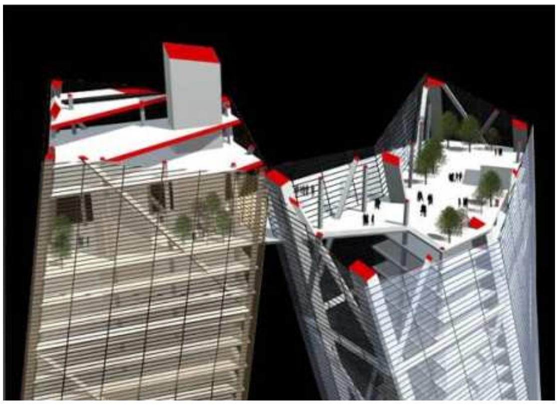


Figure 3-84 Skylobby Dubai vertical city.

3.7.5 Conclusion

In the reference projects several 600 + meter high building have been studied. In the structural design of these buildings wind engineering was a very important aspect. Each supertall building mentioned in paragraph 4.3 have some kind of measure to reduce negative effects caused by wind. Most of the supertalls mentioned in the reference projects except for the compound structures use a tapered shape to reduce the wind load. The compound structures do not taper as they mitigate the wind load by allowing the wind to flow through the building.

It can be concluded that with increasing height wind induced behavior becomes more and more important.

Name building	Height (m)	Status	City	Superstructure	Wind-mitigation
Incheon Tower	601	Proposed	Incheon	Compound	Voids/Slots
Russia Tower	+600	Cancelled	Moscow	Tube	Tapering
Burj Khalifa	828	Completed	Dubai	Core outrigger	Setbacks
Millennium tower	1000	Cancelled	Tokyo	Tube in Tube	Tapering
Nakheel Tower	1000	Proposed	Dubai	Compound	Void/Slots
Burj Mubarak	1001	Proposed	Kuwait	Compound	Ailerons
Kingdom Tower	1001	Proposed	Jeddah	Tube in Tube	Tapering
Dubai City Tower	2400	vision	Dubai	Compound	Voids/Slots

Table 3-5 Reference projects Summary

Chapter 4 Conclusions

4.1 Important design aspects

In the previous chapters a literature study was done with the aim to examine the challenges engineers encounter when designing supertall high-rise buildings. In chapter 3.3 various structural systems used in tall buildings together with their economies, relative efficiencies and advantages were discussed. It has become clear that supertall buildings require more efficient design than normal high-rise buildings and that it is not possible to simply use a scaled up structural system of a 100 meter high building for a 800 meter high building . Supertall buildings require a different and more structurally efficient design. The changes in the design are necessary for the following reasons:

- larger consequence of negative effects due to differential settlements
- increasing lateral Wind Load
- susceptibility to dynamic behaviour
- daylight entry problem
- vertical transportation
- large influence of the erection process and construction time on the projects feasibility

Larger consequence of negative effects due to differential settlements

Differential settlements result in unwanted stresses in structural members, cracking, an increase of the 2nd order effect and a larger deflection at the top of the building.
A pile and raft foundation is suitable for high-rise structures with a high slenderness ratio sensitive to differences in settlements.

Increasing lateral wind load

With increasing height the building the forces created by wind loading increase significantly therefore more efficient load bearing structures are necessary for supertall systems. The lateral stiffness is a major consideration in the design of a tall building and core-outrigger systems or trussed tube structures are the most used loadbearing systems for supertalls.
For the Rijnhaven Tower (800 m) a compound structure looks very promising because it reduces the wind loads acting on the building by allowing the wind to flow through the building and solves the problem of having a maximum internal lever arm while still ensuring sufficient daylight entry.

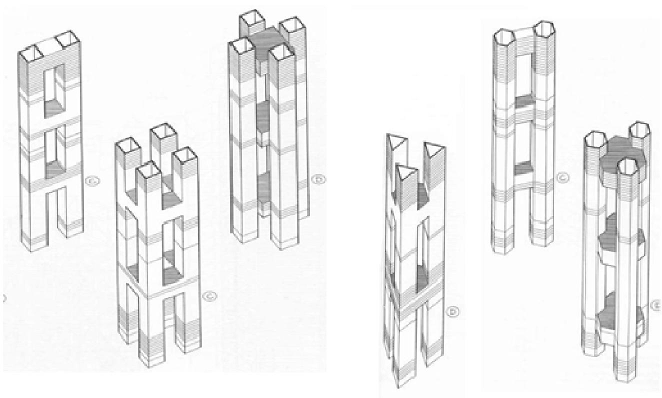


Figure 4-1 Linked towers

Dynamic behavior

As the height increases, the supertall becomes more slender and thus more susceptible to dynamic behaviour. Human comfort is an important issue in supertall buildings where movements can make inhabitants insecure or even nauseous (building sickness). This may prove the structure undesirable or un-rentable. Serviceability also requires deflections not to affect elevator rails, doors, glass partitions and sensitive equipment.

If the building does not comply with the comfort and drift demands and set in building regulation code aerodynamic modifications and increasing the damping of the building as described in paragraph 3.5.4 are the most efficient option for reducing the negative effects of dynamic behaviour.

The Wind load and dynamic effects such as vortex shedding can be reduced by the measures shown in Figure 3-50 to Figure 3-53

Figure 4-2 Dynamic mode shapes Burj khalifa

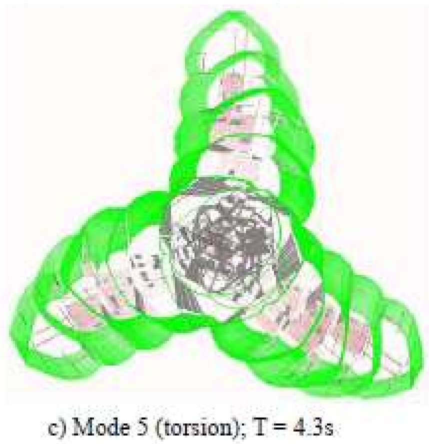


Figure 4-3 Dynamic torsional mode shape

Daylight entry

Because of the lack of daylight deep interior spaces far from the perimeter are of limited value to the client. Thus a scaled up version of a smaller building results in large proportions unusable areas.

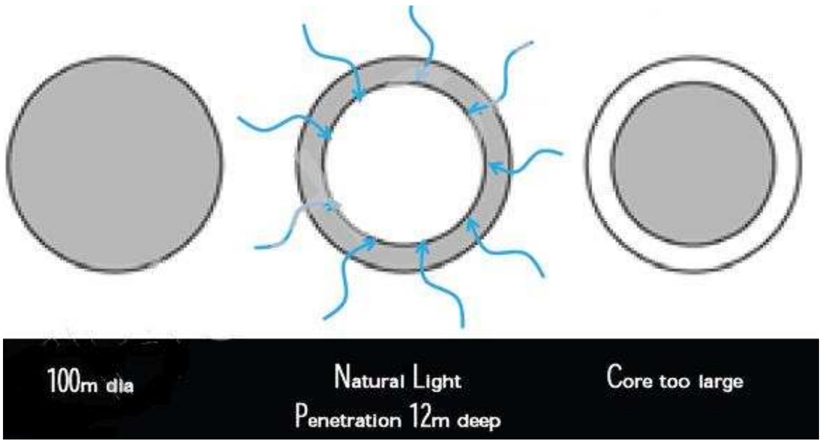


Figure 4-4 Daylight entry

Possible solutions to this problem are:

- Tapering the building (see Figure 3-59)
- Adding voids which push the usable floor area to the perimeter. Figure 3-76
- Using a Y shaped footprint similar to that of the burj khalifa (see Figure 3-60)

Vertical transport

With increasing height the challenge of accessing exiting and servicing the building floors becomes more complex.
Not only people and goods but also various building services such as water and electricity require vertical transportation. In a supertall building solutions have to be found to keep the time lost by traveling acceptable and area taken by vertical transportation within acceptable limits. The larges space taken up by vertical transports system can negatively influence the buildings nett floor ratio and thus the projects economic feasibility.

Large influence of the erection process and construction time on the projects feasibility

Construction time is a vital factor in obtaining a return on the investment by minimizing the cost of interest payments on the large capital costs involved in such large-scale projects.
Most tall buildings are constructed in congested city sites with difficult access, and with no storage areas.
Careful planning and organization of the construction sequence become essential. The story-to-story uniformity of most multi-story buildings encourages construction through repetitive operations and prefabrication techniques.
The progress in the ability to build tall buildings has gone hand in hand with the development of more efficient equipment and improved methods of construction, such as:

- Slip- and flying-formwork
- Concrete pumping
- The use of climbing tower cranes and large mobile cranes

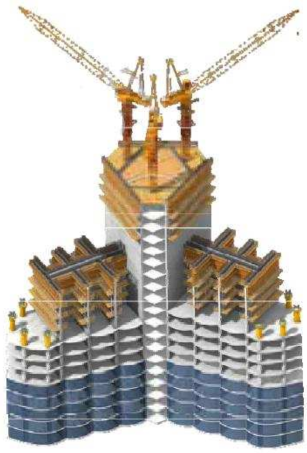


Figure 4-5 Erection process Burj Khalifa

As seen in paragraph 3.4 the influence that a structural element or system has on the construction time can be a deciding factor which outweighs their structural aspects.

4.2 Choice superstructure and foundation system

In the previous paragraph several important challenges which are encountered when designing a tall building are listed. The compound structure which was discussed in paragraph 3.3.2 has many advantages such as reduced wind loads and a solution to the problem of a lack of daylight entry for large cross-sections. Therefore the load-bearing system of the Rijnhaven Tower will be a compound structure consisting of several connected towers. The connections will make sure the towers behave as a single structural entity and by allowing the wind to flow through the building the overturning moment caused by the lateral wind load can be greatly reduced. As seen in Figure 4-7 a compound structure also has a positive effect on wind induced dynamic effects such as vortex shedding.

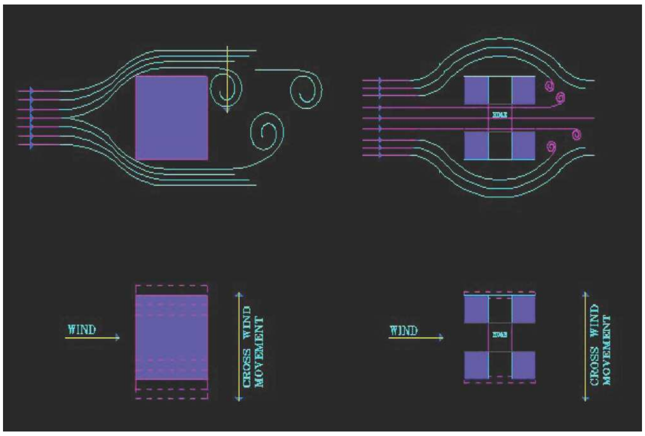


Figure 4-7 Vortex shedding

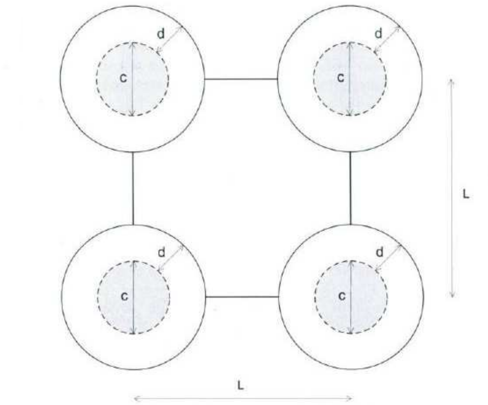


Figure 4-6 Schematic representation of a compound structure

Besides the structural advantages the compound structure also has architectural and economic advantages.
Usually a skyscraper is designed with a large footprint which tapers as the building gets higher. This is done to mitigate the wind effects. As a consequence the most valuable estate of a skyscraper, the area at the top, is lost. The top of the Burj Dubai for example has a ca 200 meter high steel structure which forms the spire of the building. Its function is merely aesthetic because this part of the building is unfit for habitation.
By reducing the wind loads through the use of openings instead of tapering a compound structure is able to maintain a more constant footprint and thus the most precious areas of the skyscraper, those at the top, can be used.
In a compound structure the individual towers can be very slender allowing natural daylight to reach (most) of the floor area but at the same time the combined structure is very strong and robust which makes it possible to reach large heights and still comply with architectural demands.

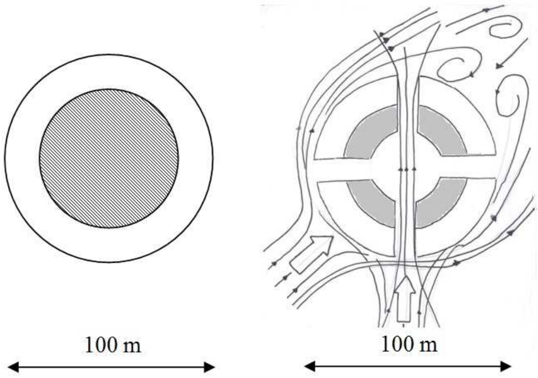


Figure 4-8 conventional structure vs compound structure

Foundation

In the Netherlands a pile foundation is usually chosen for high-rise building are due to a lack of soil layers with load bearing capacity at ground level. However the increasing interest in use of underground space in urban areas and technical developments in the area of building excavation have put relatively stiff and load-bearing soil layers within the reach of foundation slab.
Since the Tower will require a basement for parking and storage and possible to place the foundation raft on a soil layer with load-bearing capacity. In Rotterdam the first layer with a load-bearing capacity is the “Pleistocene” layer located at 18 meter N.A.P

This creates a pile-and-raft foundation where the vertical loads are transferred partly via the foundation piles and partly via the foundation raft.

Chapter 5 List of figures

Chapter 6 List of tables

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