Faculty of engineering
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The mutual relationship between structural systems and architectural concepts for tall buildings

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A Thesis
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2010

بسم الله الرحمن الرحيم

"و قل رب زدني علماً "

صدق الله الــعظيم

To my Mom, Dad, my wife and brother

for all your Support

and Unconditional love

I. Statement

This thesis is submitted to Ain Shams University for " the degree of master of science in architecture ".

The work included in this thesis was accomplished by the author at the department of architecture, faculty of engineering, Ain shams university, during the period from 2007 until 2010.

No part of this thesis has been submitted for a degree or a qualification at any other university or institute.

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II. Introducing the researcher

- Name: Ayman Ahmed Fareed Gamal Al-din Hamza
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III. Acknowledgments

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I am indebted to many people who have, directly and indirectly, influenced and inspired me throughout the different stages of this research. I highly value their guidance, enthusiasm and continuous support which pushed forward this work to be successfully accomplished. My supervisors Professor Dr. ***Khaled Dewidar,*** *Professor Dr.* ***Ruby Morcos*** *,Assistant Professor Dr* ***Ahmed Atef,****also a great thank to* ***Dr Mourad Abd-elkader ,Dr Medhat El-shazly Dr Amr Algohary ,****I thank them for their intensive help, valuable advice, constant effort, and their continuous encouragement throughout the whole research.*

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Ayman Ahmed Fareed

IV. Abstract

This research studies the mutual relationship between structure systems and architectural concepts in tall buildings form generation and design. It studies the impact of both form on structure and vice versa. This study will include tall and super tall buildings.

The era of modern sky scrapers of iron/steel or reinforced concrete as a construction material started in the middle of the 19th century specially in Chicago after its great fire. After that a race for the tallest skyscrapers took place, first in north America then all around the world.

Tall structure forms represent a great challenge in the field of structure as in the field of architecture. This is due to their need to overcoming the forces due to gravity and lateral loads. So form and structure has to work together in order to give at the end an innovative tall or a super tall structure.

V. Key words

Tall buildings - Super tall buildings - Sky scrapers - Core and skin - Interior structures - Exterior structures - Aero dynamics - Parametric design - Dia grid - Bracing.

VI. Summary

Tall buildings are nothing new, people used to build high from the ancient time, but sky scraper of iron/steel were recently introduced in the middle of the 19th century. So an era of super tall buildings then has started since that time, and a new challenge has appeared. How can an architect- with the help of different disciplines- generate an architectural form that is extremely high and at the same time capable of facing loads that affect its form.

Through studying the design process of tall buildings it was found that they are mainly composed of two main elements –**the core and the outer skin**-that have two functions , one is for structure while the other is for the internal planning and the form generation. Structurally they can include the major and minor components that resist lateral loads affecting the building, which are **(wind and earthquakes)** in addition to gravity loads. So if the major components are located within the interior of the building (the core) ,then it is an **interior structure** , but if they are located on the outer perimeter (skin) then it is an **exterior structure**.

Types of structure systems are many and each has a different characteristic that makes it suitable for some forms and not preferred for others. This is according to the form type, and its trend however, there are some trends that can be a common factor between structure and architecture such as the trend to design **aero dynamic** forms in which the form shape is designed to help in overcoming lateral forces specially wind forces.

The main aim of an architect is to choose the suitable form and its suitable structure system and construction material. For sure there is no specific datum line between systems, but an architect and structural engineer can match one or more systems together, one or more construction materials together to give at the end a new tall structural and an architectural innovative form.

Today super tall buildings can have advantages more than a building, but as a vertical city providing urban solutions to many problems such as traffic. So great tallness may be required providing both performance and sustainability for these tall structures, structural and architectural challenge will become more difficult, tall building race won't stop. The dream to explore the sky will continue forever and the challenge will become much more difficult every day.

الملخص

لا تعتبر المبانى العالية أمرا جديدا على الإطلاق فقد اعتادت الناس عليها منذ فجر التاريخ. أما ناطحات السحاب فهى ما قد ظهر حديثا تحديدا فى منتصف القرن التاسع عشر، فمعها ظهر تحد جديد ألا وهو كيفية التغلب على ارتفاعات ناطحات السحاب الشاهقة من خلال تعاون المهندس المعمارى مع شتى التخصصات الأخرى لإيجاد حلول للقوى المؤثرة على المبنى نتيجة الارتفاع.

ومن خلال الدراسة لعملية تصميم المبانى العالية، وجد أن هناك عنصرين أساسيين يتكون منهما أى مبنى عال حتى الان؛ أولهما هو مركز الخدمات (القلب الانتفاعي للمبني)والثانى هو غلاف المبنى الخارجى، ولهما وظيفتان احداهما انشائية والأخرى معمارية خاصة بالتصميم. أما عن الاولى فنجد أنهما يحويان أماكن العناصر الأساسية والفرعية التى تتصدى لقوى الرياح والزلازل بالإضافة إلى قوى الوزن والجاذبية. فإذا كانت العناصر الإنشائية الرئيسية موزعة فى مركز الخدمات داخل المبنى, فسيعتبر النظام الإنشائى فى هذه الحالة داخلياً والعكس صحيح، فإذا كانت العناصر الإنشائية الرئيسية موزعة فى الإطار الخارجى للمبنى فسوف يعد النظام الإنشائى نظاماً خارجياً.

تتعدد نظم الإنشاء وتختلف خصائصها مما يجعلها ملائمة لبعض المبانى وغير ملائمة للبعض الأخر طبقاً لنوع وشكل المبنى. وعلى الرغم من ذلك فقد تتواجد أشكال للمبنى تمثل شكلاً جماليا معماريا وأيضا شكلاً إنشائياً وظيفياً مثل الأشكال الإيروديناميكية والتى تعتمد فى أصل التصميم على شكل المبنى لتتصدى للقوى المؤثرة عليه كما ذكر من قبل.

من أهم أهداف المعمارى الوصول لإختيار أفضل شكل بحيث يكون متلائما مع مواد ونظم الإنشاء، وبالطبع ليس هناك حداً فاصلاً بين كل نظام للإنشاء وآخر، بل يمكن خلط أكثر من نظام بحيث نصل فى نهاية الأمر إلى إبداع معمارى إنشائى جديد.

لم تعد المبانى العالية ذات وظيفة واحدة هذه الايام؛ بل فقد أمتدت لتكون مدينة رأسية تمدنا بحلول تخطيطية لمشاكل مثل المرور مثلاً، فقد نجد يوماً أن المبانى العالية أصبحت ضرورة لا رفاهية بحيث توفر حالة من الإستدامة والوظيفية والكفاءة. وبهذا ستصبح مهمة المعماري والمهندس الإنشاءي أكثر صعوبة .أما سباق المبانى العالية فلن يتوقف، وحلم غزو السماء مستمر والتحدى يزداد كل يوم.

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Introduction

The research study the mutual relationship between the architectural trends in tall building form generation and their structural systems.

Tall structures are regarded to their great tallness that represents a challenge for both architects and structure engineers, so there must be an interaction between both architectural and structural concepts to give an innovative tall building as an end product.

The problem definition

During the design process of a tall building the structural idea is one of the main considerations that an architect should respect when start thinking of a concept, a proper design shouldn't neglect the structural idea when designing a tall building and maybe some times the structural idea can be an approach to the concept of the building, more than that it can be the main concept

There is a **shortage** in the information available about the relationship between structure systems used for tall buildings and the conceptual designs for them, I mean here the conceptual trends for form generation, and there is a shortage in the relationship between structural classification and conceptual classification.

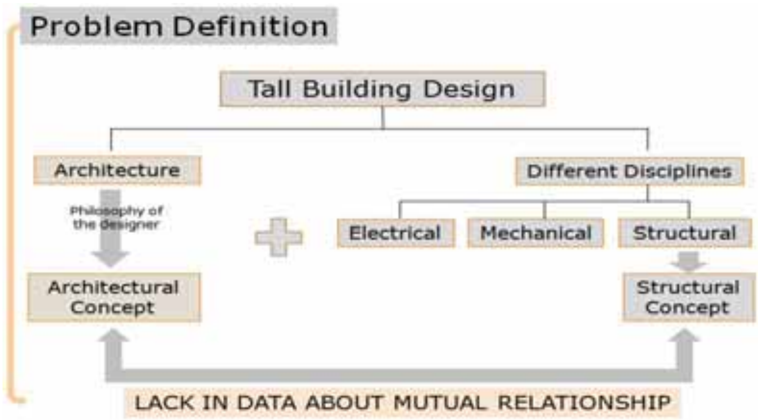

Figure (1) Problem Definition

Hypothesis and specific aims (objectives)

The main objective of the research is to find a classification for tall buildings according to the structural system ,and to reclassify them once more but according to the architectural concept of form generation. and then to match both classifications to find a relationship between them. This will be through comparative analysis. The main objectives of the research can be as follow:

1. To give a definition to the meaning of tall buildings, this includes high rise and skyscrapers, and to study briefly the historical background of the tall buildings and its development over years.
2. To Study Basics of Tall Buildings (Design Process & Philosophy).
3. To classify the main structure systems used in tall buildings design.
4. To classify the tall buildings form generation trends according to their conceptual approaches.
5. To match both classifications and show their mutual impact on each other.

Research methodology

The research will mainly use the induction method through a comparative analysis between the different types of tall buildings structure systems and their analysis, and then another analysis between their different conceptual approaches and trends in form generation to try to match both classifications in order to find the mutual relationship.

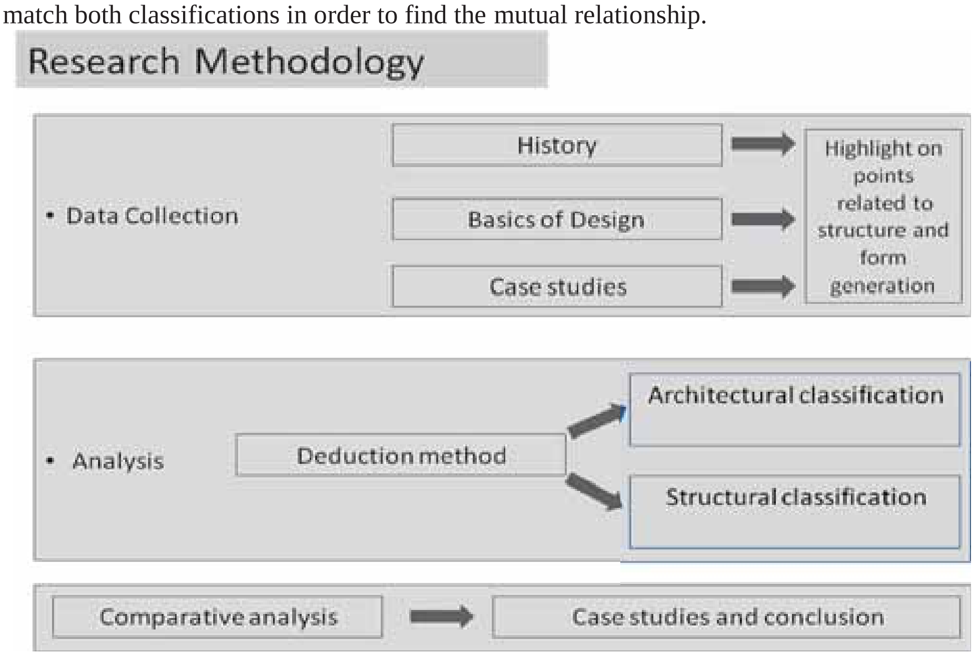

Figure (2) Research Methodology

The research will be divided into three parts that include five chapters ; the first part is composed of two chapters, the first one will be an introduction to the research and it will study mainly:

1- The main definitions related to tall building.
2- A brief historical background about tall buildings.

The second chapter will be a study for the design process of tall buildings, it will study the philosophy of tall buildings design in addition to the constrains facing the design of tall buildings on both sides architecture and structure. The second part will study and classify the main structural systems used for tall buildings in addition to the different approaches for tall buildings form generation; this study will include two chapters, one for structure and the other for the different approaches. The last part will be the matching between both classifications through a comparative analysis supported with case studies to find the relationship between both classification in addition to conclusions and recommendations for further studies.

Research Structure

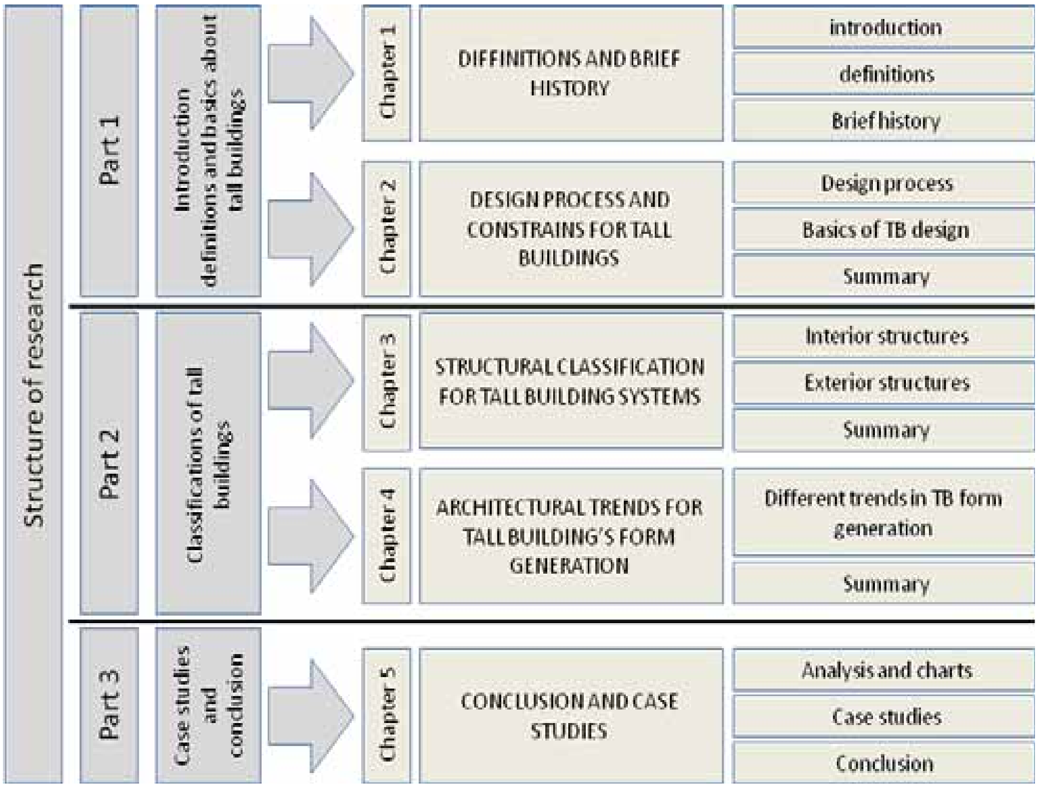

Figure (3) Research Structure

Part	Chapter	Title	Objective
Part 1	Chapter one	Diffinitions and Brief History	• To give an overview about the most important definitions related to tall buildings ,in addition to a brief historical back ground about the development of tall buildings among years starting from the ancient time reaching upto the new millennium
	Chapter Two	Design Process and Constrains for Tall Buildings	• To define the design process and basics for tall buildings ,this would help in understanding the studies in the next chapters
Part 2	Chapter Three	Structural Classification for Tall Building Systems	• To study the classifications for tall buildings from a structural point of view as follow : 1- Interior Structures 2- Exterior Structures
	Chapter Four	Architectural Trends for Tall Building's Form Generation	• To give examples for different tall building's structures, the research study in chapter five will base its results and conclosions according to this classsification and examples • To give an over view about the different trends used in tall buildinfs form generation
Part 3	Chapter Five	Conclusions and case studies.	• To sTudy the mutual relation ship between the structure systems and form generation trends in tall buildings design • To support the theoritical study with some case studies such as 1- Burj Dubai. 2- CCTV Headquarters. 3- Rotating tower of Dubai. 4- The Turning Torso . 5- Swiss Re Building.

PART ONE

BASICS ABOUT TALL BUILDINGS

CHAPTER ONE
DIFFINITIONS AND BRIEF HISTORY

CHAPTER ONE
DIFFINITIONS AND BRIEF HISTORY

1.1 Introduction

The main aim of this chapter is to highlight the brief history of tall buildings since the ancient times. **Karen Barss** wrote in the article titled **The history of sky scrapers that** "the desire to build big is nothing new, big building have been used to show of power and wealth; honor leaders or religious beliefs; to stretch the limits of what's possible; and even as simple competition among owners, families, architects, and builders". [1] A secondary aim is to give an accurate definition to the meaning of a tall building, sky scrapers and super tall building as an introduction to other chapters.

The brief history part will be divided into two major parts, this division is based on a historical event, specifically the great fire of Chicago that occurred in North America in the middle of the 19^{th}[2].After that an era of skyscrapers started.

The study of the brief history will be divided into a part studying the development of tall buildings starting from ancient time up to the 19^{th} century, and another part starting from the 19^{th} century up to the new millennium.

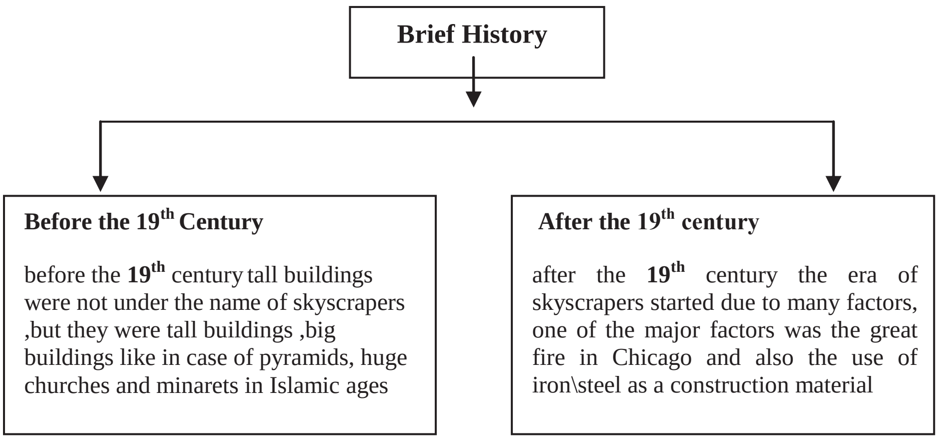

Figure (4) Diagram showing the 19^{th} century is a datum line between two decades in tall buildings developments.

1 (Barss 2007).
2 (Council on Tall Buildings and urban Habitat.CTBUH Criteria for defining and Measuring Tall Buildings 2009).

1.2 Definitions

All definitions mentioned here are according to **Council of Tall Building and Urban Habitat** Criteria for Defining and Measuring Tall Buildings.

1.2.1 Tall Building

There is no hard, fast division on what constitutes a “tall building”. It is a building that exhibits some element of 'tallness' in one or more of the following categories:

1.2.1.1 Height relative to context

It is not just about height, but about the urban situation in which it exists. Thus whereas a 12-story building may not be considered a tall building in a high-rise city such as Chicago or Hong Kong, in a provincial European city this may be distinctly taller than the urban norm.[1]

1.2.1.2 Proportion

Again, a tall building is not just about height but about proportion. There are numerous buildings which are not particularly high, but are slender enough to give the appearance of a tall building, especially against low urban backgrounds. Conversely, there are numerous big / large footprint buildings which are quite tall but their size / floor area rules them out as being classed as a tall building.[2]

1.2.1.3 Tall Building Technologies

If a building contains technologies which may be attributed as being a product of 'tall' - e.g. specific vertical transport technologies, structural wind bracing as a product of height, etc, then this building can be classed as a tall building.

1.2.2 Super-Tall Building

Again, opinions on this differ internationally. Although great heights are now being achieved with built tall buildings (in excess of 800 meters / 2600 feet), as of the end of 2008 there were actually only 38 buildings in excess of 300 meters completed and occupied globally. The CTBUH thus defines ‘super-tall’ as being any building over 300 meters / 984 feet such as the **Vertical City** in Dubai **Figure (5-a)** .[3]

1.2.3 Skyscraper

The word “sky scrapers” originally was referring to a tall mast or its main sail on a sailing ship, but the term was first applied on building in the 19th century after the great development happened in North America in New York and Chicago after the use of iron/steel in construction which was first applied on a steel-framed ten story building “**Home Insurance Building-1885**” Figure **(5**-b) which can be considered the first sky scraper.

The structural definition of the word skyscrapers was refined later by architectural historians, based on engineering development starting from second half of the 19th century. [4]

[1] (Council on Tall Buildings and urban Habitat.CTBUH Criteria for defining and Measuring Tall Buildings 2009).
[2] ibid.
[3] Same as 1
[4] (Council on Tall Buildings and urban Habitat.CTBUH Criteria for defining and Measuring Tall Buildings 2009).

1.2.4 High-rise building

The term sky scraper should not be confused with the term high rise. **Emporis standard committee** defines high rise as a multi story structure with at least 12 floors or 35 meters height (115 ft).[1]

Some structural engineers define a high rise as any vertical construction for which wind is a more significant load factor than earthquake or weight.[2]

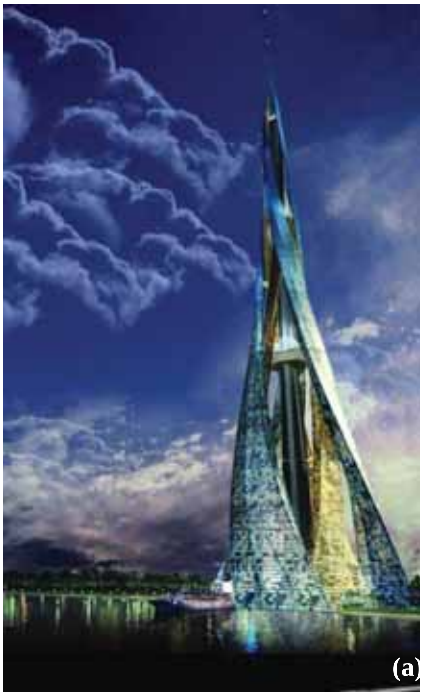

Figure (5) (a) Vertical city ,(b) Home Insurance Building in Chicago, America.
Ref: (a) http://blog.dubai.com - (b) http://www.pbs.org

1.2.5 Measurement of Tall Building Height

The CTBUH recognizes tall building height in four categories:

1.2.5.1 Height to Architectural Top

Height is measured from sidewalk level outside the main entrance to the architectural top of the building, including spires, but not including antennae, signage or flag poles. This measurement is the most widely utilized and is used to define the rankings of the 100 Tallest Buildings in the World **Figure (6)**.[3]

[1] (Wikipedia, the free encyclopedia n.d.) - (Wapedia Mobile Encyclopedia, 2010).
[2] ibind.
[3 & 2] (Council on Tall Buildings and urban Habitat.CTBUH Criteria for defining and Measuring Tall Buildings 2009).

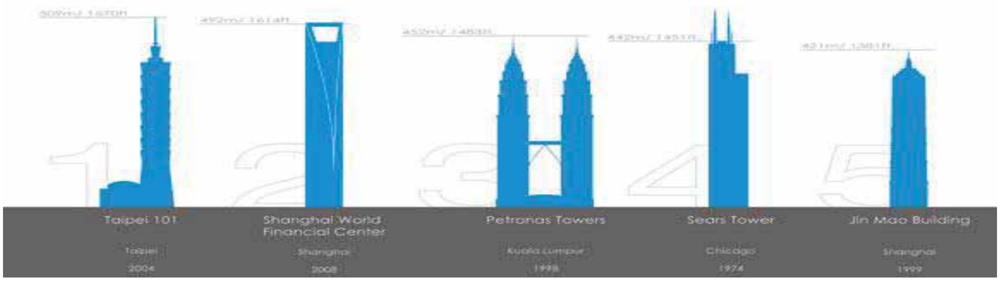

Figure (6) World's Tallest Buildings according to Height to Architectural Top.
Ref: CTBUH Criteria for Defining and Measuring Tall Buildings.
http://www.ctbuh.org/HighRiseInfo/TallestDatabase.

1.2.5.2 Highest Occupied Floor

Height is measured from sidewalk level of the main entrance to the highest continually-occupied floor within the building (i.e. not including maintenance areas) **Figure (7)**.[2]

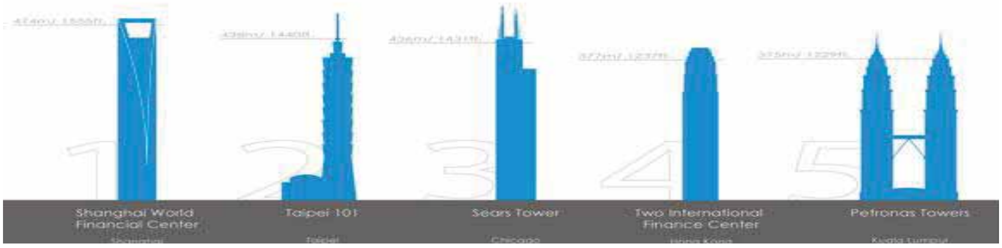

Figure (7) World's Tallest Buildings according to Highest Occupied Floor.
Ref: CTBUH Criteria for Defining and Measuring Tall Buildings.
http://www.ctbuh.org/HighRiseInfo/TallestDatabase

1.2.5.3 Height to Top of Roof

Height is measured from sidewalk level of the main entrance to the highest point of the building's main roof level, not including spires or antennas **Figure (8)**.[1]

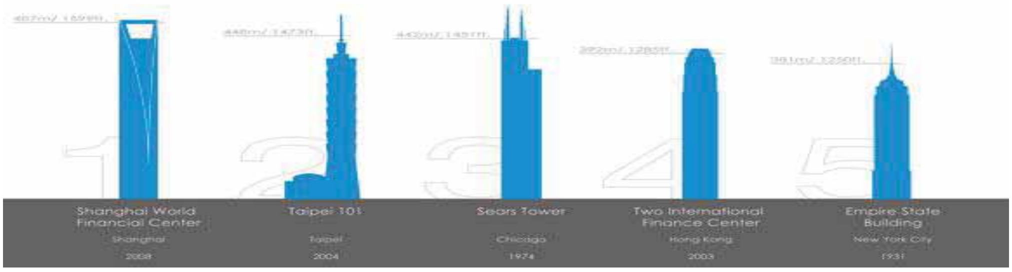

Figure (8) World's Tallest Buildings according to Height to Top of Roof.
Ref: CTBUH Criteria for Defining and Measuring Tall Buildings.
http://www.ctbuh.org/HighRiseInfo/TallestDatabase

1 & 2 (Council on Tall Buildings and urban Habitat.CTBUH Criteria for defining and Measuring Tall Buildings 2009).

1.2.5.4 Height to Tip

Height is measured from sidewalk level of the main entrance to the highest point of the building, irrespective of material or function of highest element (thus including antennae, flagpoles and signage) **Figure (9)**.[2]

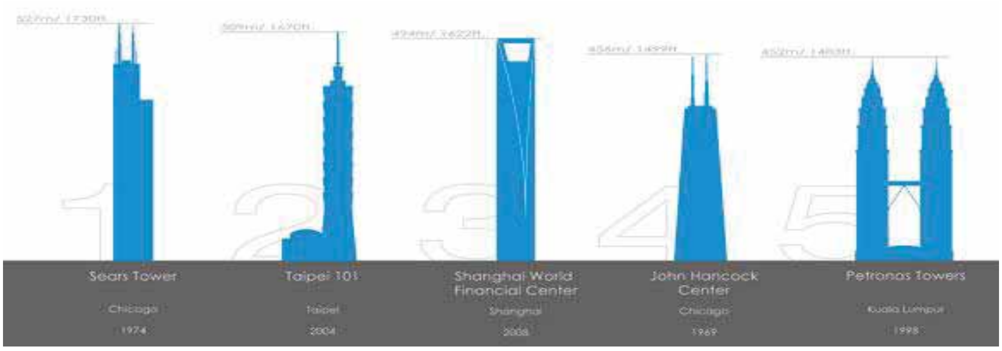

Figure (9) World's Tallest Buildings according to Height to Tip.
Ref: CTBUH Criteria for Defining and Measuring Tall Buildings.
http://www.ctbuh.org/HighRiseInfo/TallestDatabase

1.3 Tall building before the 19th century

1.3.1 Introduction

Before the skyscrapers (by its architectural full meaning), there was big buildings or high building that sometimes could be called Towers, they were mostly made of heavy stone, and thick sturdy walls, the rooms were dark and cramped, too many windows should have weakened the structure which was most of the time a load bearing structure. [1]

1.3.2 Tall buildings in old Pharaonic age

The great lighthouse of pharos of Alexandria Figure (10-a) 200 meters height which was built by Alexander the great; it was the tallest structure in the ancient world, the structure needed to be seen from about 50 km (35 miles) away in good time for approaching vessels to make realignment .[2]

From the early beginning of the history, the ancient Egyptians tried to build tall and big buildings. **The great pyramid of Cheops** at Giza **Figure (10-b)** is one of the tallest ancient buildings 146 meters (480 ft.), it was built in 26th the century BC. The pyramids of Giza had religious symbol; it refers to the tomb of the king. It was built in about 20 years. It includes latest technology found at that time **Figure (11)**.

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1 (WGBH Educational Foundation BUilding Big: Skyscraper Basics n.d.).
2 (Wells 2005).P.6

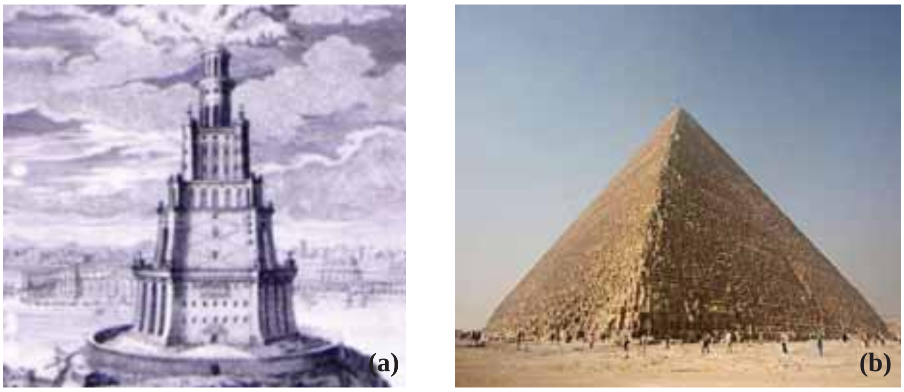

Figure (10) (a) Light House of Alexandria, (b) The Great Pyramid of Giza.
Ref: (Wells 2005). P. 7. - (Wikipedia, the free encyclopedia n.d.).

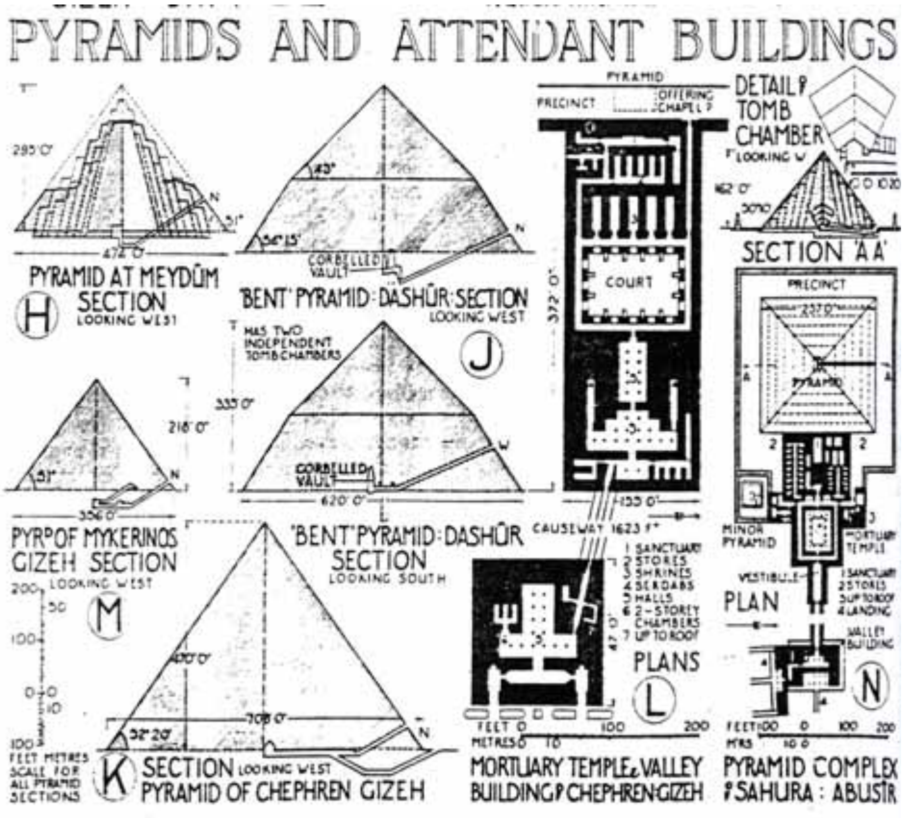

Figure (11) Ancient Egyptians and choosing the pyramid shape to represent stability.
Ref: (S. B. Fletcher 1967).P.32.

1.3.3 Tall buildings in Roman Empire

High-rise apartment buildings already flourished in an antiquity: ancient Roman insulae in Rome and other imperial cities, it reached sometimes up to 10 stories or more some with more than 200 stairs[1], they first appeared in the density populated lower class Pontine area of Rome; they were cheaply built apartment blocks **Figure (12)**.

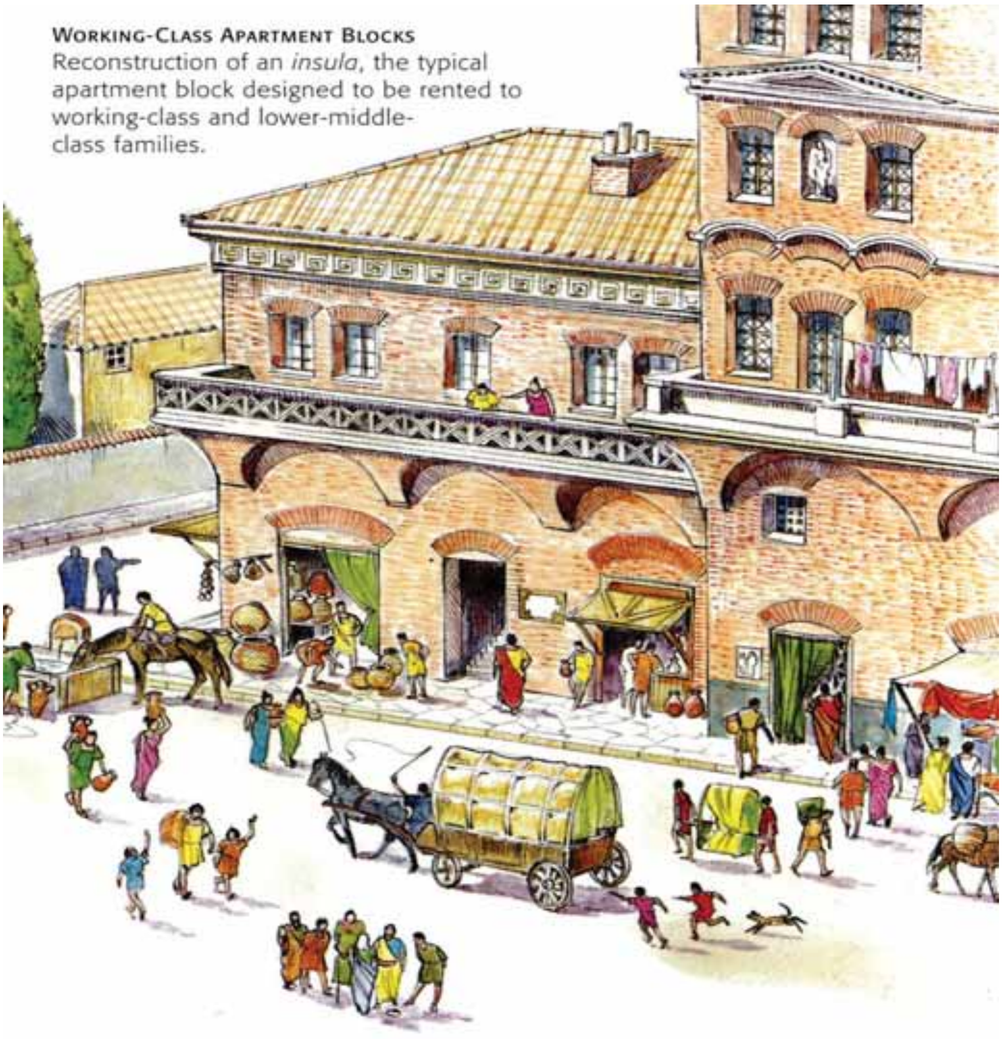

Figure (12) Roman insulae- cheaply built apartment blocks
Ref: http://nationalityinworldhistory.net

[1] (Wikipedia, the free encyclopedia n.d.) - (Wells 2005). P.6.

This can be an early example for the economic forces that push living accommodation vertically; we can say small rental area and vertical use.[1] Several emperors, beginning with Augustus (r. 30 BC-14 AD) attempted to establish limits of 20-25 m for multi story buildings. Truly they were met by limited successes; lower floors were mostly occupied by either shops or wealthy families. On the other hand upper floors were rented to the lower classes.

1.3.4 Mutual interaction between Roman and Persian Empire and its impact on development of tall buildings

Further eastwards, the encounter between both the Roman and Persian empires cross-fertilized construction technologies, to resulting technology enabled enclosures more than 30 m (100 feet) height to be constructed easier than before. Tall buildings continued to flourish and this was mainly based upon this synthesis of eastern and western technologies.[2] **The Hagia Sophia Figure (13-a)** the Byzantine church which was constructed in the sixth-century can be a perfect example for the combination of the most sophisticated devices of Roman and Eastern building technologies.[3]

1.3.5 Tall buildings in Inca Empire

On the other hand, across the ocean, the Amerindians-first then later on the Incas – were building vast artificial hills as temples with lime stone and granites **Figure (13-b)**.[4]

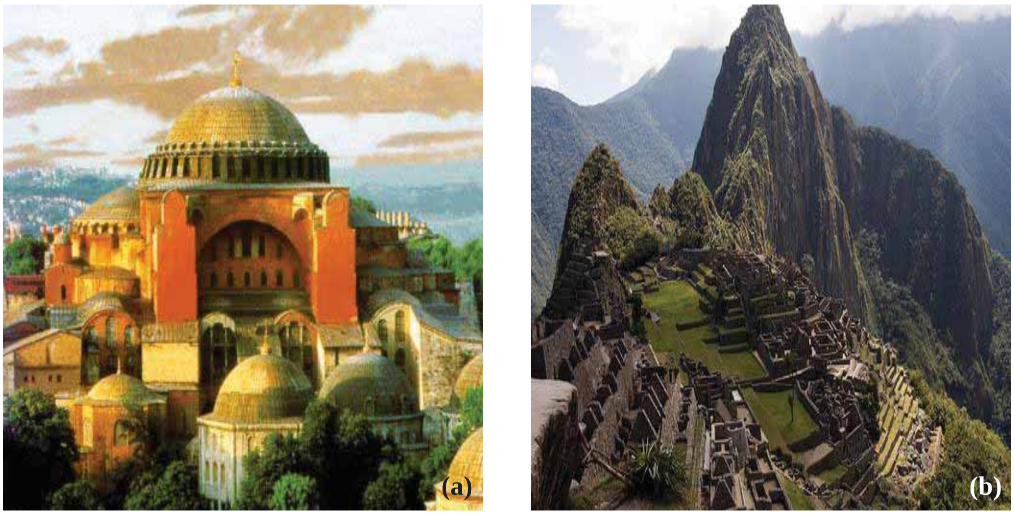

Figure (13) (a) The Hagia Sophia the Byzantine church, (b) The Inca city Machu Picchu in Peru
Ref: (a) http://www.atlantaserbs.com - (b) http://www.flickr.com

1 (Gregory 2004).
2 (Wells 2005). P.7
3 ibid.
4 (Wells 2005). P.7 - (E.Saouma 2003) - (S. B. Fletcher 1967).

1.3.6 Tall buildings in medieval age

We can recognize the sky line of many medieval cities; it had large number of high-rise urban towers. Some of them were built by wealthy families for defensive purposes and as status symbols.[1] This change was mainly due to the appearance of Gun powder in the early fifteenth century, war has changed and also the natural of the building intended to resist it.[2]

The book named **skyscrapers structure and design** declared that "the major medieval influence on building construction relevant to the development of tall buildings was actually the development of descriptive system and surveying tools to allow the construction of the geometrically laid-out forts and town defenses necessary to resist bombardment. These techniques could ensure the accuracy and precise tolerances of construction needed to built high".[3] Some examples of medieval high-rise buildings is the residential **Tower of Bologna in 12th century Figure (14-b)**; it was numbered between 80 to 100 at a time, the largest of which (known as the "two towers") rise to 97.2 meters (319 feet).[4]Also due to the war between Italian city states, beside Venetian resistance to Ottoman expansion, the science of bell-casting was improved, the new high quality castings meant that the bells could be pealed rather than struck with hammers; the movement in turn, introduced a new level of lateral forces and dynamic loads at the top of towers. Then building high technology has to be improved and that was through cellular wall sections, ring beams and binders improvement to resist these loads.[5] From the famous examples of high towers is the Pisa tilted tower near **Pisa cathedral** (1063-92) **Figure (14-a)**, it has a circular plan of 52 ft diameter and eight stories height.


Figure (14) (a) Pisa Cathedrals, (b) Residential Tower of Bologna in 12th Century
Ref: (a) http://www.flickr.com - (b) (Wikipedia, the free encyclopedia n.d.

1 (Wells 2005). P.7
2 (Wikipedia, the free encyclopedia n.d.).
3 ibid.
4 Same as 1. P.7,8&9
5 (S. B. Fletcher 1967).

1.3.7 The impact of Islam on the development of tall building

Islam also had its own impact on architecture, from the point of view of high building. It has its own achievements such as the minaret, which is a high linear element; its purpose is to call Muslims for prayer all around the country, an example of that is the spiral ramp at the great **mosque of Samarra** (848-52). [1]

Many high rise residential buildings were found in medieval Egyptian cities like Fustat especially in the 10th and 11th century; Al Muqaddasi in the 10th century which is described as resembling minarets, and the 14 stories high rise with roof gardens on the top floor. Supported with ox-drawn water wheels for irrigation (Nasir Khusraw).[2]

In Cairo, in the 16^{th} century high rise apartment building flourished with similar concept to Roman's one*(Roman insulae)*, the two lower floors were for commercial and storage purpose while upper floors were rented to tenants.

In Yemen in the 16th century there was found an early example of a city consisting of high-rise apartment buildings called Shibam, **Figure (15)** it had more than 500 tower houses sometimes reached 11 stories height, each floor was considered to be an apartment for the occupation of a single family, it was built with mud brick and still the tallest mud brick building in the world.[3]

Figure (15) The City of Shibam, Yemen
Ref: (Wikipedia, the free encyclopedia n.d.).

The interface between the west and east was repeated, the east this time was Arab, mostly Muslims ,one of the major example of this interface is the fabric of Seville cathedral; Thus. Its bell tower which is known as the Giralda[4] which was converted from the minaret left by retreating moors.[5]

1 (Wells 2005). P.7
2 (Wikipedia, the free encyclopedia n.d.) - (Abouseif, 1989)
3 (Wikipedia, the free encyclopedia n.d.).
4 (S. B. Fletcher 1967).
5 (Wells 2005). P.7, 8& 9.

1.3.8 Tall buildings in dark ages

In north Europe, in dark ages the era of cathedral buildings started. Extra ordinary heights were established by stones with high quality precise decorations; this was due to peripatetic journey men and stone masons[1].

Flying buttresses, piers, new vault forms and pointed arches were introduced which enriched the architecture of cathedrals, the techniques of cathedral construction were in its peak point is **ULM cathedral Figure (16-a)** in southern Germany[2] and Choir at **Beauvais cathedral Figure (16-b)** in France.

The beginning of the change of structural thinking was based on **Galileo Galilei** who formalized the trend of putting structural dimensions by the experience of craft men. Instead would be rationally deduced to meet new environments safely and economically. This was a new start which will be recognized in 19th century later on.[3]

Figure (16) (a) ULM Cathedral in Southern Germany, (b) Beauvais Cathedral in France
Ref: (a) (Wells 2005).P. 8. - (b) http://www.essential-architecture.com

1 ibid.
2 (Wells 2005). P.7, 8,& 9.
3 (S. B. Fletcher 1967).

1.4 Tall building starting from the 19th century starting from Chicago, North America and Graphical transition

By the middle of 19th century, the new era for sky scrapers race began. At the beginning it was centralized in North America specially in Chicago and New York, this was related to many factors and events that occurred at that time. However North America began to be the host of major tallest sky scrapers starting from second middle of the 19th century up to the middle of the 20th century mainly located in New York and Chicago.[1] Mostly were characterized by their steel construction as a major material in addition to concrete. [2]

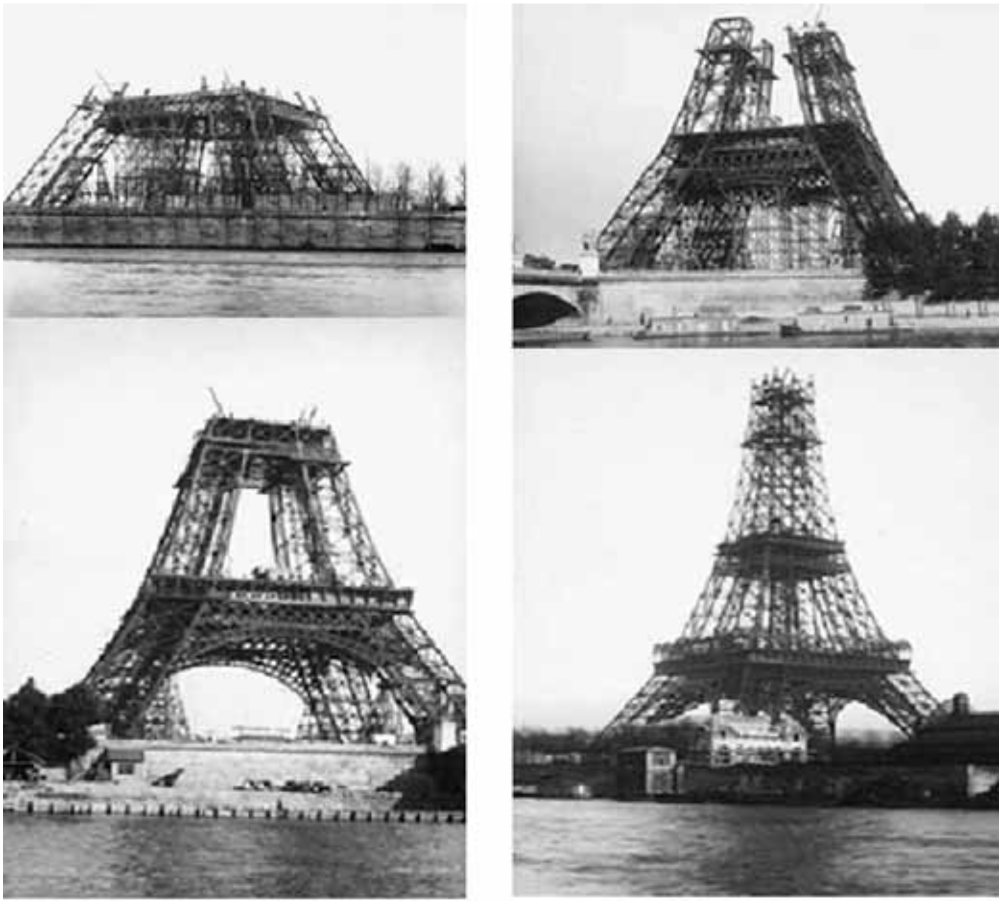

Figure (17) Construction Of The Eiffel Tower
Ref: (Moma's n.d.)

[1] (Contributors, Tall Buildings and Urban Habitat 2001). P.482 - (Wikipedia, the free encyclopedia n.d.).
[2] (Dewidar 2006-2007).

On the other hand, there were some trials in Europe especially in London and Paris with its **Eiffel tower Figure (17)** that reached 300 meters height[1], but for first half of the 20th century limitations such as fire restrictions (fire safety) and some concerns about aesthetics had likewise hampered the development of sky scrapers across Europe but with some exceptions such as:

- **Boerentoren** in Antuerp ,Belgium (1932) of 26 stories **Figure (18-a)**.
- **Torre Piacentini** in Genoa, Italy (1940) of 31 stories **Figure (18-b)**.[2]

Figure (18) (a) Boerentoen in Antuerp, Belgium, (b) Torre Piacentini in Genoa, Italy
Ref: http://www.flickr.com

Probably until the middle of the 20th century there was an opposition between the urban growth in North America and Europe, North America was growing up vertically with the release of new architecture and style of modern elevations and curtain walls. On the other hand buildings were still growing horizontally in Europe. [3]

Far in Australia between (1888 -1891) there were some trials of a significant numbers of early sky scrapers; but none of these were from steel ;but Starting from 1930, sky scrapers began to appear in:

1 (Wells 2005). P.9 - (E.Saouma 2003). P.154 - (Moma's n.d.).
2 (Foster 2006) - (Council on Tall Buildings n.d.)
3 (Foster 2006) - (Dewidar 2006-2007) - (Wikipedia, the free encyclopedia n.d.)

- Latin America especially in São Paulo, Caracas and Mexico City **Figure (19)**.
- Asia especially in Tokyo, Shanghai, Hong Kong, Manila, Singapore, Mumbai, Jakarta, Kuala Lumpur, Taipei and Bangkok **Figure (20)**. [1]

Figure (19) Sao Paulo, Brazil
Ref: http://www.centerforstudyabroad.com/sao-paulo.html

Figure (20) Shanghai Sky Line
Ref: http://tejiendoelmundo.wordpress.com

Starting from 1950 Europe also slowly began to introduce sky scrapers and to grow vertically there in Madrid, Spain, London and Paris. Then this trend was transferred slowly to Africa, Middle East and Australia.[1]

[1] (Council on Tall Buildings and urban Habitat.CTBUH Criteria for defining and Measuring Tall Buildings 2009)

All around the 20th Century some cities were dominating and leading the building of tall sky scrapers. Chicago and New York in South America, Hong Kong in Asia were known as the big three due to having the most compelling sky line in the world.[2]

By the end of the 20th century there were some graphical transitions in tall buildings location around the world. Some countries and cities started to take place on world's map as countries and cities hosting tall buildings and can be called the tallest building around the world. An example of these mentioned is Shanghai in China, Malaysia and Dubai in United States of Emirates with **Burj Dubai Figure (21)**, the tallest sky scraper in 2010.

Figure (21) Burj Dubai
Ref: http://hawtaction.com

[1] (Wikipedia, the free encyclopedia n.d.).
[2] (Chung 2003) - (Wikipedia, the free encyclopedia n.d.).

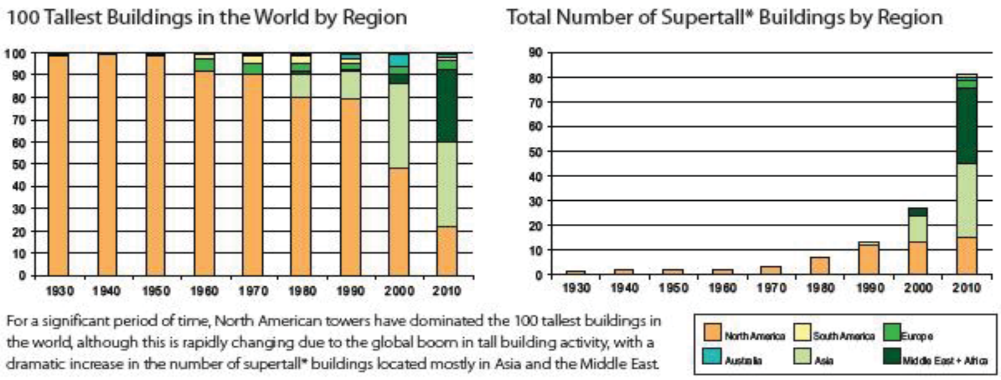

Figure (22) Tallest Building in the World Region
Ref: (Tall Buildings in Numbers 2008).

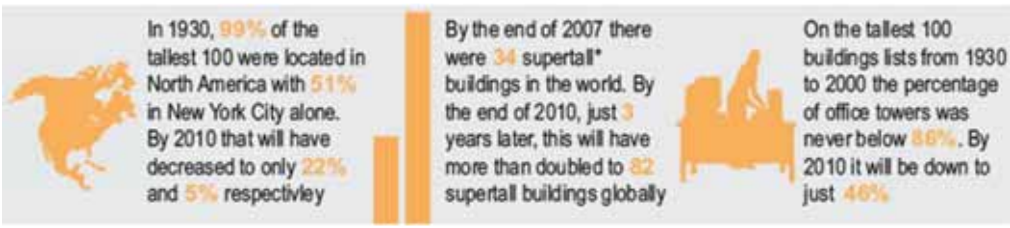

Figure (23) Tallest Building in the World Region
Ref: (Tall Buildings in Numbers 2008).

1.4.1 Factors affecting the appearance of early sky scrapers in Chicago by the middle of the 19th century

1.4.1.1 Bell’s telephone (1876)

The invention of Bell’s telephone and its wide spread had changed the meaning of face to face meetings. It is no longer people were in need to meet each other to finish work. This has an economic value, no more companies has to spread horizontally on expensive lands. Thus it can just grow vertically.[1]

1.4.1.2 The invention of safe elevator (1853)

Growing vertically has a major problem; large numbers of stairs has to be climbed up unless there is another way-so called elevator. In 1853 the American inventor Elisha Otis was able to invent the self-braking electrical elevator, so five stories was no longer the practical maximum height for a tall building. [2]

[1] (Wells 2005). P.10.
[2] (Wells 2005). P.10 - (Barss 2007). - (Dewidar 2006-2007).

1.4.1.3 The new approach to use steel construction after Chicago fire

By increasing the height of the building, structural elements grow wider thicker specially in wall bearing system, even in a skeleton system of concrete and stone or masonry construction limitation are still found. [1]

In 1848 James Bogardu’s was able to invite the iron frame this gave the ability to introduce new construction technology but with limitation due to lack of fire resistance technology.[2] In 1871 **Nixon Building Figure (24-b)** was the first building designed for fire combat, metallic members in this structure were covered by Inch of plaster of Paris.[3] In 1871 Chicago suffered a devastating fire. Most of the city was built up with timber frame structure, so called balloon frame, which help fire to grow widely. The city has to recover but instead of recovering slowly the city experienced explosive growth, architect in Chicago started to think differently, new vision of the city can be achieved, no longer they have to built horizontally specially after they found themselves capable of using steel construction after the discovery of fire protection. [4] The first application of a skeleton steel structure that does not depend on masonry was the **Home Insurance Building Figure (24-a)** in Chicago (1884-1885) that reached 10 stories and can be considered as the first known load bearing structural frame which was created by major architect William Le Baron Jenney (a steel frame supported the entire weight of the walls). Some can consider this as a new development that lead to the Chicago skeleton frame of construction.[5]

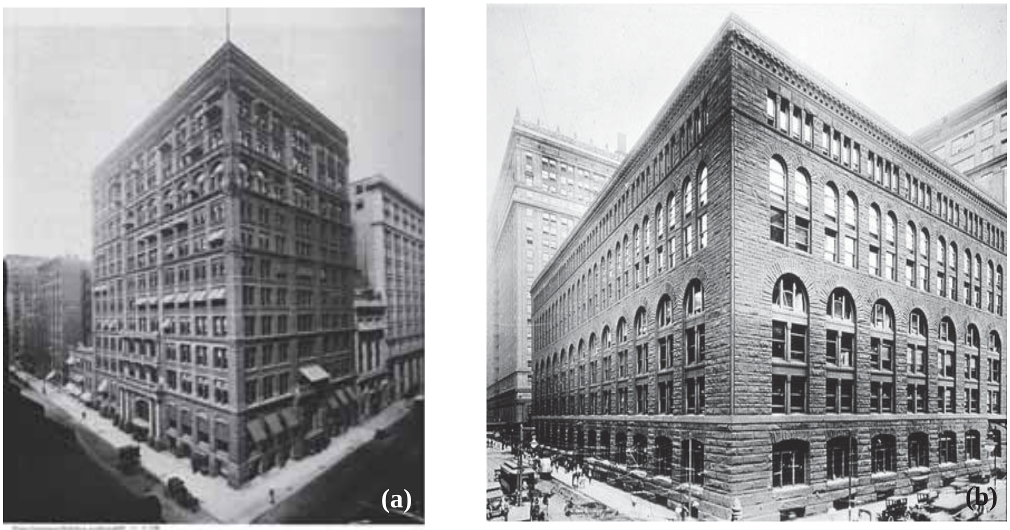

Figure (24) (a) Home Insurance Building, (b) Nixon Building.
Ref: (a) http://ecuip.lib.uchicago.edu - (b) http://www.brynmawr.edu

[1] (WGBH Educational Foundation BUilding Big: Skyscraper Basics n.d.).
[2] (Dewidar 2006-2007).
[3] Ibid.
[4] (Wells 2005). P.9,10& 11 - (Barss 2007). - (Contributors, Tall Buildings and Urban Habitat 2001)
[5] (Contributors, Tall Buildings and Urban Habitat 2001) - (Tall Buildings in Numbers 2008)- (Dewidar 2006-2007).

In 1891 **Wain Wright Building** in St. Louis was considered to be the first true sky scraper, it is the first steel framed building with soaring vertical bans to emphasis the building height (by **Louis Sullivan**).[1]

1.4.1.4 Transition from classical style to modern style in sky scrappers

Early tall building development was based on economic equations which is increasing rentable area by building vertically instead of horizontally and increasing the entrance of natural light to the space through wide window bays and curtain walls. [2]

An early example to the appearance of the wide window bay which became available after the use of iron/steel structure is the **Reliance Building** (1894) **Figure (25-a)**, Chicago designed by **CharlesB.Atwwood** of **Daniel H.Burnham's** architectural firm. It is considered as the first sky scraper to have large plate glass windows. [3]

In the early age of sky scrapers there were many different outlooks to the sky scrapers profile. This was due to the change of construction technology to iron/steel; building profile has to change from classical wall bearing masonry or concrete appearance to iron/steel appearance. At the beginning iron steel structures were cladded with other solid materials such as brick or terra cotta. Different from traditional load bearing masonry walls, these claddings did not carry any loads from building but their own weight only and this was the start toward a new cladding which is the curtain wall. [4]

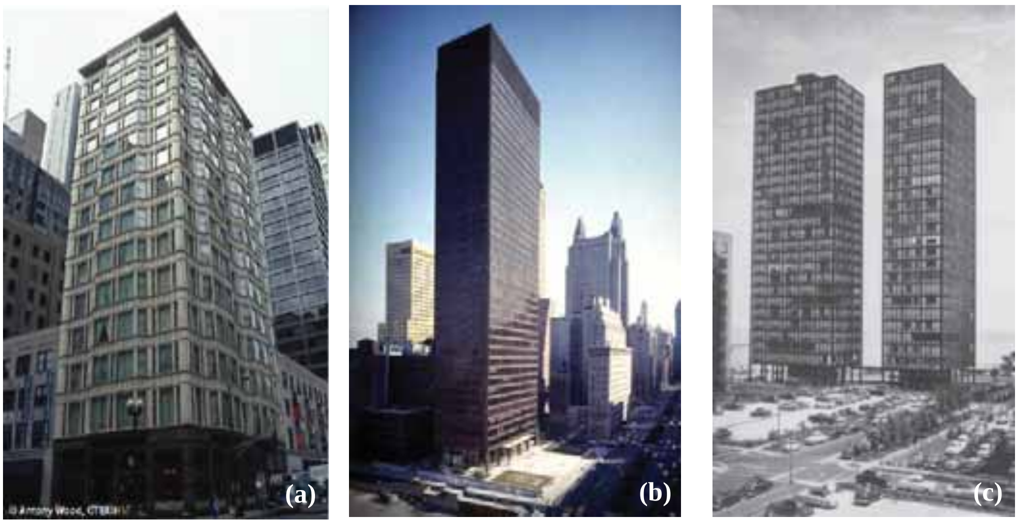

Figure (25) (a)Reliance Building in Chicago, America, (b) Segram building, (c) 860–880 North Lake Shore Drive
Ref: (a) http://www.ctbuh.org -(b) (Wells 2005). P. 15- (c) (Contributors, Tall Buildings and Urban Habitat, The Futur High Rise Buildings 2001)- George Schipporeit P.349.

[1] (E.Saouma 2003) - (Wikipedia, the free encyclopedia n.d.).
[2] (Dewidar 2006-2007) - (Moon 2007).
[3] (Wells 2005). P.12.
[4] ibid . P. 9-15 - (Moon 2007).

Mies van der Rohe was one of the most important architects who expressed the new profile of modern sky scrapers in the middle of 20th century from famous examples of these sky scrapers is the **Seagram Building Figure (25-b)** in New York 1954 and **lake shore drive Figure (25-c)** in New York.[1]

Nowadays sky scrapers are completely modern with its new construction technology, forms, structures and building materials. They are no more glass box as in middle of 20th century or old classical tower as in 19th century.

1.4.1.5 The race of tall building around the world

Starting from the middle of 19th century most of tallest sky scrapers were located in North America especially in New York and Chicago. The two cities were in competition to host world tallest building, New York took the lead by 1895 with the compilation of American **Surety Building** then **Chrysler building** 1930 followed by the **Empire State Building** 1931 which become the world tallest building for forty years until the construction of first WTC which became the world tallest building in 1972, Chicago took the hand in 1974 with the compellation of **Sears tower** (Willis tower) which became world tallest building for many years. The race didn't stop and won't stop, after sears tower there was the twin towers of **Petronas** followed by **Taipei 101** and today in 2010 **Burj Elkhaleefa** in Dubai is completed to be the world tallest tower, and the race will continue.

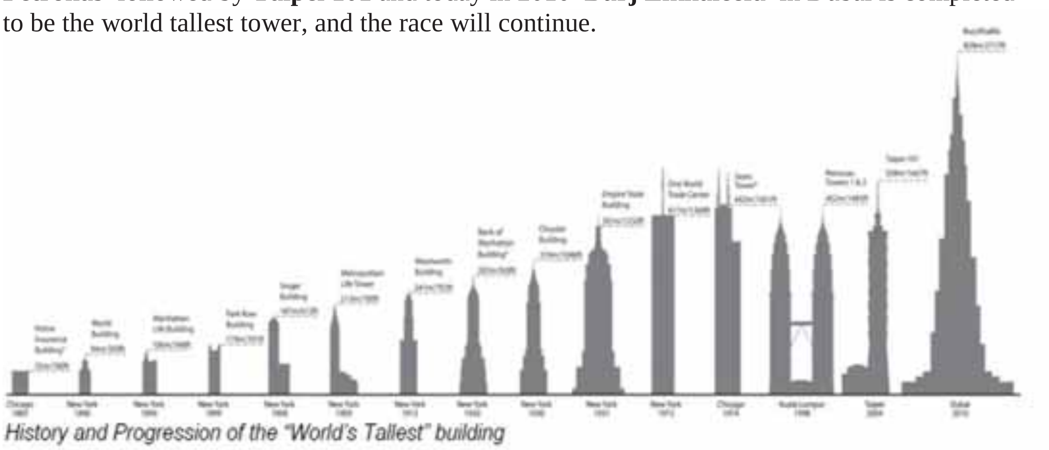

Figure (26) Showing the race of tall building around the world
Ref: (Council on Tall Buildings and urban Habitat.CTBUH Criteria for defining and Measuring Tall Buildings (2009).

Summary

Tall buildings are nothing new but starting from the 19th century and after Chicago great fire tall buildings became a challenge and a race among cities to host the tallest building first in North America until it reached the Middle East countries.

1 (Contributors, Tall Buildings and Urban Habitat, The Future of High Rise Buildings 2001). P. 348,349

CHAPTER TWO

DESIGN PROCESS AND CONSTRAINS FOR TALL BUILDINGS

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DESIGN PROCESS AND CONSTRAINS FOR TALL BUILDINGS

2.1 Introduction

Tall buildings have a very powerful symbolic value on the environment and the urban context in which it exist, it is not only a matter of function, but also it represents a sky line of the city; cities began a great race to built the tallest building, since the middle of the 19th century; although it is expensive and hard to build high[1].

A tall building's form is one of the major elements that have an impact on building aesthetics and behavior. However it is a complex task to develop an innovative concept for a tall building, architecturally, structurally and aesthetically, this is because of the inter-relation between many factors and requirements such as building function, its structure system, and its relationship with the building's form, regulations, economics, and politics, each represent a problem that need a solution but with respect to the others[2].

During the design process these requirements interact together to generate at the end a final symbolic aesthetic form, tall buildings differ than normal height buildings in two main requirements. The first one is a structural requirement, which is due to the great tallness of the building that should be designed to resist lateral loads in addition to gravity loads. The second requirement is the building function that requires an internal planning but with special treatment due to the presence of a fixed basic element which is the core, i.e. a core for a tall building is an important element from both point of views structural and architectural[3].

Core design needs a special treatment to decide how to arrange elevators, stairs, technical room which can be a third requirement, that's why an architect finds it a great challenge to design a tall building.

2.2 Structural constrains facing tall buildings design

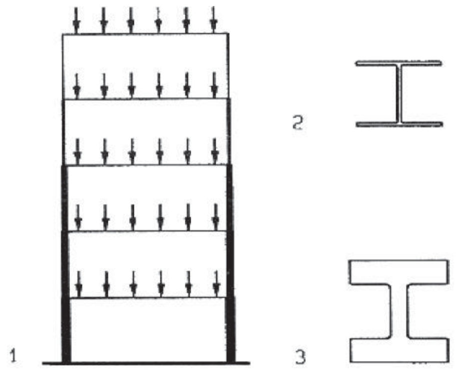
Tall buildings can be considered as a vertical cantilever with its base fixed on the ground, basically it is exposed to two main kinds of loads that cause bending, shear and tortional effects. These loads are simply the gravity and lateral loads.[4]

2.2.1 Gravity loads

Gravity loads are a combination of live and dead loads, it acts in a vertical direction generating a compressive stress in supporting columns or walls. And as it is well known,

[1] (Sang Min Park n.d.).P.1,2.
[2] ibid.
[3] Same as 1.
[4] (Schierle 1990-2006.).P. 15.

members which receive gravity loads increase from base to top in its cross sectional area[1] **Figure (27).**



1 structure with increasing columns size as load increases from top to down
2 light -weight, wide-flange column
3 heavy weight wide-flange column of equal nominal size as in 2 above

we can recognize that structural elements decreases vertically from bottom to top due to the decrease of loads

Figure (27) The effect of Gravity loads on tall structures.
Ref: (Schierle 1990-2006.). P.15-3.

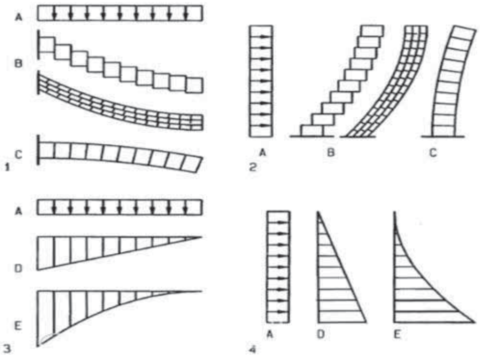
2.2.2 Lateral loads

The effect of lateral loads on buildings is similar to the effect of gravity loads on cantilevers; these loads are wind and seismic loads. They are the major factors that cause bending, shear and tortional effects on a tall building. Wind and seismic loads are not uniform along the buildings height. Wind and seismic force increases from bottom to top due to higher wind speed and reduced friction. On the other hand, shear increases from top to bottom because the structure at each floor must resist forces in its level, in addition to forces from all floors above as well[2] **Figure (28).**

Lateral load resistance will be explained in the next chapter, however the elements to resist loads are usually arranged on the outer perimeter of the tall building and inside it, it is preferred to have the structural elements centralized inside the building to provide a symmetrical resistance to loads from all directions[3].

Generally for any tall structural form, there are main and secondary components, both act together to overcome external loads and forces affecting the building. The arrangement and type of the two components gives a variety of systems, each is suitable for a specific form . This can be recognized through the arrangement and location of major and minor components within that specific form[4].

1 (couil 1991).P.15-3 - 15-6
2 ibid.
3 (DAVID SCOTT Published online 2 November 2007). P.441-444.
4 (Moon 2007). P. 207.



1 Cantilever beam with shear and bending deformation.
2 Tall building with shear and bending deformation.
3 Shear and bending diagrams for uniform load on a cantilever beam.
4 Shear and bending diagrams for idealized uniform load on a building.

A Load/force diagram.
B Shear deformation.
C Bending deformation.
D Shear diagram.
E Moment diagram.

Figure (28) The effect of lateral loads on tall structures.
Ref: (Schierle 1990-2006.), P.15-4.

2.3 Tall Building's Form Design process

Any tall building is mainly composed of either a single or multi cores inside its geometry or at its corners according to the architectural idea **Figure (29)**, in addition to an outer skin (Exterior Wall) which represents the building geometry and style.

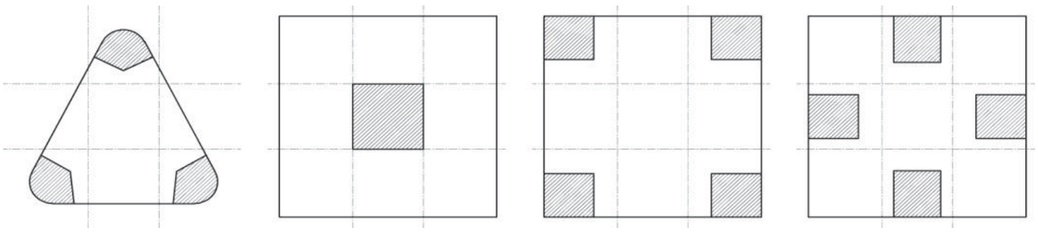


Figure (29) Examples of the location of cores inside the tall building
Ref: By the researcher.

There are unlimited numbers of profiles for tall buildings that generate unlimited forms, but most of these forms undergo the rule of core and skin, it is preferred to use a central core for tall buildings, because it serves in providing a kind of lateral load resisting for the structure thus, many of the key structural elements such as shear walls, bracings are integrated into the core; elevator shafts, and stair, which are ideal for this purpose. Also the central core can collect the most required spaces need for the tall building centrally to be equalized in all directions such as, fire stairs, elevators shafts and lobbies, toilets, machine rooms for the air handling units, electrical and telephone closets are all collected inside the core, this can help in complex form's generation where its floor plates varies in shape, size and direction where the presence of outer structural elements cannot be easily achieved, the main core has to be centralized to be the main load resisting element[1] **Figure (30).**

[1](A.Kliment 2002).

Figure (30) Different examples for cores inside tall buildings
Ref: Building type basics for office buildings P.36.

The design of tall building involves professionals from several disciplines, the role of an architect in this design process is very important from the point of view of form generation. Architects and engineers together create a set of possible alternative forms for a certain tall building according to its requirements and needs taking in consideration the three main requirements mentioned before, in additional to aesthetic needs. “80 percent of the resources required to build a structure are committed by decision made during conceptual design stage”[1]. **Figure (31)** shows the design elements of tall building forms , these elements are not the only elements that compose a tall structure but they are the major elements which are mentioned before (core + outside skin or building geometry + structural elements), for any design process there are requirements, in tall buildings design some of the major requirements that cannot be neglected are structural and architectural requirements including core design and internal planning to satisfy design and client needs.

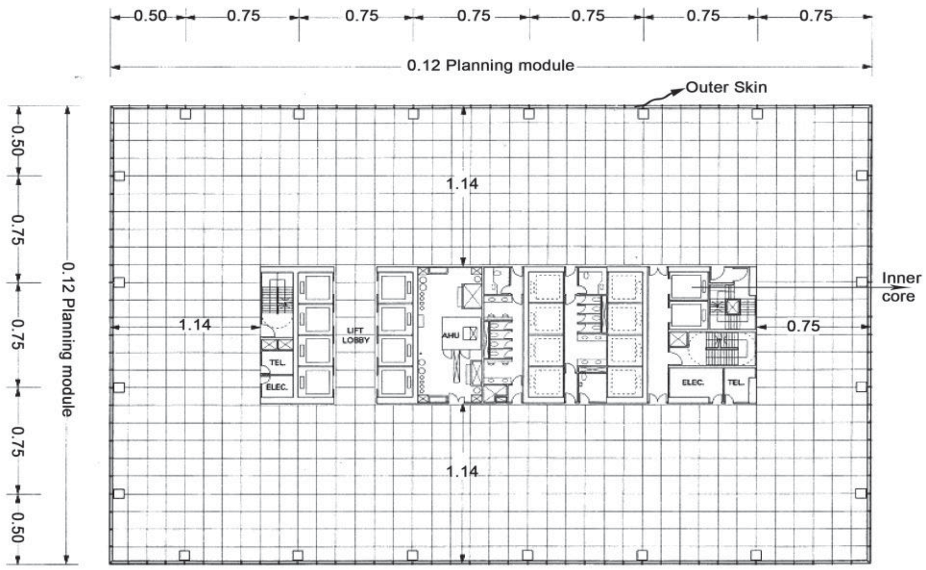


Figure (31) The Typical floor plan for a high rise.
Ref: (A.Kliment 2002). P.36.

1 (Sang Min Park n.d.).P.2.

The following sketch represent the design parameters for tall buildings during the design process, it is a development of a flow chart proposed in 2004 (CHBUH Seoul conference) in a paper discussing the design process of tall buildings by the Para Metric method **Figure (32)**.

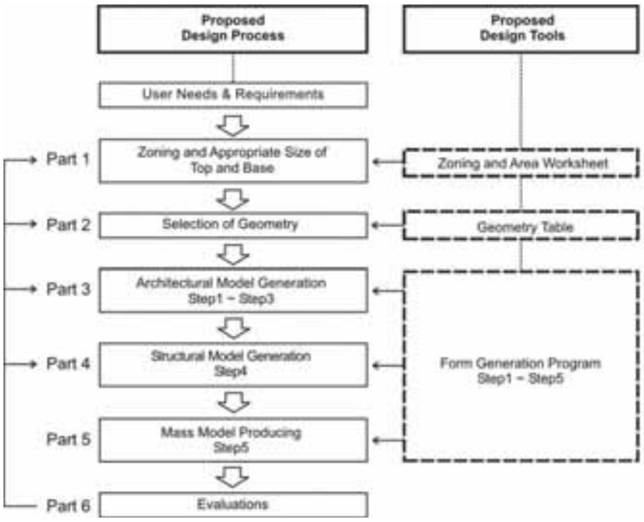


Figure (32) Proposed Design Process and Tools
Ref: (Park n.d.). P.4.

According to all considerations, the architects start to generate concepts for tall buildings, generally since the 19th century, there has been more than one trend for designing tall buildings these trends will be briefly discussed in chapter(4).

2.4 Factors That Affect the Structural Form in Tall Buildings

There are many factors that can affect the design of a tall building's structural form, economics, politics, building height, urban context, material and methods of construction etc., but concerning the relation between the form generation and its structure,the major factors can be as follow.

- Function of the building.
- Height of the structure
- Materials and methods of construction.
- Form shape and type.

2.4.1 Function of the building

A major consideration affecting the structural form of tall buildings is its function, for example modern offices has different considerations than residential buildings, it calls for large open wide spaces with less number of columns and vertical elements inside the space to give more flexibility to the space internal arrangement through portable partitions that can be rearranged according to the building needs. In this case structural elements need to be arranged as far as possible, more than that it is preferred to be arranged on the exterior perimeter of the plan if possible and for internal elements to be arranged in groups inside the core of the building adjacent to elevators, stairs and service shafts, services are mainly distributed horizontally in each story above partitions usually above false ceiling. This requires more clear height than a residential building with same number of stories, thus a typical floor plan of an office building need a height of 3.5-4.2 meter while a residential typical floor plan can be just 2.7 meter height[1] **Figure (33).**

Also there are much more restrictions in the design of tall residential buildings than in case of offices due to the presence of fixed service elements such as bathrooms and kitchens which obstruct the form ,i.e. an architect has less options to design complex geometry form for a tall building in case of residential towers than in case of offices. So it is advised in case of designing a tall complex residential tower to collect all service rooms near the core and to let the outer skin just to include free open spaces such as receptions and dining rooms which have some possibilities to let the elevation to be designed freely.

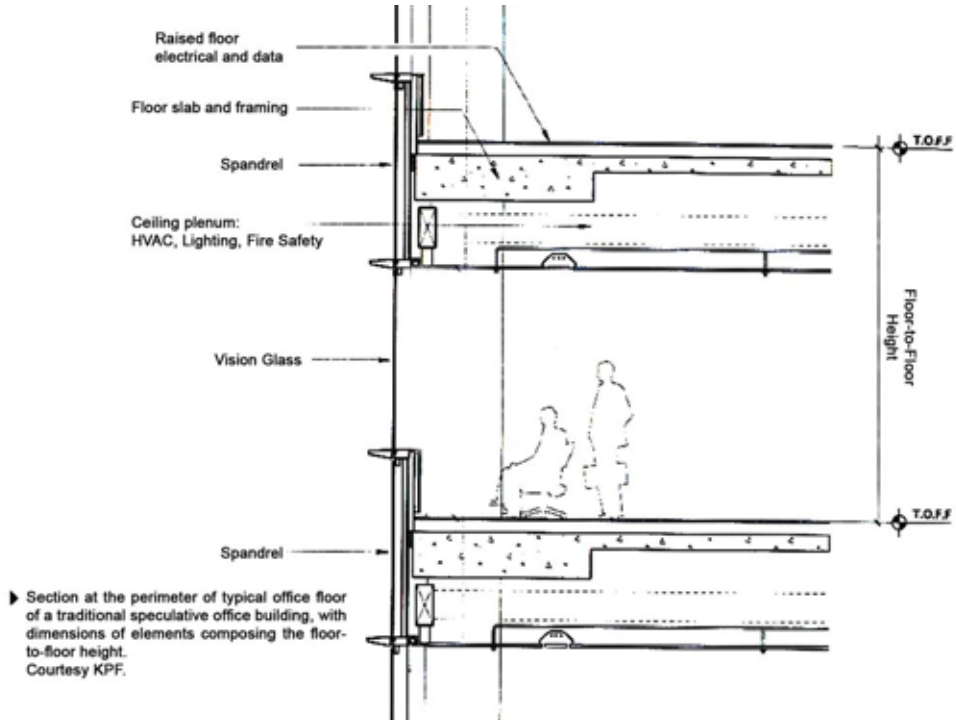


Figure (33) Section at the perimeter of a typical office floor of a traditional speculative office building**.**
Ref: (A.Kliment 2002). P.36.

1 (couil 1991).P.34 - (A.Kliment 2002).P.35&36

For residential buildings, its internal planning gives more flexibility in the arrangement of structural components that are not necessary to be arranged just only on the exterior perimeter of the building, but also it can be arranged to fit within the walls and corridors as show in **Figure (34).**

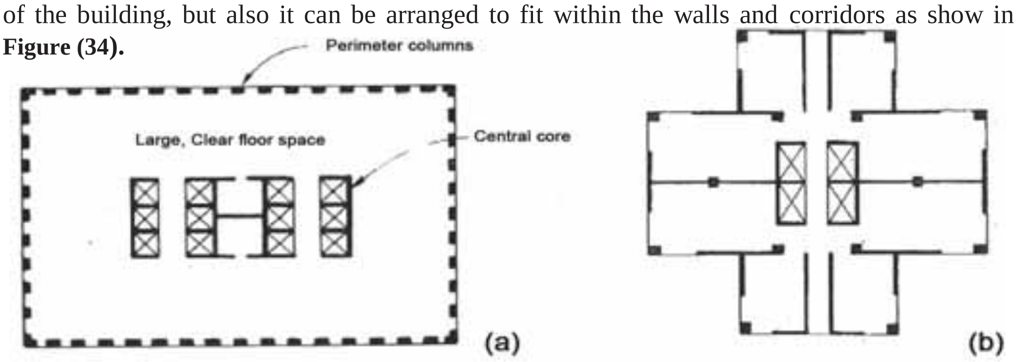


Figure (34) (a) Plan of office block (tube-type), (b) Plan of Residential Block.
Ref: (McGraw-Hill 1995). P.35 & 36

2.4.2 Height of the structure

In most tall building a structure system should offer a type of floor framing connected somehow to vertical columns, in addition to a wind bracing solution. Not all tall buildings require all of these together, but the case of the building itself can determine which is required and which is not. The points just mention has a great relationship with the structure height, for example, by increasing the height of vertical members like columns, its size will increase specially in buildings higher than 10 stories, while floor framing will not be affected mainly by height, but by the flooring span, so choosing a suitable system related to height is very important or otherwise, there would be a great loss in construction materials which may be critical for economy [1] **Figure (35).**

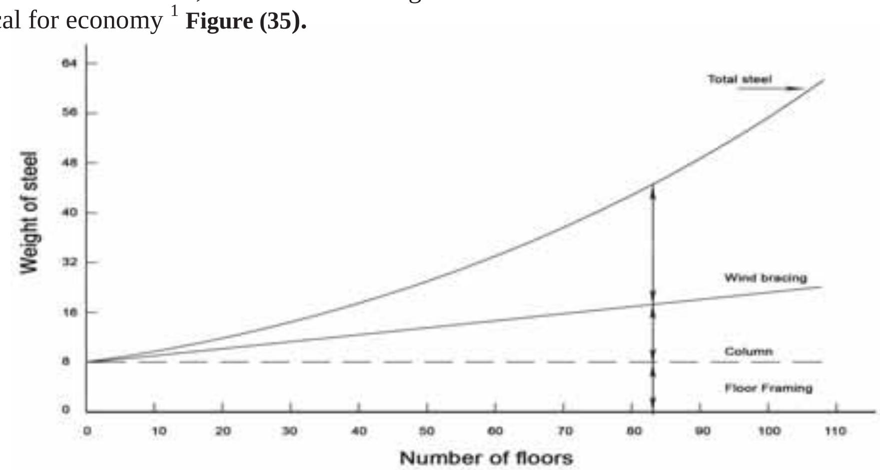


Figure (35) Weight of steel in tall building
Ref: (McGraw-Hill 1995). P.35.

[1] (couil 1991).P.35.

2.4.3 Material and method of construction

Choosing the suitable construction material can easily protect the building from a great economic loss and non efficiency. For example, for some systems and spans steel can show more efficiency than concrete and vice versa according to building height. Member size increases with height as mentioned before, for concrete members size is much more greater than those for steel so with large heights, it is preferred to choose vertical steel; while floors can be left with concrete; however sometimes there can be a mix of both materials to give more efficiency[1].

2.4.4 Form shape and type

Mostly concepts for tall building is somehow represented through its form , there are many trends to generate tall buildings forms, these trends will be discussed later in the next chapters. However architects and engineers can find solutions for lateral load resistance facing these buildings . Today forms became variable and unlimited due to the new era of computer aided design; such as parametric design method, tall buildings forms are also land marks in its location.

Mainly form generation is the most complicated issue that the designer face during the design process, because it can give a solution to most of the constrains facing the design process.

Form generation today has passed by variable number of trends, these trends will be explained in chapter (4) in details. However form generation will last forever a challenge for each architect.

Summary

Tall buildings are exposed to two kinds of loads which are gravity loads and lateral loads (wind & earthquakes), and they mainly consist of two fundamental elements which are the inner core and the skin where structural elements are arranged. The design process for tall building involves professionals form several disciplines. The major factors affecting structural form for tall building are the function of the building, the height of the structure ,the material and method of construction and the form shape and type(form generation trend). See chapter (4)

[1] (Tall Building and Urban Habitat-Cities in Third Millennium March 2001).P.484.

PART TWO

STRUCTURAL AND ARCHITECTURAL CLASSIFICATIONS

CHAPTER THREE

Structural Classification for Tall Building Systems

CHAPTER THREE
Structural Classification for Tall Building Systems

3.1 Introduction

Tall buildings are classified into two categories according to the arrangement of primary lateral loads resisting systems component over the building; which are:- [1]

I. Interior structures

A system is characterized as an interior structure, when the major lateral load resisting components are located within the interior of the building (inside the building) and the minor components on its perimeter[2] **Figure (36).**

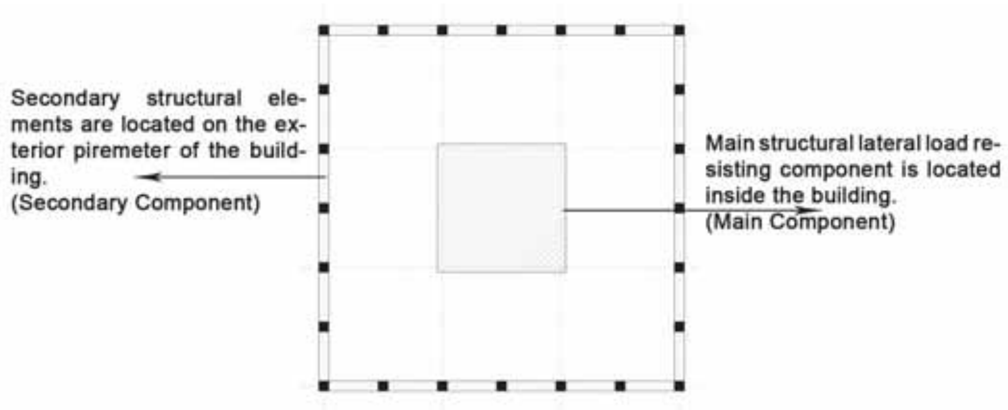


Figure (36) The typical diagram for interior structures

Examples of interior structures are:

- Rigid frames.
- Braced hinged frames.
- Shear wall / Hinged frames.
- Shear wall (or shear truss) – frame interaction system.
- Out-rigger structures.
- Suspended structures.
- Core structures.

[1] (Moon 2007).
[2] ibid.

These systems will be explained in details later see **Figure (37).**

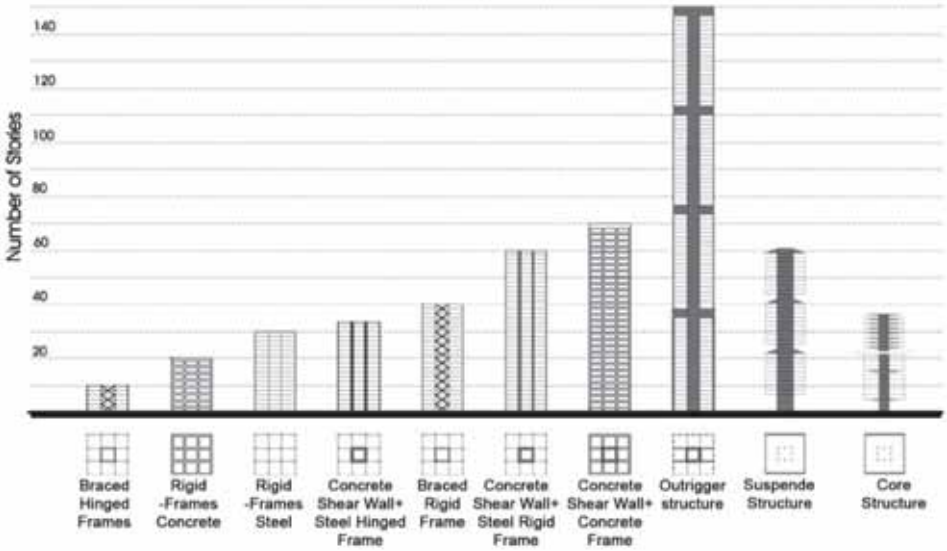


Figure (37) Different types of interior structures.
Ref: (Moon 2007). P.211.

II. Exterior Structures

A system is characterized as an exterior structure, when the major lateral load resisting components are located at the building perimeter and the minor components within the interior of the building[1] **Figure (38).**

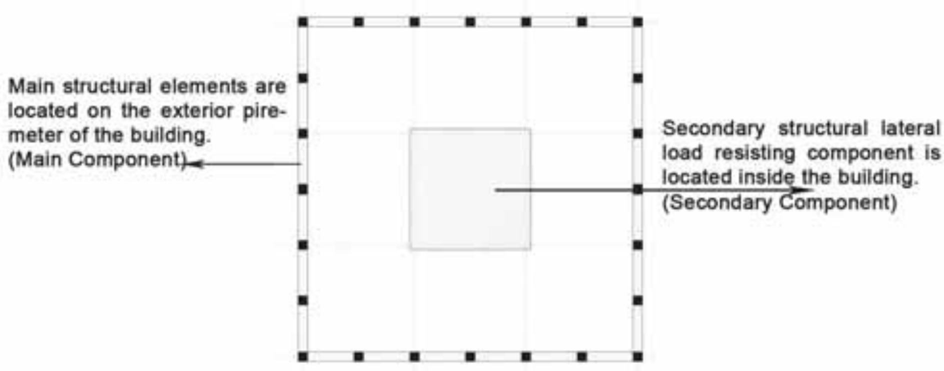


Figure (38) The typical diagram for exterior structure

1 (Moon 2007). P. 208,209&210

Some examples of exterior structures are:

- Tube structures (Framed tube - Braced tube – Bundled tube – Tube in tube).
- Dia-grid.
- Space truss structure.
- Super frames.
- Exoskeleton.

These systems will be explained in details later **Figure (39).**

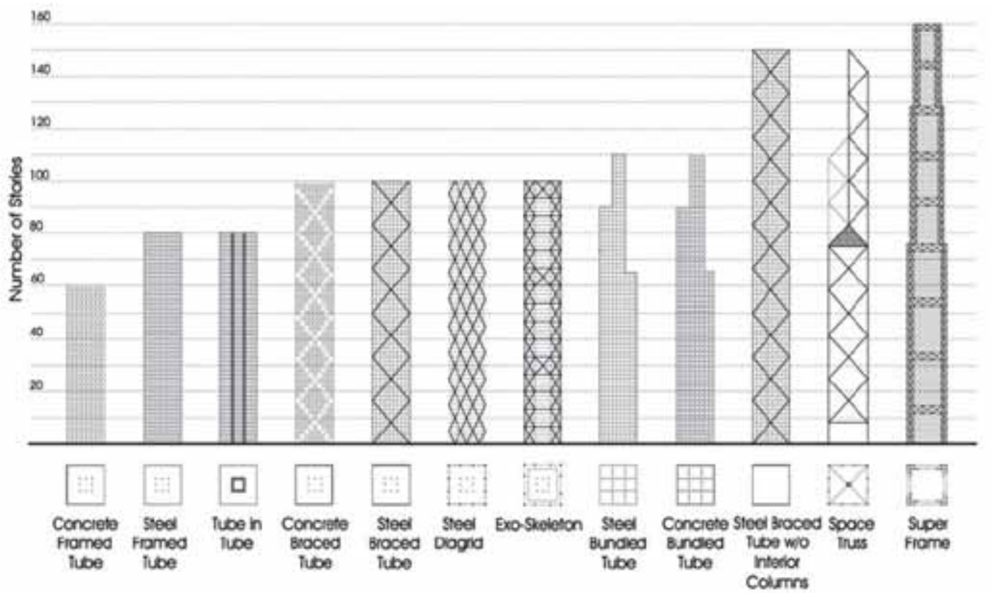


Figure (39) Different types of Exterior Structure.
Ref: (Moon 2007). P.211.

This classification is only a guide line and it is not necessary to match always with all tall buildings. There are many other factors that can affect the structural idea of the tall buildings such as; load condition, type of the building, height of the building, and even its shape, sometimes an exterior structures may be combined with an interior one such as when a tubular frame is also braced with a core supported out-rigger and belt trusses to enhance the building[1].

This classification was proposed in June 2007 through a research published in Architectural ***Science Review Volume 50.3, pp 205-223*** under the title of "*structural development in tall buildings: current trends and future prospects*" and it was based on previous classification by **Fazlur Khan** in 1969, he classified tall buildings, structures and this was the start of an era of sky scraper revolution in terms of multiple structural systems ,he divided his classification into two diagrams one for steel and the other for concrete[2] **Figure (40).**

1 (Moon 2007). P.208.
2 (couil 1991). P.5 - (Moon 2007). P.207& 208.

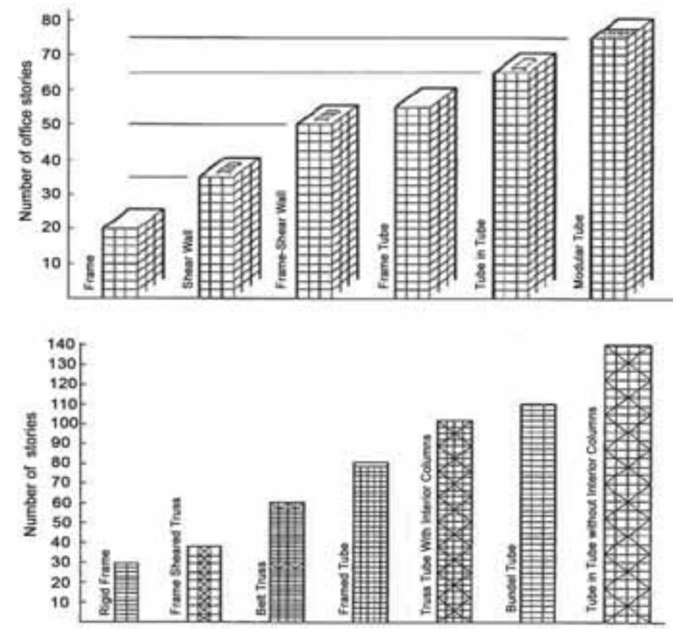


Figure (40) Classification of tall building structural systems by Fazlur Khan (above: Concrete; below: Steel).
Ref: (Moon 2007). P.208.

3.2 Interior structures analysis and examples

The two fundamental lateral load resisting systems in the interior structures are[1]:

- Moment resisting frame (known as moment frame or rigid frame) (M.R.F).
- Braced frame known as shear truss or vertical truss.

These systems in common are arranged as planar assemblies in orthogonal directions, in order to create planer frame or planar tube frame system, both systems can also be combined together to create an interactive systems, also in addition to these two fundamental systems there are core-supported out-rigger structures which are very widely used in tall and super tall buildings[2].There are some additional systems depending on the core structure such as suspended and core with cantilever structures.

3.2.1 Moment resisting frame (M.R.F)

It consists mainly of horizontal beams (Girders) and vertical columns rigidly connected to each other on a planar grid form to resist lateral loads, column size increases from top to bottom due to the gravity loads while beams remain constant most of the time, the beams (girders) size is mostly controlled by the stiffness of the frame [3] **Figure (41).**

[1] (Moon 2007). P.51.
[2] ibid. P.208&209
[3] (McGraw-Hill 1995). P.53 - (couil 1991). P. 38,39.

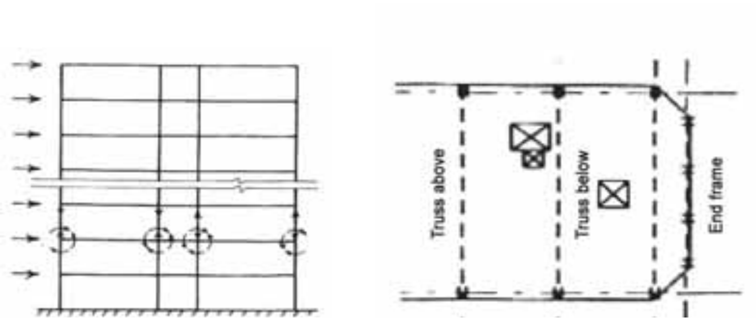
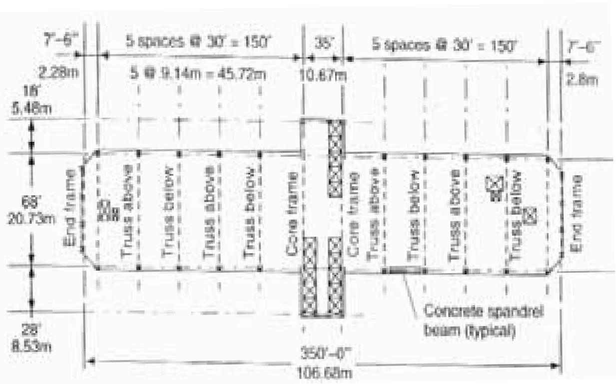


Figure (41) Moment resisting frame (M.R.F)
Ref: (couil 1991). P.39.-(McGraw-Hill 1995).P.97.

M.R.F can be either from concrete or steel but steel M.R.F can give more efficient height limit, the most recent advances of the rigid frame has occurred in the steel concrete composite arrangements through mixing steel and concrete sections to give a superior system better than both steel and concrete individually[1].M.R.F is normally efficient for buildings not more than 20-30 stories in height, because building higher than these limits; would need member proportions and material coasts that become unreasonable for construction, also it has advantages in high rise constructions due to their flexibility in architectural planning specially for their wide span. This is similar to the benefits of frames in other types of buildings[2]. M.R.F can be located in or around the core, on the exterior, and the interior along the gridlines of the building.**860 & 880 Lake Shore Drive Apartments** (Chicago, USA) **Figure (42-a)** is one of the well known examples for the use of steel rigid frame, another example for concrete rigid frame is **Ngalls Building** (Cincinnati, USA) **Figure (42-b)**.

Figure (42) An example of using Moment resisting frame. (a) 860 & 880 Lake Shore Drive Apartments, (b) Ngalls Building.
Ref: http://www.flickr.com

1 (Moon, 2007) P.209 &210
2 (McGraw-Hill, 1995) P.53.



On the left perspective of Tag Mahal and beside the architectural plan.

Figure (43) Another example of using Moment resisting frame, Tag Mahal Hotel.
Ref: (McGraw-Hill 1995). P.96 & 97.

3.2.2 Braced frame (shear truss)

Braced frames are cantilevered vertical trusses, sometimes called vertical shear trusses which resist lateral loads primarily through the axial stiffness of the member, columns act in this system as chord members, while the concentric braces having the shape X, K or V acts as the web members[1] **Figure (44)**.

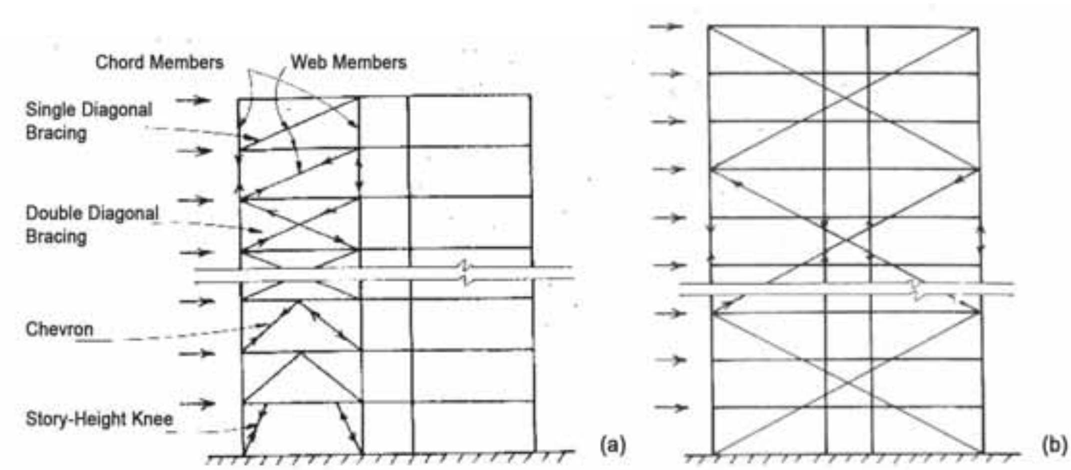
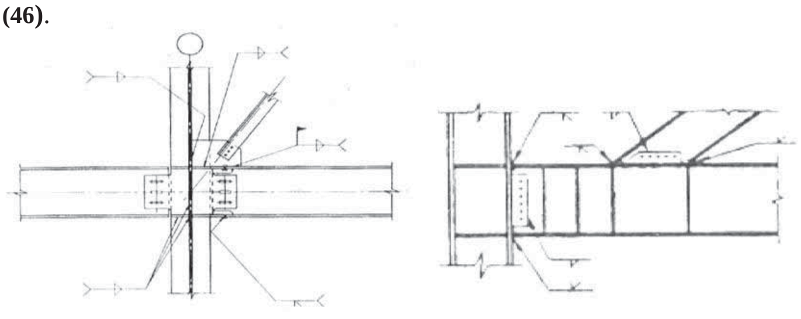


Figure (44) Braced Frame (Shear truss), (a) Trusses per floor, (b) large scale truss.
Ref: (couil 1991). P.38 & 39

[1] (couil 1991). P.37 - (M. Halis Gunel 2006). P.2669.

There are two main groups in braced frames (braced hinged frames), the first group is called concentric braced frames (C.B.F) **Figure (45-a)**, and the other group is called eccentric braced frames (E.B.F) **Figure (45-b)**, in (C.B.F) the axis of the members intersect at a point that means the forces are axial. So it is suitable for areas of low seismic activity because it mainly gives great amount of stiffness; but low ductility. On the other hand (E.B.F) utilized axis offsets to introduce flexure, and shear into the frame, which lower the stiffness to weight ratio but increases ductility and that is suitable for seismic zones where ductility is an essential requirement of structural design, braces here are connected to the floor girder as shown in [1] **Figure (46)**.



(a) **(b)**

Figure (45) Typical connection detail (a) C.B.F, (b) E.B.F.
Ref: (couil 1991). P.54 & 55.

Concentric and eccentric braced frames can be located in the services and elevators zone area of tall buildings, diagonals can be enclosed within permanent walls, braced frame structures are commonly built up with steel sections; which is easier in construction. This system is suitable for up to 10 stories[2].

Bracing is generally regarded as an exclusively steel system, because diagonals are inevitably subjected to tension due to lateral forces; the efficiency of bracing is the production of a laterally very stiff structure with minimum materials which is economically preferred[3].

A major disadvantages of diagonal bracing is that it obstructs the internal planning and the location of windows and doors, in addition to the diagonal connections which are expensive to fabricate and erect, traditionally bracing was used in story height bays with modules and that make many constrains within the façade, but now bracing can be with larger scales including more than one story to give higher efficient structures and aesthetically attractive buildings[4] **Figure (47).**

Generally a braced frame are used for low rise buildings but by combining this system with other systems greater heights can be achieved, **Kobe commerce industry center** can be a good example of combining braced core with a perimeter frame tube [5] **Figure (47)**.

[1] (couil 1991). P.51 - (Moon 2007). P.209,210
[2] (couil 1991). P.37&38.
[3] ibid.
[4] Same as 1. P. 38.
[5] (McGraw-Hill 1995). P. 85,86&87.

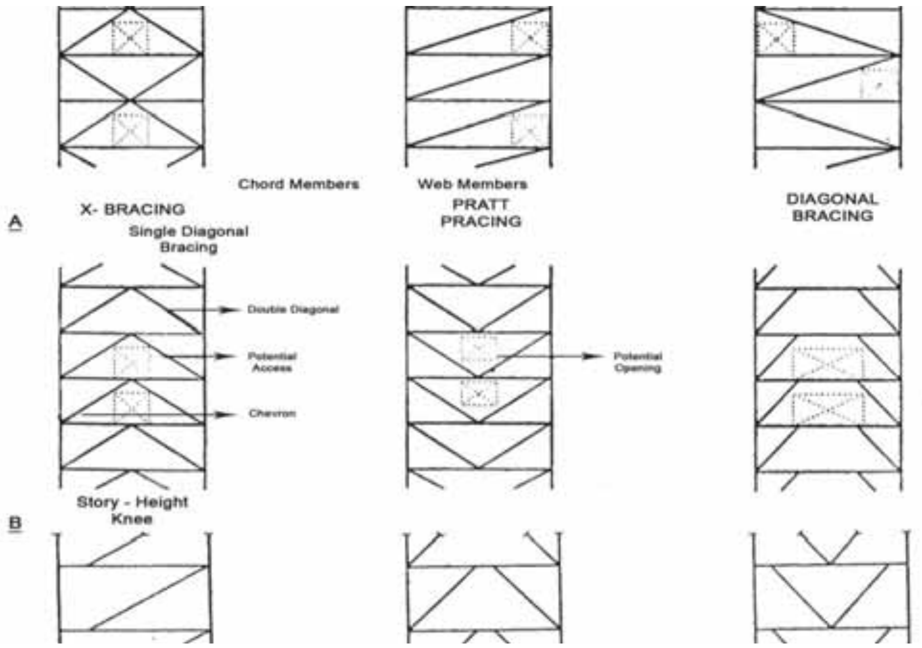


Figure (46) Typical connection detail (a) C.B.F, (b) E.B.F.
Ref: (couil 1991). P.52 & 53.

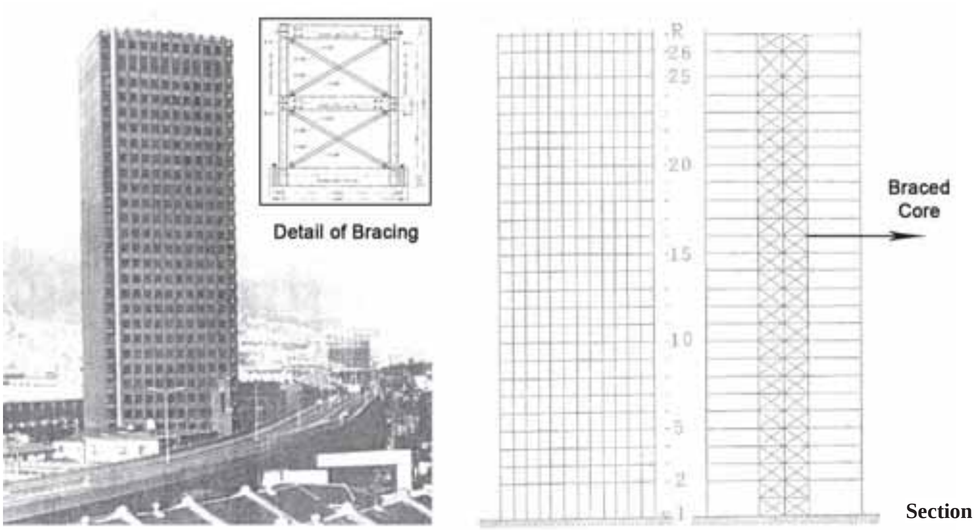


Figure (47) Kobe Commerce Industry and Trade Center, Kobe, Japan.
Ref: (McGraw-Hill 1995). P.86, 87 & 89.

3.2.3 Shear walls

Concrete or masonry continuous vertical wall can be used architecturally and structurally, mainly concrete continuous vertical wall; which is named as shear wall. It can act as a vertical cantilever fixed at the base to resist the lateral loads (seismic and wind) which is suitable for tall building.[1]

Shear wall acts as a plainer elements, sometimes more than one shear wall in the same plane or almost in the same plan can be connected together at floor levels by beams or stiff slabs; to create a coupled shear wall, this can create a system that exceed the sum of the individual wall stiffness **Figure (48).**

Mostly shear walls are combined with steel frames. Shear walls can resist lateral forces; while frames can be designed to resist gravity loads. Unlike rigid frames or braced hinged frames, shear walls has many restrictions in the internal planning specially in the location of doors and windows and in creating free spaces, so it is much more suitable in building having its internal planning uniformly divided with an architectural and structural module such as hotels and residential buildings, where the floor by floor repetitive planning which allows wall to be vertical and continuous[2].

Shear wall structures can be economical up to about 35 stories and they are generally located embedded in the walls or in the core especially around elevators and stairs.[3]

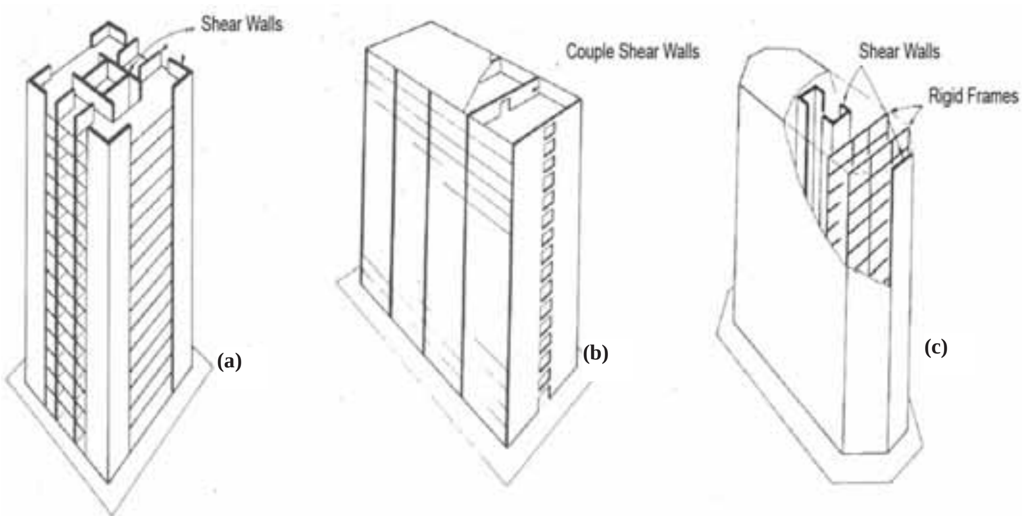


Figure (48) (a) Shear Wall Structure, (b) Coupled Shear Wall Structure, (c) Wall Frame Structure.
Ref: Structural system for tall buildings P.42 & 43.

1 (McGraw-Hill 1995). P.41,42&43 - (Moon 2007). P.210.- (M. Halis Gunel 2006). P.2669&2670.
2 (Moon 2007). P.210
3 ibid.

Metropolitian Tower (New York, USA) **Figure (49-a)**, **77 West Wacker Drive** (Chicago, USA) **Figure (50-a)** and **Casselden Place** (Melbourne, Australia) **Figure (50-b)** used the shear walls inside the core to resist lateral loads.

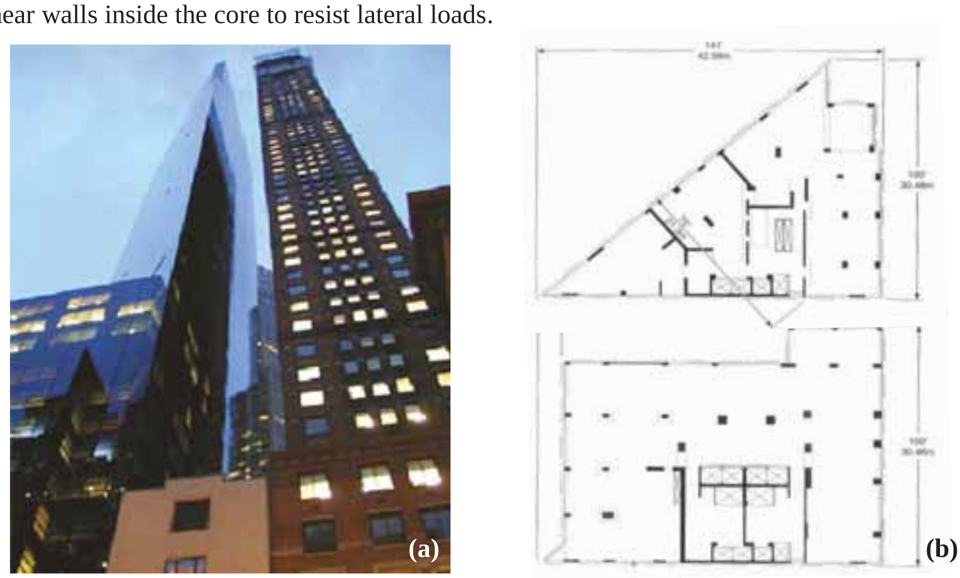


Figure (49) An Example of using Shear Wall. Metropoltian tower.
Ref: (a) (M. Halis Gunel 2006). P.2670.- (b)(McGraw-Hill 1995). P114.

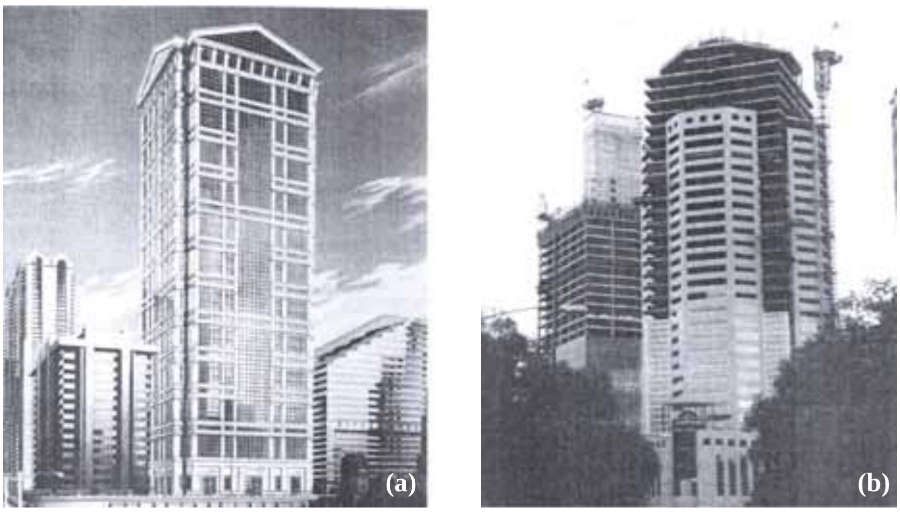


Figure (50) Another Example of using Shear Wall Structures (a) 77 West Wacker Drive, (b) Casselden Place.
Ref: (McGraw-Hill 1995). P. 125 & 128.

3.2.4 Shear wall or shear truss frame interaction system

Rigid frames, when combined with vertical steel trusses or reinforced concrete shear wall, the result will be frame interacting system[1].

Steel shear truss (Braced Frame) + steel rigid frame = Braced Rigid frames (Interacting System).
Concrete Shear Wall + Steel Rigid or concrete Frame = Shear Wall / Rigid Frames (Interacting System).

This interaction can give a better result in load resistance; because it combines the linear wind sway of moment frame with the cantilever parabolic sway of the truss[2] **Figure (51).**

As mentioned before rigid frames, braced frames and shear walls can only be efficient up to 35 stories; but due to their interaction; they can reach a range starting from 40 up to 70 stories height, as usual there are some disadvantages due to the limitations of each system for the inner planning of the building; so when combining the systems limitations will increase[3].

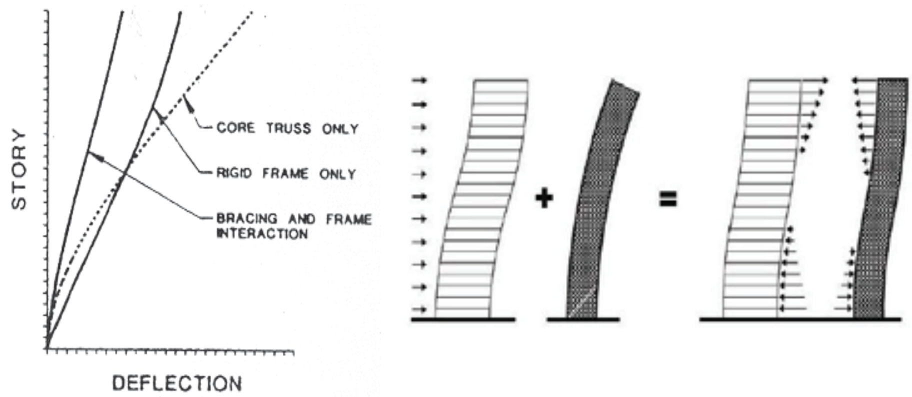


Figure (51) Shear Wall or Shear Truss Frame Interaction Systems.
Ref: (McGraw-Hill 1995). P. 59 & 212.

Elements are located inside the core and around the external perimeter of the building; **Empire state building Figure (52)** is a good example of combination of steel shear truss and steel rigid frame it reached up to 102 stories height, while **Segram building** (New York) **Figure (53)** is a good example of combination of concrete shear walls, steel rigid trusses and rigid frames. On the other hands 311 South Walker drive is a complete concrete shear wall and concrete frame. [4]

[1] (McGraw-Hill 1995). P.57,58&59.-(Moon 2007). P.211.-(Schierle 1990-2006.). P.15&16
[2] ibid.
[3] (McGraw-Hill 1995). P.57,58&59.- (Moon 2007).P.211.
[4] (McGraw-Hill 1995).P.209.

Figure (52) An Example of Using Shear Wall or Shear Truss Frame Interaction System, Empire State Building.
Ref: (Ivan Zaknic 1998). P.200 & 201

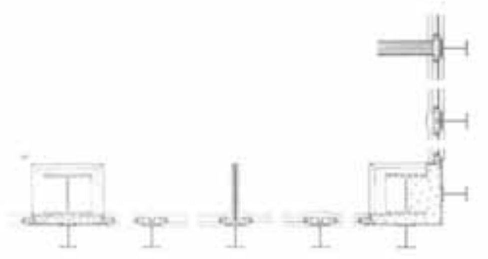


Figure (53) An Example of Using Shear Wall or Shear Truss Frame Interaction System, Seagram building.
Ref: (Leuthauser 1991). P.230.

3.2.5 Out-rigger- Braced structure (core and out-rigger)

It is a very efficient structural form, it has a historical background, and it was used by sailing ships to help in resisting wind forces in their sails; so it makes the mast of the ship much more stable[1].

[1] (McGraw-Hill 1995).P.140.

It consists of a structural core, mainly a core of shear walls or braced frames connected horizontally with horizontal cantilever which is called out-rigger and(can be formed of trusses or girders) to the outer columns, this out-riggers by joining the core to the columns make the structure behave as a composite cantilever and help also in reducing the over turning moment in the core[1].

The core may be centrally located with the out-rigger or on one side. It is suitable for buildings between 30 to 70 stories[2].

Out-rigger has a great depth and it may reaches up to two floor depth and can be repeated each couple of floors to be more efficient, four or five levels of out-riggers are the economical limit of out-riggers[3] **Figure (54)**.

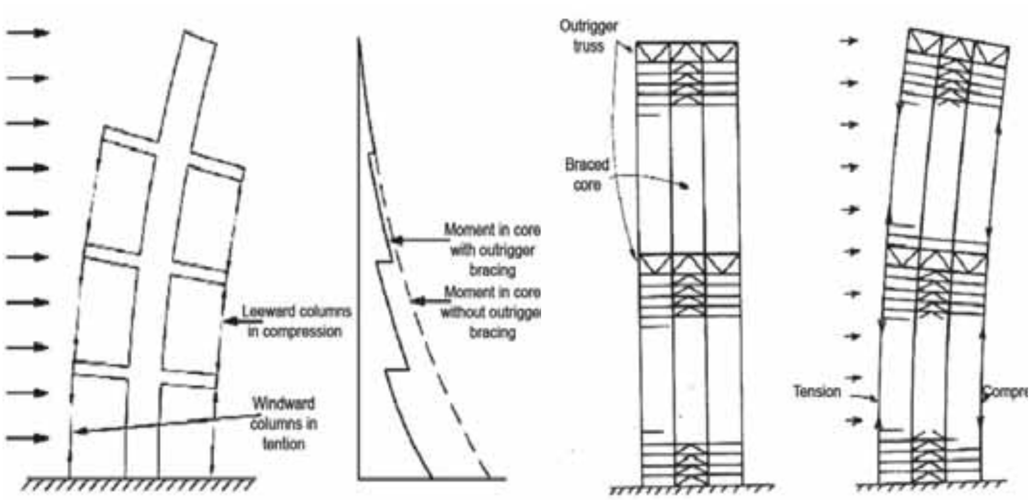


Figure (54) Out-rigger-Braced Structure (Core and Outrigger).
Ref: (couil 1991). P.49.

Outrigger is used in many tall buildings because it can help in providing a kind of form modification that help in the aerodynamic treatment structurally and can give an aesthetic meaning architecturally. **Taipei 101 Figure (55)**, **one liberty place Figure (56)**, **Figueroa towers Figure (57)** are examples for tall buildings using the outrigger structure[4].

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1 (couil 1991)P.49.
2 (couil 1991). P.50 - (M. Halis Gunel 2006). P.212&213.
3 ibid.
4 (McGraw-Hill 1995). P.162 - (Moon 2007). P.209.


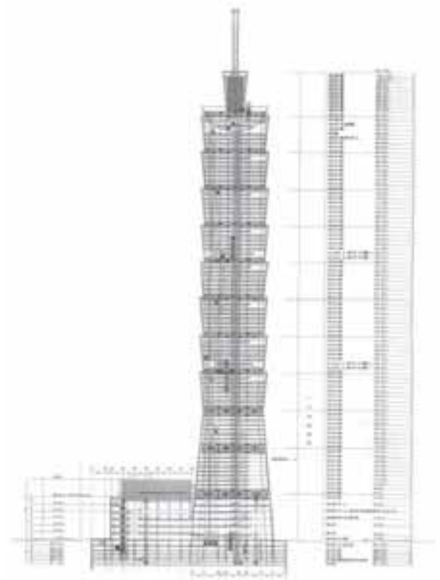

Figure (55) An example of using Outrigger System Taipei 101.
Ref: Archie world 2005/07.


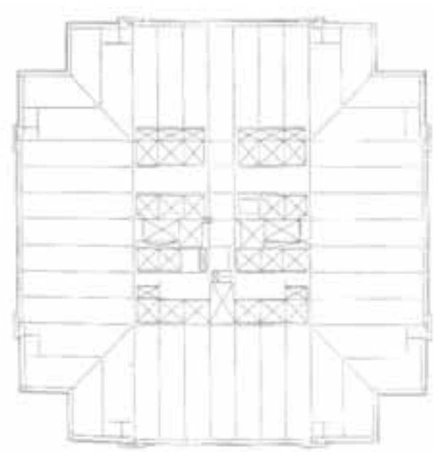

Figure (56) An Example of Using Outrigger System One Liberty Place Tower.
Ref: (McGraw-Hill 1995). P.155 & 156.

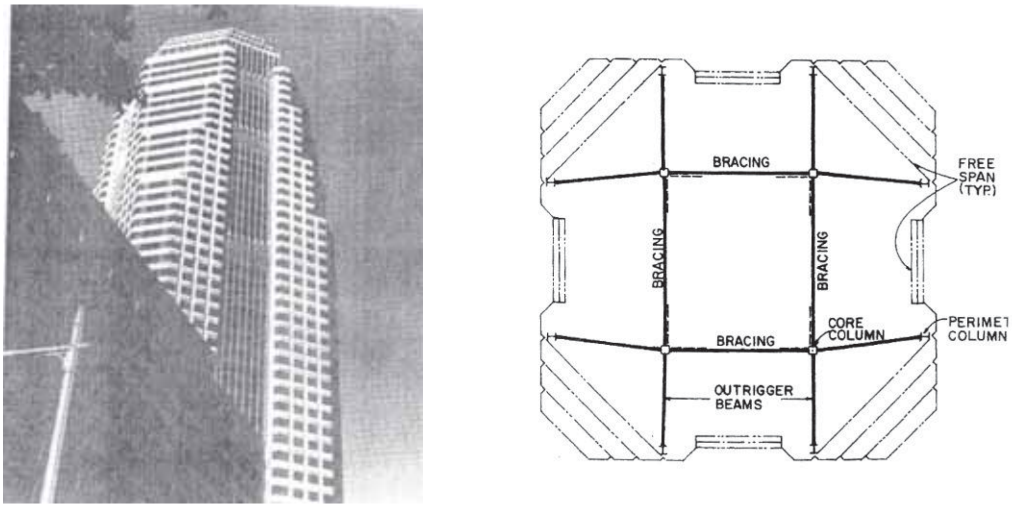

Figure (57) An Example of Using Out-rigger System, Figueroa Towers.
Ref: (McGraw-Hill 1995). P.163 & 164.

3.2.6 Suspended structures

Basically a tall suspended structure consists of a central core or cores having a horizontal cantilever similar to out-rigger at the roof level which have a vertical members in tension attached together and it is called hangers they can be steel cables, rods or plates, floor slabs are suspended from those hangers[1] **Figure (58).**

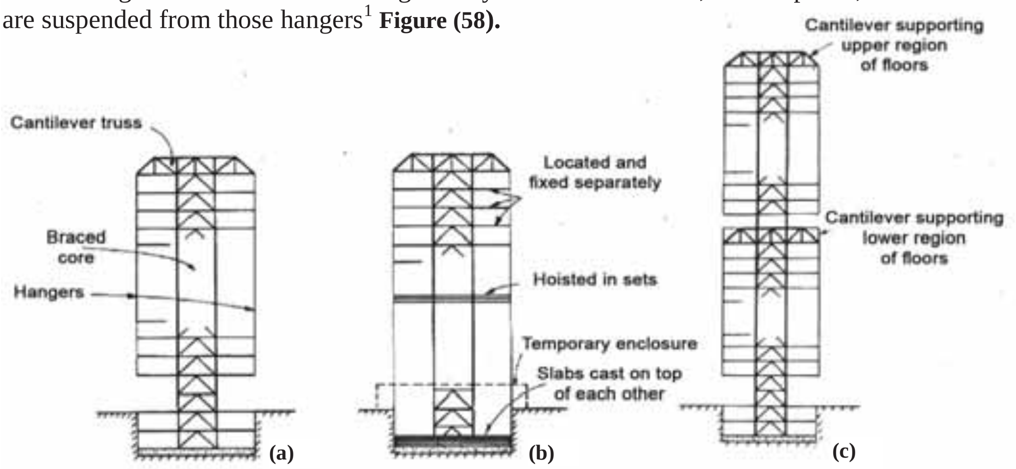

Figure (58) (a) Suspended Structure, (b) Sequence of Construction-Suspended Structure, (c) Two-Tiered Suspended Structure.
Ref: (couil 1991). P.52.

[1] (couil 1991).P.50 - (Schierle 1990-2006.).P.19&20.

This system offers many advantages to architects, first of all is the vertical members (hangers) which are most of the time made of high tensile steel are in tension; so this help in reducing members size; therefore less Obstructive, the second advantage is during construction, core hanger and cantilever can be constructed in parallel to slabs, which can be poured on top of each other at the ground level then lifted up in sets in their floor level and fixed, due to suspension of slabs architects can achieve column free ground floor[1].

Unlike other systems load transfer in suspended tall structures up to the top then down to the foundations, that's why the members are supposed to tension, for this structural reason it's preferred to have 10 floor slabs carried by hangers as a maximum range, that means that suspended structure might have more than one cantilever as in out-rigger structures[2].

3.2.6.1 Design options

Tall suspended structures can be designed in various configurations and options for example:

- Single Tower/ Single or Multi Stack (one vertical core support) **Figure (59-a&c)**.
- Multi Tower / Single or Multi Stack (several vertical core supports) **Figure (59-b&d)**.

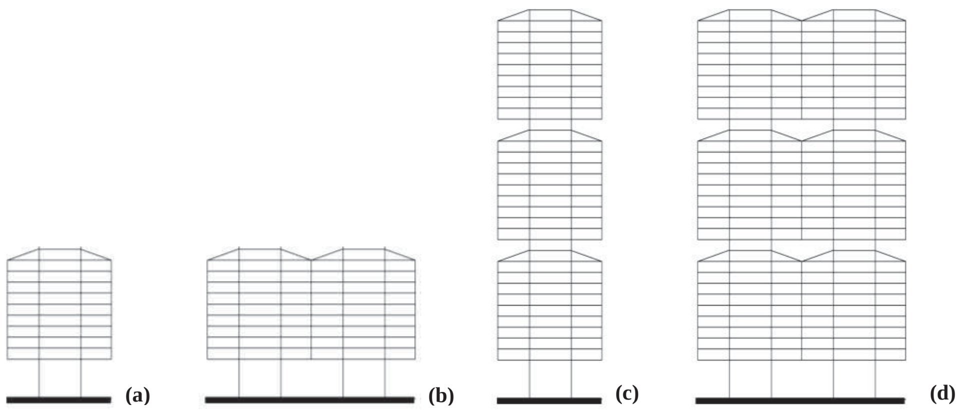

Figure (59) (a) Single Tower with one core, (b) Multi Tower with several cores, (c) Multi Tower With one core, (d) Multi Tower with several cores.
Ref: **(**Schierle 1990-2006.). P.19-3.

The usage of multi cores suspended towers together can give more stability specially in case of joint footing in addition to providing wider spans, **Westcost Transmission Tower** (Vancouver) **Figure (60)**, **BMW Headquarter** (Munich) **Figure (61)**, **Hong Kong and Shanghais Bank** (Hong Kong) **Figure (62)** used suspended structures in their structural design.

1 (couil 1991).P.50.
2 (Schierle 1990-2006.).P.19&20.

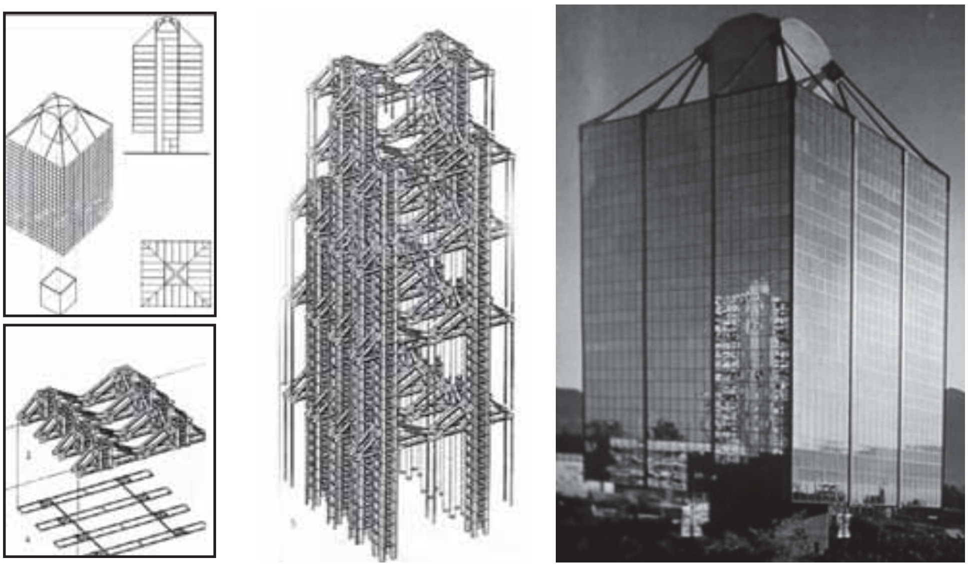

Figure (60) An Example of Suspended Structure, Westcost Transmission Tower.
Ref: (Schierle 1990-2006.).P.19-4 & 19-8.

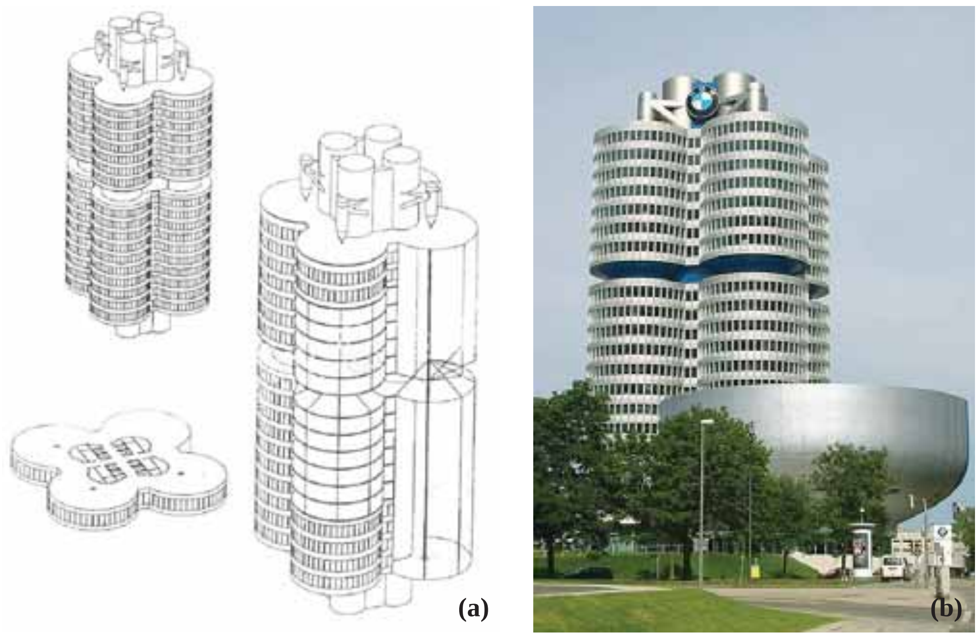

Figure (61) An Example of Suspended Structure, BMW Headquarter.
Ref: (a) (Schierle 1990-2006.). P.19-5. - (b) http://kereta.info

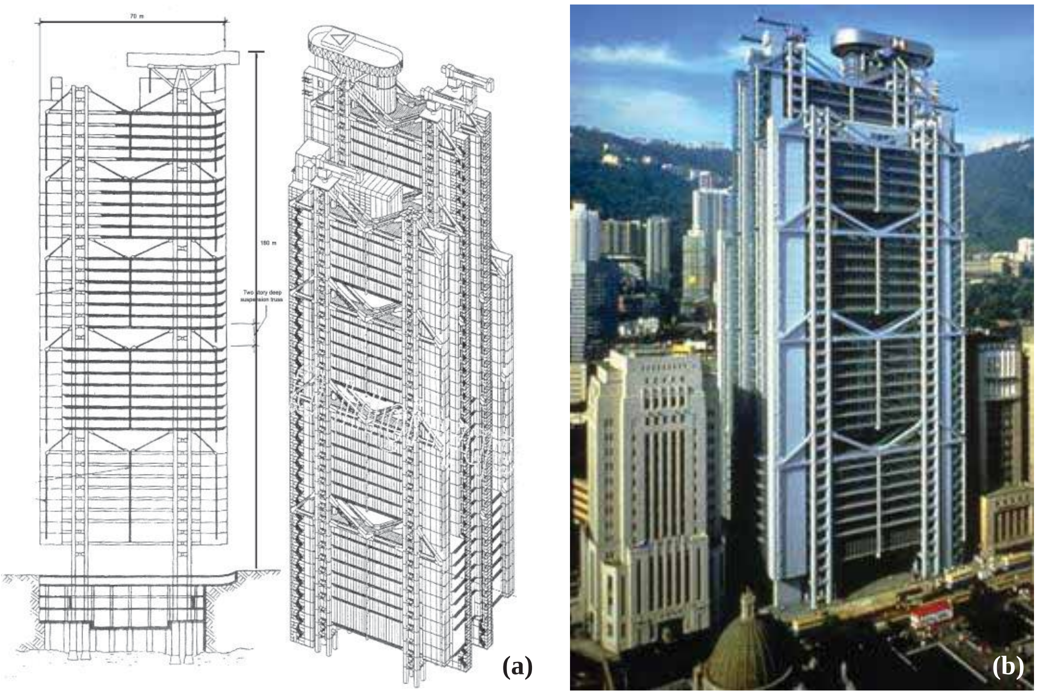

Figure (62) An Example of Suspended Structure, Hong Kong and Shanghai's Bank.
Ref: (a) (Schierle 1990-2006.). P.19-7.- (b)(McGraw-Hill 1995). P.336 & 337.
(b)http://www.archcairo.com

3.2.7 Core structures (core with cantilever structures)

It consists of a single core that serves in caring gravity and horizontal loading, in some structures the slabs are supported at each level by a cantilever girder or spandrel, in this case possible no external columns are needed on the external perimeter of the building; while in some other structures slabs are left to be carried by columns; which are supported on either one massive cantilever a few stories above the ground or smaller cantilevers each couple of floors.[1]

This system gives a great advantage similar to the suspended structures; which is the ability of having free column ground floor plan which can also be repeated as a free column floors bellow repeated cantilevers.[2]also this can help in some complex forms which are in need of having an external profile free of continuous columns such as in twisting forms where the floor plates are shifted each floor ,so an external columns are not preferred but instead there must be a vertical core to carry the floor plates as cantilevers, This system served to heights up to 30 stories **Figure (63).**

1 (couil 1991).
2 (Tall Building and Urban Habitat-Cities in Third Millennium March 2001).P.489.

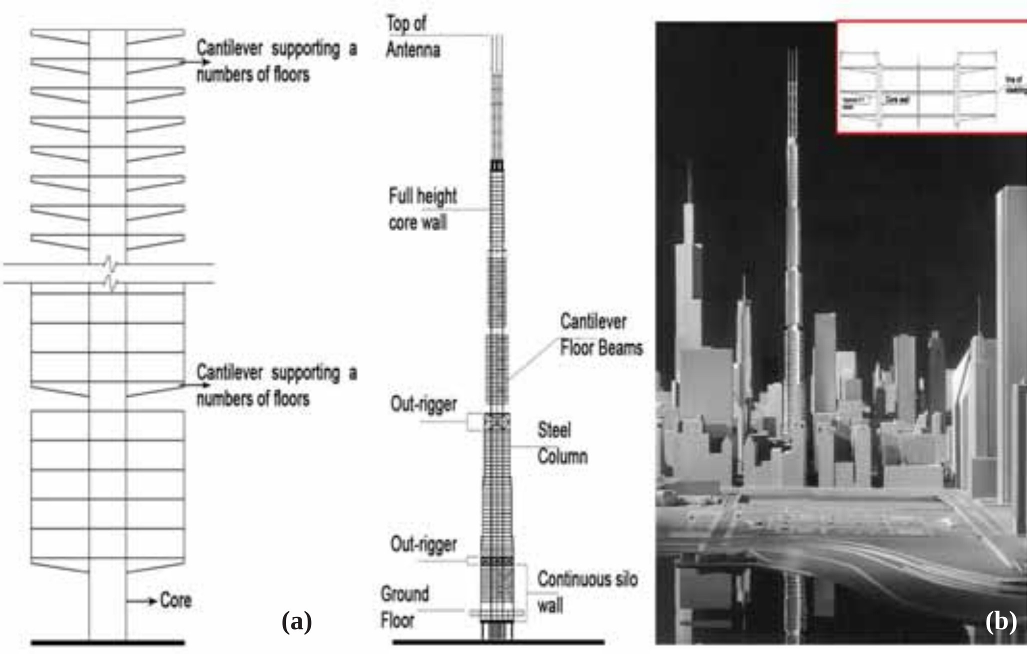

Figure (63) An Example of Core Structure, 7 South Dearborn, Chicago, IL.
Ref: (a) (couil 1991). P.52.
(b)(Tall Building and Urban Habitat-Cities in Third Millennium March 2001). P.489 & 490.

3.3 Exterior structure analysis and examples

The external forces on tall buildings specially lateral loads as mentioned before are the most critical loads affecting tall structures so the perimeter of the tall building is the first defensive screen that meet this loads, so it is desirable if possible to concentrate as much as possible the lateral load resistance element on the perimeter of the building than the core[1].

3.3.1 Tube Systems

Tube structures represent a change in the design of steel frame buildings; it gave the chance for buildings to be very tall and yet remain strong enough to resist the lateral forces of winds and possible effects of earthquakes[2].

Tube systems have many varieties such as braced tube, framed tube, bundle tube and tube in tube structures, Tube structures are very widely used in tall buildings due to their great benefits in lateral load resisting if compared to other systems, most of the well known tall structures are somehow a tube structures specially tallest buildings among the world such as Sears tower, Petronas and Burj Elkhleefa (known as **Burj Dubai**).

1 (Moon 2007).P213 - (M. Halis Gunel 2006).P.2672.
2 (couil, 1991) P. 44&45.

3.3.2 Framed tube system

It is the basic tubular form, it is an outer tube composed of a grid of columns of 1.5 to 4.5 meter spacing on centers, and deep spandrel beams rigidly connected together, these tubes mainly carry the lateral loads, while the gravity loading is shared between, inner columns and tube. The closely spaced columns and spandrel beams haves many benefits in addition to their structural resistance to lateral loads. Exterior columns can eliminate the need for intermediate mullions on the exterior elevation cladding; which help in reducing the total cost, as it reduces the need of a total curtain wall, in addition, by exposing the exterior tubular members there can be a structural expression to the façade which can be used in architectural representation[1].

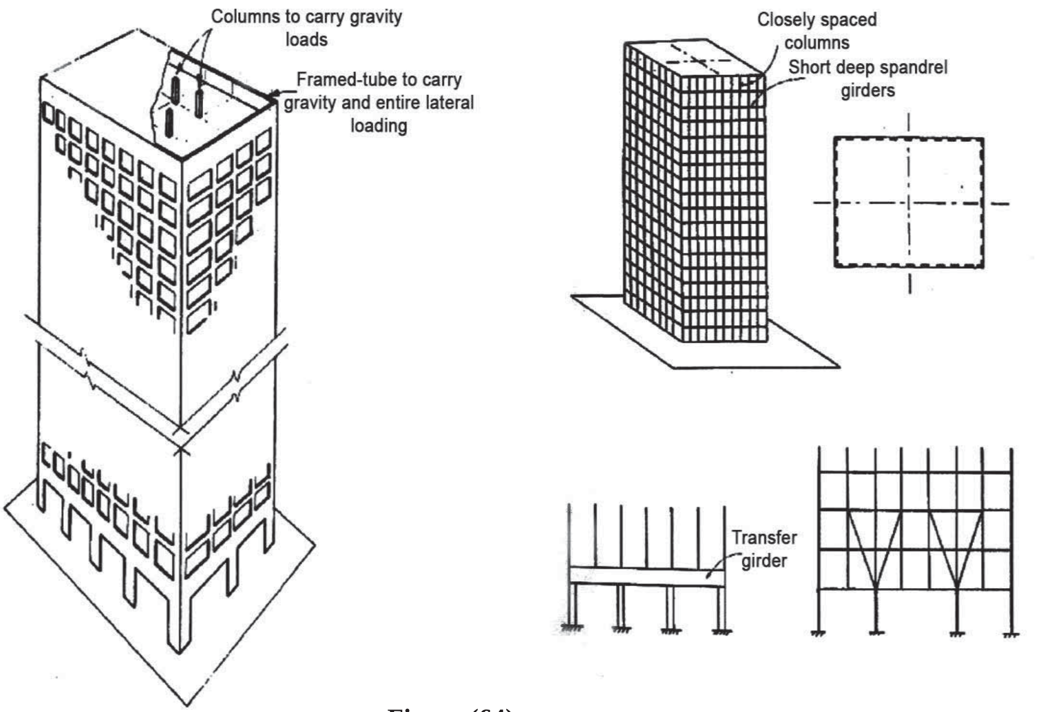

Figure (64) Framed Tube System.
Ref: (McGraw-Hill 1995).P.284.

Framed tube can be from steel or concrete, in case of concrete it can offer a height up to 60 stories while in case of steel it can reach a limit up to 80 stories or more **Figure (64)**.**Amoco Building** (Chicago) **Figure (65-a)**, and **AON center** (Chicago) **Figure (65-b)** used the perimeter framed tube to carry all lateral loads in there structures.

[1] (couil 1991).P.44 - (Moon 2007).P.213 - (M. Halis Gunel 2006).P.2672.

Figure (65) An example of using Framed Tube System, (a) Amoco Building, (b) AON Center.
Ref: http://www.ctbuh.org/

3.3.3 Braced Tube System

Instead of using a closely spaced column as in framed tube. It is possible to keep them at wider distances and do not affect the idea of external tubes by adding braces between columns[1].This was the first time applied on **John Hancock center** [2] **Figure (66-c)**, however braces also have its own benefits, it collect gravity loads from floors and act as inclined columns, also it can help in reducing the size of spandrels and columns; which offer a wider window bays and openings, braces have some limitations in the exterior wall design, it is recognizable as a facade characteristic in addition to its restricts to adding a window in its location[3].Braced tube can be from steel **Figure (66-a)** or concrete **Figure (66-b)**, and it offers heights up to 100 stories, due to the presents of braces window openings are omitted to create diagonal braces, this can be recognized in braced concrete tube structures than in steel for example **the 780 Third Avenue Building** (New York) **Figure (66-d)**.

[1] (couil 1991).P.48 - (Moon 2007).P.213.
[2] (Sev 2001).P.27.
[3] Same as 1 - (M. Halis Gunel 2006).

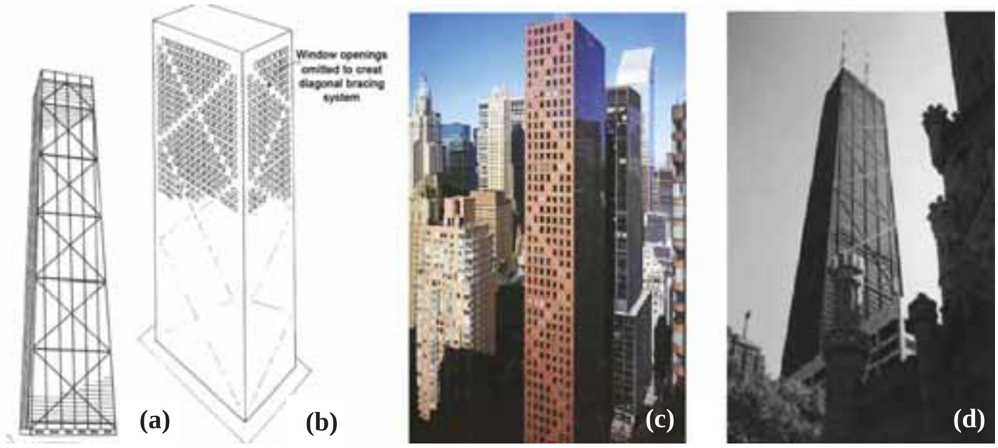

Figure (66) Braced Tube System, (a) Steel-Braced Tube, (b) Concrete-Braced Tube,
An Example of Using Braced Tube System, (a) John Hancock center, (b) Third Avenue Building.
Ref: (a&b) (couil 1991).P.48 - (c&d)(M. Halis Gunel 2006)

3.3.4 Tube in tube or hull core structures

It consists of an outer tube called the hull acting with the inner core together to resist loads, in case of concrete tube in tube the core can be of shear walls and in case of steel core it may consists of braced frames[1] **Figure (67)**,for example to control the lateral sway in the **world trade center (Twin Tower)** **Figure (**68**-a)** framed tube was supplemented by a tube in the core to create a tube in tube steel structure, in addition to the use of a large transfer girder or inclined column arrangement to overcome closely spaced column configuration at the base, another example for concrete tube in tube structure is the **DeWitt-Chestnut Apartment Building** [2] **Figure** (68**-b)** ,the concept of tube in tube structure is that it is exterior structure is supported from inside so it act as an interior and exterior structure at same time although it is mainly and interior structure, similarly in diagrid structure wish will be explained later the idea of interacting of the core and the outer skin to act together is repeated but instead of an external tube it is replaced by an outer dia-grid bracing to resist lateral loads, now it is clear that in most of structures there can be mix between inside and outside either through tube in tube, diagrid or out-rigger bracing this system can reach up to 85 stories.

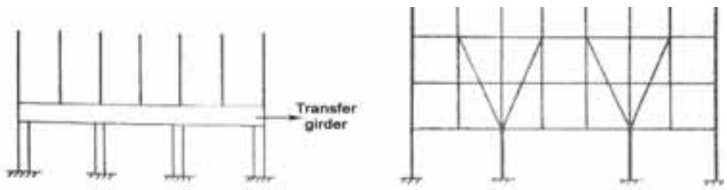

Figure (67) **S**ketch diagram showing the transfer girder
Ref: (McGraw-Hill 1995).P.284.

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1 (Moon 2007).P.214.
2 (M. Halis Gunel 2006).P.2672.

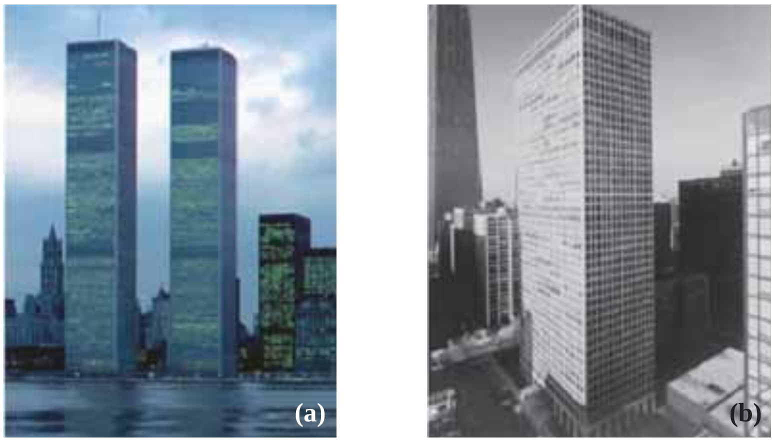


Figure (68) Tube in Tube System or Hull Core Structure, (a) World Trade Center, (b) DeWitt-Chestnut Apartment Building.
Ref: (M. Halis Gunel 2006).P. 2673.

3.3.5 Bundled tube structures

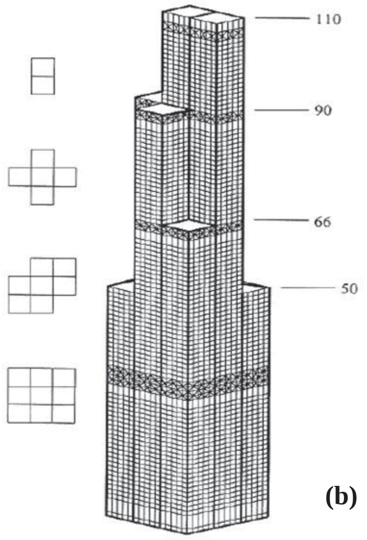
It consist of a clusters of tubes arranged together, for a single tube building there is a problem, which is the ratio between width -represented in floor area at the base- and height to keep the structure stable and away from sway.

In case of multi-number of tubes the system can offer large floor area at the base smaller at the top, because not all tubes in the base will continue to the end, but instead each interval of floors some of the tubes stop and the others continue so net floor area decreases and also the structural form at the top, bundled system allows for wider columns spacing in each tube which gives less limitation in internal planning of the building, bundled tube can be framed or braced, can be from steel or concrete and it reach up to 110 stories[1] .

Sears tower is considered to be one of the best examples for steel bundle tube systems **Figure (70)**.

Figure (69) Plans of Sears Tower at different levels showing the treatment of bundled tube.

[1] (McGraw-Hill 1995).P.280 - (Moon 2007).P.214 - (M. Halis Gunel 2006).P.2674.



As shown in the upper sketch we can observe the change of number of tubes as we go up.

Figure (70) An example of using Steel Bundled Tube System, Sears Tower.
Ref: (a)(M. Halis Gunel 2006).P. 2675 - (b) (Moon 2007).P.214.

Figure (71) An example of using Concrete Bundled Tube System, (a) Carnegie Hall Tower, (b) One Peachtree Center (c) One Magnificent Mile building
Ref: (a) http://www.emporis.com. - (b) ,http://en.wikipedia.org - (c) http://www.ejse.org

3.3.6 Space structures

It is modified braced tube or bundled braced tube sometimes called 3d bundled tube anyway; it consists of 3 dimensional triangular frames whose members serve in resisting both gravity and horizontal loading. This system is composed from steel and can reach up to 150 stories[1].

Bank of China Figure (72) is an example of space structures mainly it is a composition between braced tubes and bundle tube system in 3d configuration, sometimes called 3d bundled tube.

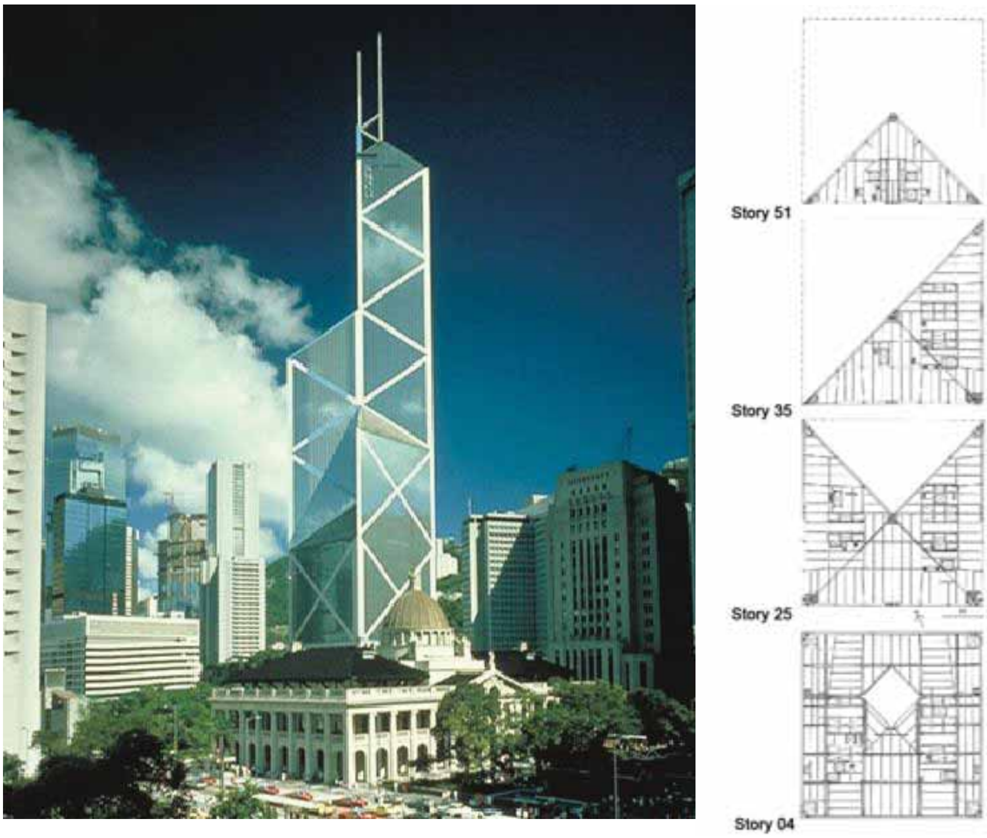


Figure (72) An examples of using space structures, Bank of China.
Ref: (Ivan Zaknic 1998).P.196.

3.3.7 Dia-grids structures

In this system ordinary conventional vertical columns are eliminated; this is due to the exit of diagonal members from which dia-grid system is composed, these diagonal members can

1 (couil 1991).P.53 - (Sev 2001).P.28&29

be curved or straight and they carry the gravity loads as well as lateral loads due to their triangulated configuration in a distributive and uniform manner[1].

In case of conventional tubular system, shear is carried by bending of columns and spandrels, while in case of dia-grid shear is carried by axial action of diagonal members so this helps in minimizing shear deformation. Structure employing out-rigger systems require cores having significant shear rigidity, although it reduces the over turning moment- this is structurally known- but in case of dia-grid shear can be carried by the diagonals located in the building perimeter so do not need high shear rigidity cores, but by adding a core the system becomes stronger generating system similar to tube in tube structures[2].Advantages of dia-grid systems are many some are aesthetics, because they can give a distinctive elevations which can be architecturally unique; in addition to its greatly new expressionism on the facade, also it can serve in much more free internal planning.

Dia-grid systems were first applied with steel members reaching heights up to 100 stories; such as in **Hearst Tower Figure (73-a)**, and **Swiss Re building Figure (73-b)**, which can be famous Examples of dia-grid structures. New design approach uses reinforced concrete creating new architectural aesthetic vision giving the tall building more dynamic expression and more fluidity such as **COR Building Figure (74-a)** and **O-14 building Figure (74-b)**.Tall buildings in case of dia-grid reinforced concrete can reach up to 100 stories.

Figure (73) An example of using Dia-Grid Structure, (a) Hearst Tower, (b) Swiss re Building.
Ref: (a)Structure magazine February 2006. P. 28 & 29- (b) Swiss Re´s Building, London 7 & 8.

[1] (Moon 2007).P.218&219.
[2] ibid.P.218,219, 210.

Figure (74) An examples of using Dia-grid Structure, (a) COR Building, (b) O-14 Tower.
Ref.: (Moon 2007).P.216.

3.3.8 Exoskeleton structures

In this system lateral load resisting elements are located outside the building away from its facade that gives some structural and architectural expression and characteristics to the building, fire proofing is not as serious as in case of other structural systems due to the distance separating load resisting elements and the façade, this system may reach up to 100 stories[1].An Example of Exoskeleton System in tall structures is **Hotel De Las Artes**, (Barcelona, Spain) **Figure (76)**.

3.3.9 Super frame structures

It is composed of mega columns at the building corners or perimeters linked together by a multi story trusses of steel or concrete, each 15-20 stories these columns carry the lateral loads and the truss linked them together, These mega columns act a super frame that's why the system is called mega column.

concrete, in case of steel it can reach up to 160 stories; while in concrete it can reach up to 100 stories[2] **Figure (75)**.

[1] (Moon 2007). P.210 - (Sev 2001).P.29.
[2] ibid.P.215&216.

Figure (75) An example of using Super-Frame Structure System, (a) Parque central Tower.
Ref: http://commons.wikimedia.org

Figure (76) An example of using Exo-Skelaton System, (a) Hotel De Las Artes.
Ref: Integrating Architecture and Structural Form in Tall Steel Building Design P.29.

Summary

Tall building structures are classified in to two categories according to the location of major and minor components which are interior and exterior structures. This classification is only a guide line and the architect can choose a mix of different structures together, the tube and out-rigger structure are very widely used in tall buildings, also Diagrid structures are the most advance in tall buildings structure system.

Table 1 Interior Structure

<u>Ref:</u> (Moon 2007) edited by the researcher

Category	Sub-Category	Material/Configuration	Efficient height limit	Advantages	Disadvantages	Building Examples
Rigid Frames	---------	Steel	30	Provide flexibility in floor planning. Fast construction	Expensive moment connections. Expensive fire proofing.	860 & 880 Lake Shore Drive Apartments (Chicago, USA, 26 stories, 82 m), Business Men's Assurance Tower (Kansas City, USA, 19 stories), Seagram Building, 30th to the top floor (New York, USA, 38 stories, 157 m).
		Concrete	20	. Provide flexibility in floor planning. Easily moldable.	Expensive formwork. Slow construction.	Ingalls Building (Cincinnati, USA, 16 stories, 65 m).
Braced Hinged Frames	---------	Steel Shear Trusses + Steel Hinged Frames	10	Efficiently resist lateral loads by axial forces in the shear truss members. Allows shallower beams compared with the rigid frames without diagonals.	Interior planning limitations due to diagonals in the shear trusses. Expensive diagonal connections.	Low-rise buildings

Category	Sub-Category	Material/Configuration	Efficient height limit	Advantages	Disadvantages	Building Examples
Shear Wall / Hinged Frames	---------	Concrete Shear Wall + Steel Hinged Frame	35	Effectively resists lateral shear by concrete shear walls.	Interior planning limitations due to shear walls.	77 West Wacker Drive (Chicago, USA, 50 stories, 203.6 m), Casselden Place (Melbourne, Australia, 43 stories, 160 m)
Shear Wall (or Shear Truss) - Frame Interaction System	Braced Rigid Frames	Steel Shear Trusses + Steel Rigid Frames	40	Effectively resists lateral loads by producing shear truss - frame interacting system.	Interior planning limitations due to shear trusses.	Empire State Building (New York, USA, 102 stories, 381 m), Seagram Building, 17th to 29th floor (New York, USA, 38 stories, 157 m)
	Shear Wall / Rigid Frames	Concrete Shear Wall + Steel Rigid Frame	60	Effectively resists lateral loads by producing shear wall - frame interacting system.	Interior planning limitations due to shear walls.	Seagram Building, up to the 17th floor (New York, USA, 38 stories, 157 m)
		Concrete Shear Wall + Concrete Frame	70	Effectively resists lateral loads by producing shear wall - frame interacting system.	Interior planning limitations due to shear walls.	311 South Wacker Drive (Chicago, USA, 75 stories, 284 m), Cook County Administration Building, former Brunswick Building (Chicago, USA, 38 stories, 145m)

Category	Sub-Category	Material/Configuration	Efficient height limit	Advantages	Disadvantages	Building Examples
Outrigger Structures	---------	Shear Cores (Steel Trusses or Concrete Shear Walls) + Outriggers (Steel Trusses or Concrete Walls) + (Belt Trusses) + Steel or Concrete Composite (Super) Columns	150	Effectively resists bending by exterior columns connected to outriggers extended from the core.	Outrigger structure does not add shear resistance.	Taipei 101 (Taipei, Taiwan, 101 stories, 509 m), Jin Mao Building (Shanghai, China, 88 stories, 421 m)
Suspended structures	---------					Hong Kong bank(HSBC)
Core structures	---------		120			7 South Dearborn, Chicago

Table 2 Exterior Structure

<u>Ref:</u> (Moon 2007) edited by the researcher

Category	Sub-Category	Material/Configuration	Efficient height limit	Advantages	Disadvantages	Building Examples
Tube	Framed Tube	Steel	80	Efficiently resists lateral loads by locating lateral systems at the building perimeter.	Shear lag hinders true tubular behavior. Narrow column spacing obstructs the view.	Aon Center (Chicago, USA, 83 stories, 346 m) Amoco building (Chicago,USA)
		Concrete	60	Efficiently resists lateral loads by locating lateral systems at the building perimeter.	Shear lag hinders true tubular behavior. Narrow column spacing obstructs the view.	Water Tower Place (Chicago, USA, 74 stories, 262 m)
	Braced Tube	Steel	100 (With Interior Columns) – 150 (Without Interior Columns)	Efficiently resists lateral shear by axial forces in the diagonal members. Wider column spacing possible compared with framed tubes. Reduced shear lag.	Bracings obstruct the view.	John Hancock Center (Chicago, USA, 100 stories 344 m)
		Concrete	100	Efficiently resists lateral shear by axial forces in the diagonal members. Wider column spacing possible compared with framed tubes. Reduced shear lag.	Bracings obstruct the view.	Onterie Center (Chicago, 58 stories, 174 m), 780 Third Avenue (New York, USA, 50 stories, 174 m)

Category	Sub-Category	Material/Configuration	Efficient height limit	Advantages	Disadvantages	Building Examples
Tube	Bundled Tube	Steel	110	Reduced shear lag.	Interior planning limitations due to the bundled tube configuration.	Sears Tower (Chicago, USA, 108 stories, 442 m)
		Concrete	110	Reduced shear lag.	Interior planning limitations due to the bundled tube configuration.	Carnegie Hall Tower (New York, USA, 62 stories, 230.7 m)
	Tube in Tube	Ext. Framed Tube (Steel or Concrete) + Int. Core Tube (Steel or Concrete)	80	Effectively resists lateral loads by producing interior shear core - exterior framed tube interacting system.	Interior Planning limitations due to shear core.	181 West Madison Street (Chicago, USA, 50 stories, 207 m) Old world trade center Dewitt-chestnut apartment building
Diagrid	-----------	Steel	100	Efficiently resists lateral shear by axial forces in the diagonal members.	Complicated joints.	Hearst Building (New York, USA, 42 stories, 182 m), 30 St Mary Axe, also known as Swiss Re Building (London, UK, 41 stories, 181 m)

Category	Sub-Category	Material/Configuration	Efficient height limit	Advantages	Disadvantages	Building Examples
Diagrid	-----------	Concrete	60	Efficiently resists lateral shear by axial forces in the diagonal members.	Expensive formwork. Slow construction.	O-14 Building (Dubai)
Space Truss Structures	-----------	Steel	150	Efficiently resists lateral shear by axial forces in the space truss members.	Obstruct the view. May obstruct the view.	Bank of China (Hong Kong, China, 72 stories, 367 m)
Super frames	-----------	Steel	160	Could produce super tall buildings.	Building form depends to a great degree on the structural system.	Chicago World Trade Center (Chicago, USA, 168 stories, Unbuilt)
		Concrete	100	Could produce super tall buildings.	Building form depends to a great degree on the structural system.	Parque Central Tower (Caracas, Venezuela, 56 stories, 221 m)
Exo-skeleton	-----------	Steel	100	Interior floor is never obstructed by perimeter columns.	Thermal expansion / contraction. Systemic thermal bridges.	Hotel de las Artes (Barcelona, Spain, 43 stories, 137 m)

CHAPTER FOUR

Architectural Trends for Tall Building's Form Generation

CHAPTER FOUR
Architectural Trends for Tall Building's Form Generation

4.1 Introduction

Traditionally tall buildings were designed to be used as commercial offices on small lands if compared to land used for this purpose before by stacking floors vertically in addition to having large window bays to provide maximum natural light. Later another uses were developed such as residential, mixed uses and hotels.[1]

Tall buildings development involves multiple complex factors such as economics, technological regulations, and politics but economics are on the top of these factors followed by technologies, unless suitable technology was found, it would not be possible to build high.[2]

From the early beginning, tall buildings had a symbolic power in its urban context; many trends were thus evolved to represent forms and geometries for tall buildings.

4.2 The transition of tall buildings from classical style to modern expressions

In the middle of the 19th century iron/steel construction helped in the appearance of sky scrapers, at the beginning there were many limitation for any new expressions concerning sky scrapers because steel construction was recently introduced at that time, and people were not used to see building from steel, buildings most of the time were classic with thick wall bearing masonry or concrete and with narrow openings, but on the opposite direction iron/steel construction was able to provide frame systems with thin walls and wider openings in the form of box buildings with rectangular or polygonal plan growing vertically, but in order to overcome the problem of its new expression that was not accepted in the early beginning from most people ,architects introduced tall building with iron/steel construction cladded with bricks or terracotta to give classical expression that was clear in the early sky scrapers such as **Home Insurance Building Figure (77-a), Flat Iron Building Figure (77-b)** and other[3]. (See chapter (1).

[1] (Moon 2007). P.206.
[2] (Mark 2005).
[3] (Craighead 2003).

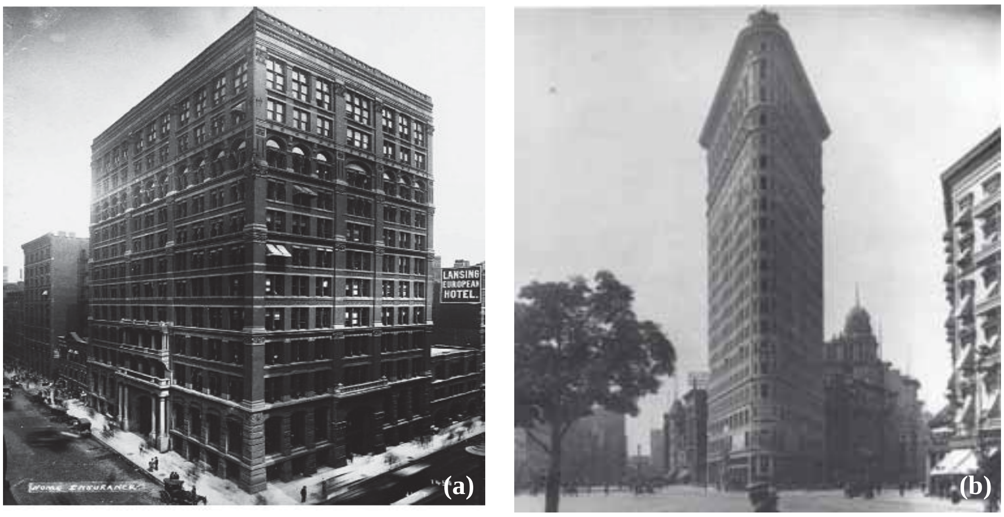


Figure (77) An example of iron/steel construction. (a) Home Insurance Building, (b) Flat Iron Building.
Ref: (a) (Craighead 2003).P.5- (b) (Leuthauser 1991).P.32.

Then gradually this box style was upgraded and curtain walls were introduced with its new modern expression that was clear in **Seagram building Figure (78-a) and 860-880 Lake Shore Drive by Mies Van De Roe Figure (78-b)** and later on other towers of complete curtain walls such as **Sears Tower Figure (78-c)**.[1]

Figure (78) An example of box style with curtain walls, (a) Segram Building, (b) Lakeshore Drive Apartments, Sears Tower.
Ref: **(a)** (Tall Building and Urban Habitat-Cities in Third Millennium March 2001).P.349 -(b&c) (Sev 2001).P.26.

1 (Craighead 2003).P.8,9 - (Leuthauser 1991).P.32,33,230&231.

4.3 Structural evolution and architectural expression

Structure systems for tall buildings has a great influence on its form expression. In the past it was not taken in consideration as an aesthetic meaning presented inside or outside the building. For example in traditional old braced frame; which consists of a core braced with steel members to overcome lateral loads, bracings were inside the core for only structural function, but architecturally it has many limitations in the internal planning.[1]

Although structural elements can give an aesthetic expression on the façade, it was not clearly recognized until the appearance of tubular structure forms, especially braced tube structures. It is a grid of columns on the outer perimeter of the building acting together as an outer tube through diagonal bracing. These bracing on the outer façade gave a new expression related to architectural and structural beauty at the same time, **John Hancock tower in Chicago Figure (79-c)**, **third Avenue Figure (79-a)** and **Bank of China Figure (79-b)** are Perfect examples for the use of bracing on the outer façade.[2]

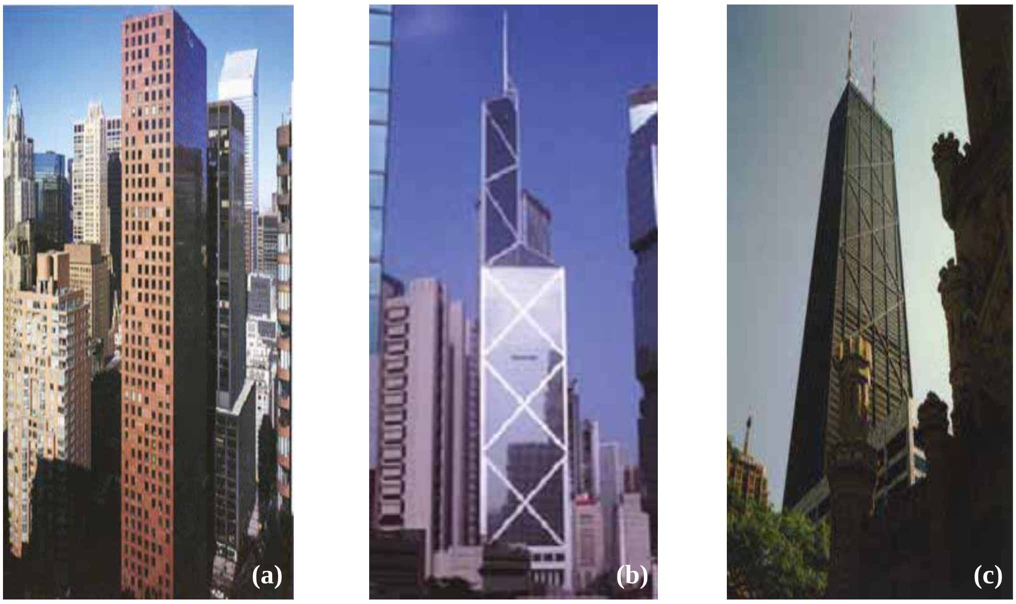


Figure (79) An example of using structural elements in building' façade, (a) Third Avenue Building, (b) Bank of China, (c) John Hancock Center

Ref: (a) & (b) (M. Halis Gunel, 2006) 2673,2674 - (c) (Sev 2001).P.28.

In other systems such as out-rigger the **First Wisconsin center in Milwaukee Figure (80)** clearly expressed the belt truss on the façade at the level of the out-rigger truss as a building aesthetic element.[3]

[1] (Moon 2007). 218.

[2] (Sev 2001).

[3] Same as 1 - Same as 2

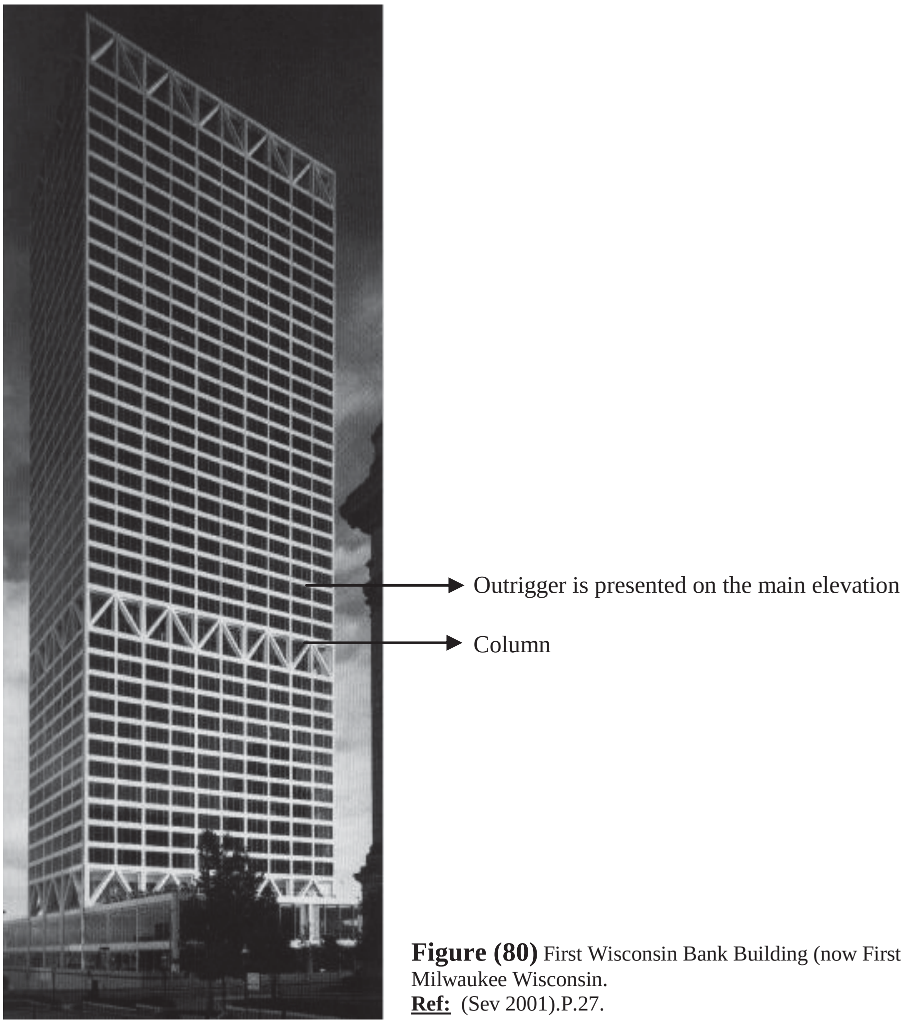


Figure (80) First Wisconsin Bank Building (now First Star), Milwaukee Wisconsin.
Ref: (Sev 2001).P.27.

Systems such as diagrid use its major structural component on the façade offering new expressions related to architectural and structural beauty, for example the diagrid system in **Hearst Tower** by **Norman Foster Figure (81-a)** the diagonal bracing of steel members gives a unique symbolic powerful tower in its urban context, similarly **Swiss Tower Figure (81-c)** which gave a new meaning to the façade from outside and the space from inside, the absence of vertical columns give a shock experience to users, another example of diagrid is the **CCTV head quarter in China Figure (81-b)** which is constructed as to include tubes connected to each other at the top and bottom from different directions and braced with non uniform diagrid members[1].

[1] (Foster 2006).P.144.

Figure (81) An example of using dia-grid structures in buildings' façade, (a) Hearst Tower, (b) CCTV Tower, (c) Swiss Tower.

Ref: (a) & (b)(Cain) - (b) (Moon, 2007) .

Diagrid can be also from concrete giving more fluidity to the buildings form, for example **COR building in Miami by Chad Oppen Heim architects** and **Ysrael Seink** of Yas consulting engineers **Figure (82-a)** and the **0-14 building in Dubai by RUR architects Figure (82-b)** employ reinforced concrete in the diagrid form as a primary lateral load resisting elements, architecturally, it grave a new meaning for the tall building more dynamic than before[1].

Figure (82) Another example of using diagrid structures in building's façade, (a) COR building, (b) 0-14building.

Ref: desmena.com

4.4 Capturing the spirit of the place, culture, and time

"The real success of the tall building lies in its ability to inspire and become a treasured place in the city"[1]

One of the new trends for tall building s design is to capture something from the location it is built in, something cultural, traditional, features, something that represents the spirit of the place. This can be seen in individual trials such as the **Triumph Palace (Moscow, Russia) Figure (83)**; its design continues the glorious tradition of the monumental architectural style of the Russian capitals seven high rise buildings built in the late 1940's[2].

Figure (83) An example of using monumental style, Triumph Palace (Moscow, Russia).
Ref: Archie world 198 P.63.

As mentioned before in chapter (1), there has been a graphical transition in the location of tall buildings construction from North America to Asia in the last decades, the most significant trend in tall building forms in these countries is the trend of using the spirit of the place through traditional and cultural features and vocabularies.

[1] (Lee 2004).
[2] (Foster 2006).P.198.

This can easily be recognized; for example **Burj Dubai Figure (84),** the design of this tower was derived from the geometries of the desert flower, which is indigenous to the region in addition to the patterning system embodied in Islamic architecture. So there is a combination between historical and cultural influences. [1]

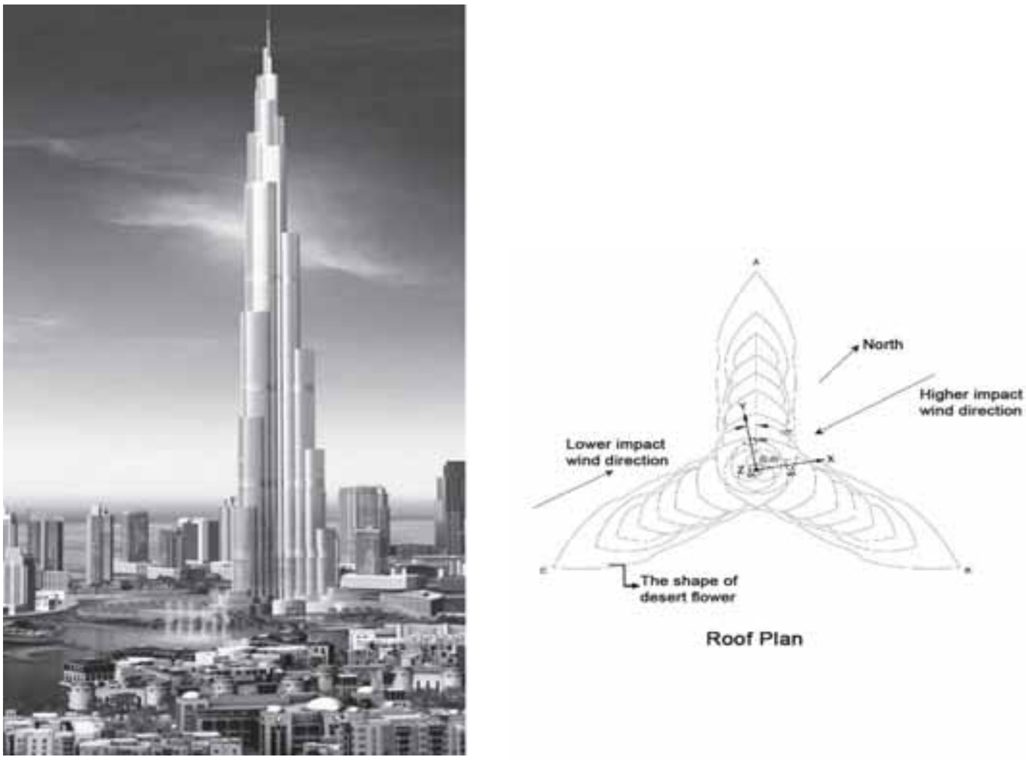


Figure (84) An example of using the spirit of the place in design concept, Burj Dubai.
Ref: (Tall Building and Urban Habitat-Cities in Third Millennium March 2001).P.489 & 490.

Another example is the **Burj Al Arab Tower Figure (85-a),** that resembles the spinnaker sail of AJ-class Yacht and reflects the seafaring heritage of Dubai, also another example referring to the sailing ship is **Bahrain world trade center** in Manama Kingdom of Bahrain **Figure (85-b)**, having the spirit of sea and water[2].

Again in Kuala Lumpur the twin towers (**Petronas Tower**) **Figure (85-c)**, the architect uses the star Islamic plan to generate a setback form that represent a unique architectural tower with the help of tubular structural system[3].

1 (Foster 2006).P.323.
2 ibid.
3 (Moon 2007). P.218.

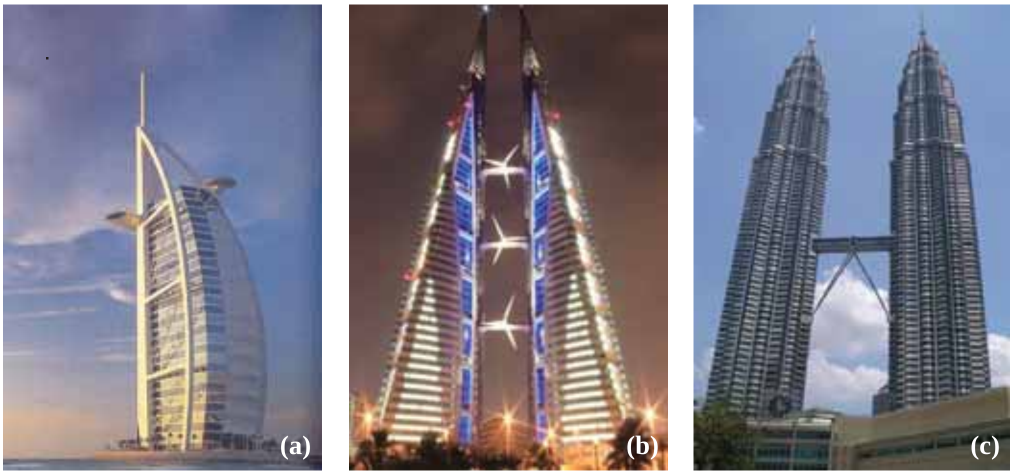


Figure (85) Another example of using the spirit of the place in design concept, (a) Burj Al-Arab Tower, (b) Bahrain World Trade Center, (c) Petronas Tower.
Ref: (a) (Foster, 2006), (b) http://www.flickr.com, (c) (Ivan Zaknic, 1998)

Figure (86) An example of using regional expressional form, (a) Taipei 101.
Ref: Archie world 198 P.90.

Taipei 101 (Figure (86)**),** again used the regional expressional form with the help of the outrigger system.

4.5 Aero dynamic modifications in the form of tall buildings (Aero Dynamics form)

It is well known that the major problem for a tall building as a structure is the effects of lateral loads on it especially wind loads.

Wind loads cause motions for the building such as sway, bending and tortional motions **Figure (87)**, this motions cause many problems structurally, architecturally and may be it extends to reach occupants causing sickness (motion sickness), fear, headaches and other symptoms according to the persons. [1]

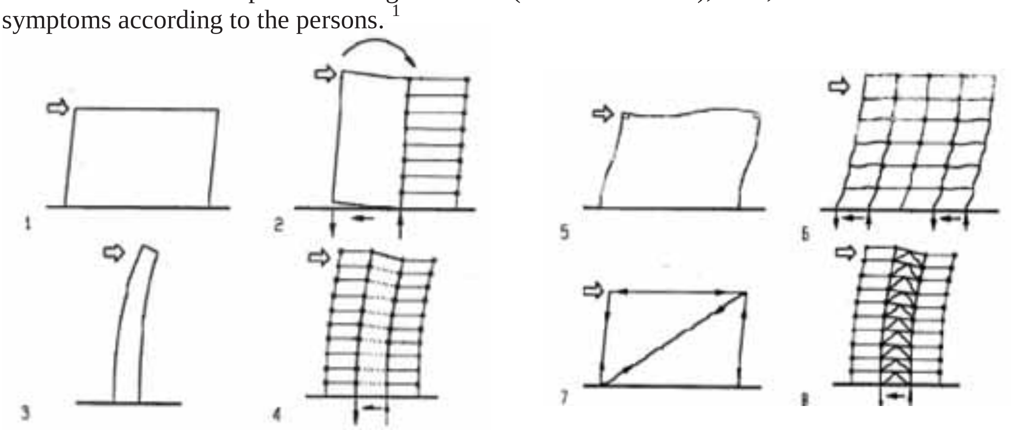


Figure (87) The effect of Lateral Loads.
Ref: (Schierle 1990-2006.).P.15-5.

4.5.1 Types of motions in tall buildings due to lateral loads

The motion of a tall building occurs primarily in three modes **Figure (88)**:

- Along wind.-Across wind.-Tortional mode.

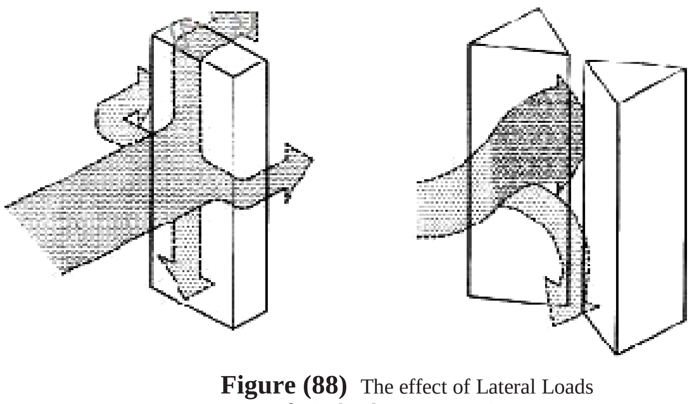


Figure (88) The effect of Lateral Loads
Ref: (Schierle 1990-2006.).P.9-3.

[1] (Ahsan Kareem 2007).P.2.

Due to this motion the phenomenon called vortex-shedding results, the role of aero-dynamic modifications in the form of tall building is to generate a solution that helps in the reduction of building motion, but in order to understand these modifications concept, we must first understand the nature of motions that occurs for tall building. [1]

4.5.1.1 Along wind motion

It is the motion of the building in the direction of wind due to wind drag forces that causes a pressure fluctuation on wind ward (building's frontal face that wind hits) and leeward face (back face of the building) **Figure (89-a)**. [2]

4.5.1.2 Across wind motion

It is the motion of the building in a plan perpendicular to the direction of wind. In the design of most tall buildings, the across wind response often dominates over the along wind response **Figure (89-a)**. [3]

4.5.1.3 Vortex-shedding phenomenon

Vortices are the forces produced on both transverse sides of the building due to the displacement of the parallel wind stream lines on these sides.
In case of low speed wind vortices are shed symmetrically on both transverse sides so building does not vibrate in the across wind direction **Figure (89-b)**.[4]

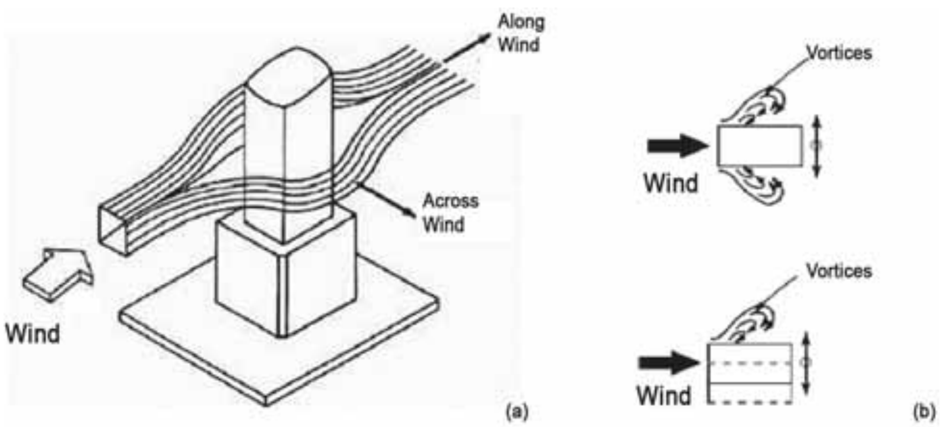


Figure (89) (a) Simplified two-dimensional flow of wind, (b) Vortices in different wind speed conditions.
Ref: (GÜNEL 2007). P.19.

[1] (McGraw-Hill 1995).P.340-345.
[2] (Ahsan Kareem 2007).P.18&19
[3] ibid.
[4] Same as 2.

On the other hand in case of high speed wind, vortices are shed internally, first form one side then from the other, this kind of shedding causes structural vibrations in the flow and the cross wind direction which is called vortex-shedding[1].

Through the design of tall building form and across sectional plans(floor plate); an architect with the help of structural engineer can control wind excitation, in addition to giving the tall building a significant form and aesthetic meaning at the same time. From the point of view of architect the aero-dynamic modifications are methods for form generation and from the point of view of wind engineers, it is a method to control wind excitation. Any way aero-dynamic design for tall building can be on two levels[2].

4.5.2 Level 1: major architectural modifications.

It is a modification that has an effect on the architectural concept this can be achieved through different actions such as[3]:

- Tapering
- Set backs
- Sculptured building top
- Varying the shape
- Openings

4.5.2.1 Tapering

Wind loads are reduced at the top of the building through the decrease of upper floor areas (floor plate) and the increase of lower floor area. The **John Hancock center** **Figure (**90**-a)**, **Chase Tower** **Figure (**90**-b)** and **Trans America pyramids** **Figure (**90**-c)**, are significant examples for tapered forms.

Figure (90) An examples of tapering effect utilization; (a) The John Hancock Center, (b) Chase Tower, The Transamerica Pyramid.

Ref: (GÜNEL 2007). P.21.

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[1] (GÜNEL 2007). P. 18,19&20

[2] ibid.

[3] Same as 1.

4.5.2.2 Setback and sculptured tops

It is similar to tapering, set backs are used to slightly taper the building shape providing sometimes sculptured tops that give an aesthetics meaning and also solve a structural problem, the more sculptured building top is better, it can minimize the along wind and across wind responses. The **Jin Maw building Figure (91-a)**, and **Petronas Tower Figure (91-b)**, are a perfect example for the idea of setback.

Figure (91) An example of Setback and sculptured tops, (a) Jin Maw Building, (b) Petronas Tower.
Ref: (a) (M. Halis Gunel 2006).P. 2673 - (b) Archie world 122 P.63.

4.5.2.3 Variation of the building shape

The variation of the building shape along height can include tapering, setback and other forms such as bundled tubular forms; it can provide a method of wind effect reduction by preventing the wind to be organized, **Burj Dubai Tower** and the **Sears tower** are good examples for variation of the building shape.[1]

4.5.2.4 Addition of openings

It is another way to reduce the vortex shedding induced forces especially at the top of the building, its effect decreases if openings are provided at lower levels of the building, from the famous examples is the **Shanghai world financial center Figure (92-a)** and **Burj Al Mamlaka Figure (92-b)**.[2]

[1] (Ahsan Kareem 2007).P.9.
[2] (Foster 2006).P.212,213 - (GÜNEL 2007). P. 10.

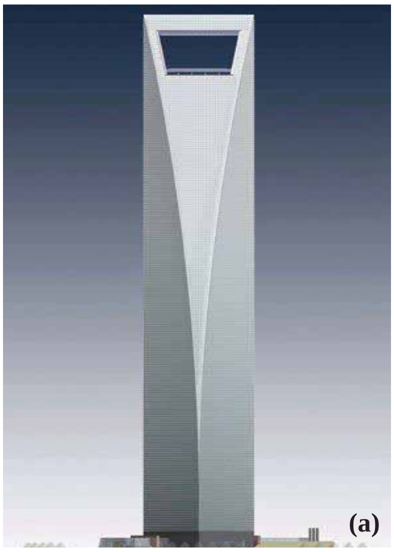


Figure (92) An examples of addition of openings, (a) Shanghai World Financial Center, (b) Burj Al-Mamlaka .

Ref: (GÜNEL 2007). P.23.

4.5.3 Level 2: Minor Architectural modifications[1]

It is a modification that does not have a great influence on the architectural concept such as:

- Corner modifications.
- Orientation of the building to the most frequent wind direction.

4.5.3.1 Corner modifications

Sometimes a small modification in the plan cross section can reduce lateral loads effect; rectangular forms are not as cylindrical or elliptical, crescent, triangular forms because their shapes have inherent strength in their geometrical form, they can provide higher buildings with lower cost. Some modification on a rectangular building such as slotted, chamfered rounded corners and corner cuts can have great effects on both along and across wind responses of the building to wind **Figure (93)**. [2]

Figure (93) Corner modifications.

Ref: The rule of Aerodynamic modifications in the form of tall buildings against wind excitation. P.19.

[1] (GÜNEL 2007). P. 20.
[2] (Ahsan Kareem 2007).P.8.

As modifying corners to reach circular cross section with cone or cylindrical forms as the building becomes stronger to face lateral loads.

For example in **Taipei 101 tower Figure (94),** the modification of the rectangular cross section by chamfers of the order of 10% provides a lateral load reduction from 25-40%; if compared to same cross section before modification.[1]

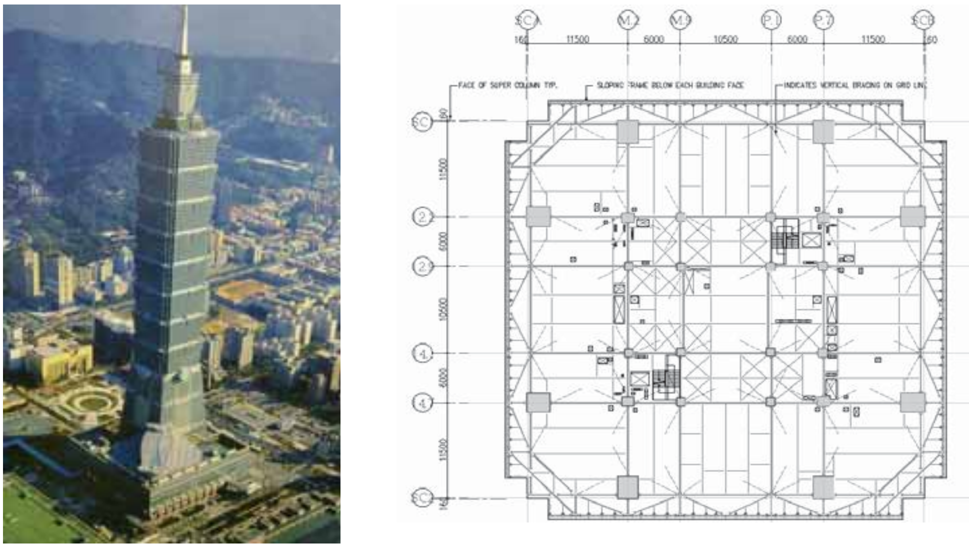


Figure (94) Taipei 101 Tower
Ref: Archie world.

4.6 Complex geometries in design

Complex geometry towers are one of the new important trends in tall building designs, their forms are generated from mainly two ways which are:

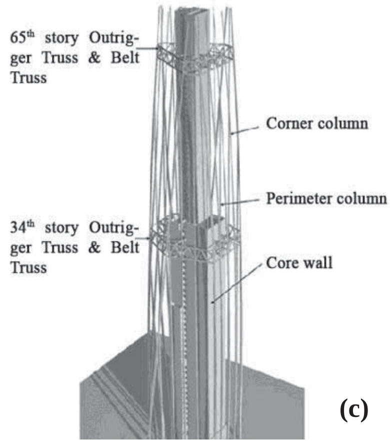
- The variations of floor area cross-section (floor plate) vertically.
- Floor plate shifting (twisting, leaning or tapering).

Generally in most cases each floor will be unique, due to this shifting or variation, the key to make these buildings work lies in the architect's ability to arrange the architectural program to fit within the floor area shape with respect to structural and technical needs.

For examples in residential towers spaces can be classified as a flexible spaces such as receptions and living rooms and less flexible spaces such as kitchen, bathrooms and bed rooms, and as mentioned before any tower is composed of core and skin, the outer skin in these forms will be exposed to some kind of morphing, so it is preferred to locate the flexible spaces at the outer perimeter of the tower; while the less flexible spaces inside the building near the core and to stack them vertically[2].

[1] (GÜNEL 2007). P. 21.
[2](Foster 2006).P.300-306 - (DAVID SCOTT Published online 2 November 2007). P.450.

Songdo trade tower Figure (95), is a perfect example of how to deal with morphing facades in residential towers.



As clear in figure the common zones for bath rooms and kitchens area are located near the core area, while the free flexible spaces are located on the outer perimeter to serve in form slopping.

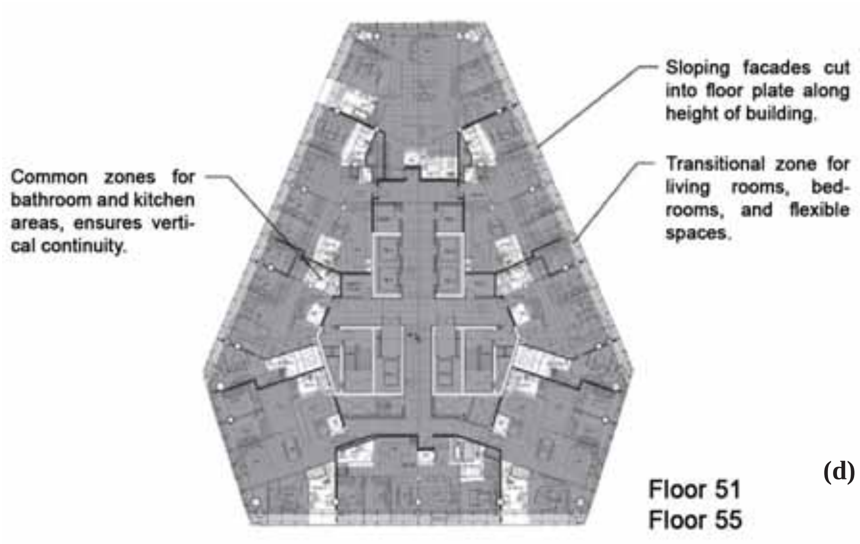


Figure (95) Songdo Trade Tower, (a) Perspective, (b) 3D configuration, (c) Structural system analysis, (d) plan of 51th & 55th floor

Ref: (a) (DAVID SCOTT Published online 2 November 2007) - (b) (Young 2009) - (c) (Kwang Ryang Chung, 2008)

4.6.1 Leaning forms

It is easy to create repetitive floor plans within a leaning tower, in case of leaning elevators, stairs and services inside the core but the problem is how to deal with leaning structural elements and leaning core.

In market, leaning elevators are available, but they are too expensive if compared to vertical ones, so in most cases designers choose to use vertical cores in their designs which mean that there are limitations for a tower to lean due to the presence of a vertical core and leaning floors, So architects have to choose the intersection point between both vertical and leaning elements[1].

From the point of view of structure, leaning cause an overturning moment which causes deflection in the direction of lean, solution in steel structures is easier than in concrete, There are some structural solutions to minimize these overturning forces which are **Figure (**96**)**:

- To drive a form for the tower where the overall center of mass of the building is directly over the base where it meets the ground, in this case there will be no additional loads on the foundations.
- To allow loads to travel vertically as possible because in case of transferring gravity loads in an inclined column, an additional horizontal forces will be generated on the building, and to avoid or decrease the use of inclined columns, core with cantilever can be used instead of outside columns which need to be inclined and will not exist, another solution is the usage of diagrid structure system; which is structurally and economically effective in this case.

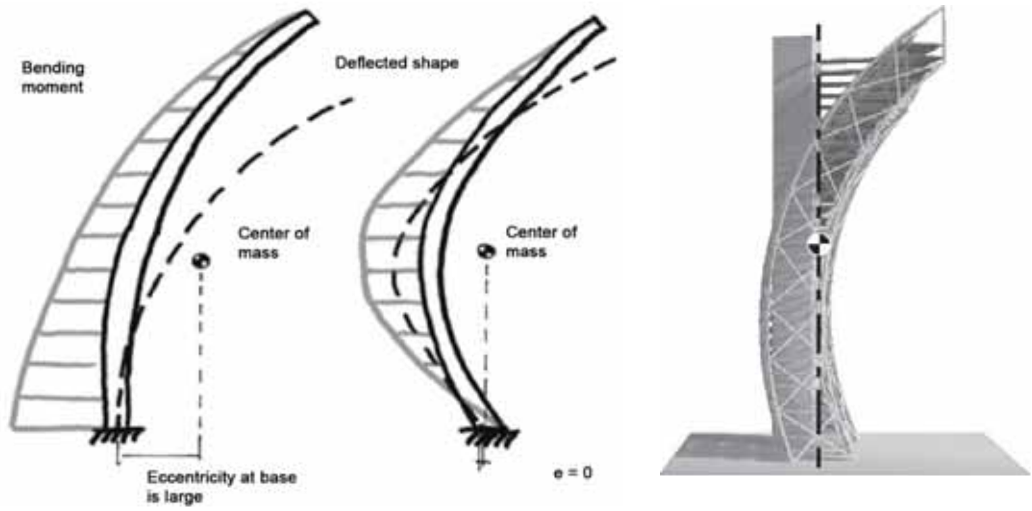


Figure (96) Minimization of overall bending moments through centering the mass of the mass of the building over the centeroid of the base support,on the right Milan Fiera: side elevation showing center of mass, and force plot
Ref: (DAVID SCOTT Published online 2 November 2007)

[1] (DAVID SCOTT Published online 2 November 2007). P.441-450.

- To choose symmetrical form and cross sections, this help in reducing and minimizing any additional horizontal forces generated due to inclined columns which will be balanced by an equal and opposite forces from the symmetrically opposing column.

Those three main solutions can be used together by mixing them to have at the end a leaning form. From the examples that fit these solutions are the **Songdo trade tower** and **Milan Fiera Tower Figure (97-b)**, which is designed by **Danial Libskind and zaha hadid** chose the center of mass of the tower to be just directly over the base in addition to the use of steel diagrid system to overcome the overturning moment and wind loads[1].

Figure (97) examples of complex geometries (a) Hyatt at Capital Gate (b) Milan Fiera tower
Ref: http://aedesign.wordpress.com/

4.6.2 Twisting tower

For a practical reason core in twisted forms should be vertical, it is very difficult to twist services and elevators, so the problem here is how to design a rentable floor plan at each twisted floor level and its relationship with the core, it is not preferred to make columns on the outer skin follows the twisting form but instead of that it can be eliminated and core with cantilever can be used instead of adding counter rotating columns to balance tensional force induced due to twisting as in case of **turning torso by Calitrava Figure (98)** [2]. Adding shear walls to the core and bracing on the outer façade can help in reducing loads on the twisted form.

4.7 Tall building form generation by parametric design process [3]

From the age of early sky scrapers, tall buildings development has been dependent on technology. During the past few years, there has been a great development of computer aided tools; to help in the architectural design process. Computer can be used as a tool to present , study, simulate the architectural building ever known, it can be a tool to design with specially

1 (Foster 2006).P.116-117.
2 ibid.P.159,155.
3 (Sang Min Park n.d.).

in cases of complex geometry buildings that are not easy to design or study manually. The use of digital tools in the schematic design phase of tall building design is still quite limited this method can be called parametric method for design **Figure (99)**.The advantages of this method are that, it can have the ability to generate and study an architectural form for tall building with an interrelation of large number of design consideration.

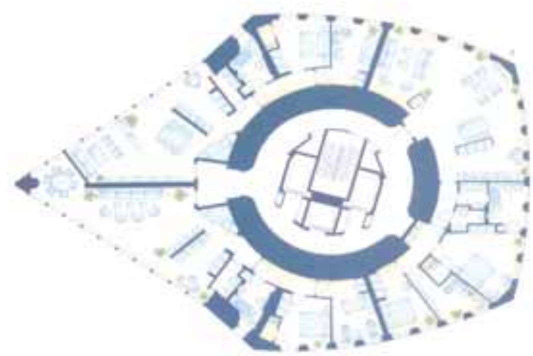


Figure (98) Turning Torso by Calitrava.
Ref: (Foster 2006).P.154 & 155

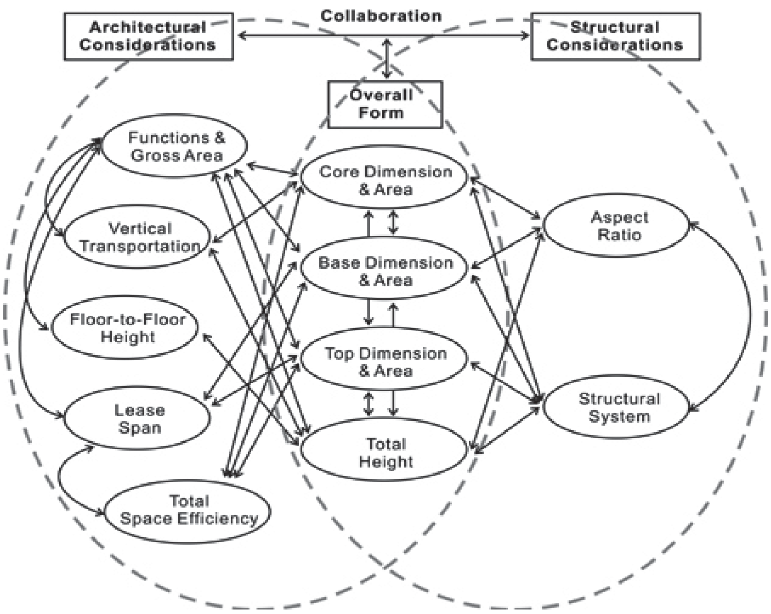


Figure (99) The interrelation of large number of design considerations.
Ref: (Park n.d.).P.4.

Conventional design methods always have some limitations such as time, architects abilities to think of complex geometries and others; computer and digital tools are capable of exploring in imaginary complex forms and giving a complete study for them.

According to the paper titled *"tall building form generation by parametric design "published by CTBUH 2004 Seoul conference"* and *"Innovative tall building form development"* again published by CTBUH by same author **Sany Min Park**, we can find that he has determined a proposal for the parametric process; in the first paper he mentioned the process as a chart, and then he developed this chart in to six major steps or parts **Figure (100)**.

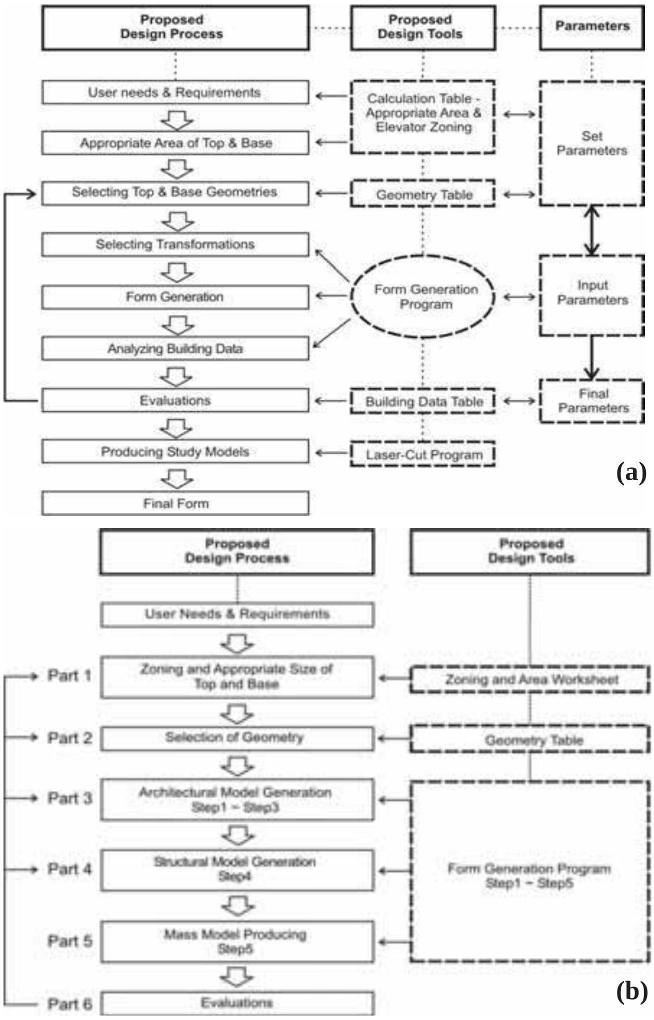


Figure (100) Proposed design process and tools.

Ref: (a) (Sang Min Park n.d.). P.2 - (b) (Park n.d.). P.4.

<u>Part 1</u>: Zoning and Area Calculation (Using Area and Zoning Worksheet)
Preparing vertical transportation systems and appropriate core size
Preparing appropriate base and top size **Figure (101)** .

Program

Function	Gross Area		# of Unit	Area / unit
Office	2000000.0	sqft		
Hotel	300000.0	units	400.0	600.0
Residential	600000.0	units	400.0	1200.0
Hotel Back of the House	150000.0	sqft		
Sky Restaurant	1.0	floor		
Observatory	1.0	floor		
Total	3050000.0	sqft		

Office

Guideline	Passenger	50000.0	sqft/ 1 elevator
	Freight	300000.0	sqft/ 1 elevator

Total Office Passenger Elevators	40.0

2 Zones

	Total	2 Banks	3 Banks	4 Banks	Decision
Number of Elev. - Zone1	20.0	10.0	6.7	5.0	7.0
		10.0	6.7	5.0	7.0
			6.7	5.0	7.0
Number of Elev. - Zone2	20.0	10.0	6.7	5.0	7.0
		10.0	6.7	5.0	7.0
			6.7	5.0	7.0
Number of Sky lobby	1.0				
Number of Express Elev.	10.0				8.0
Number of Freight Elev.	6.7				5.0
Total Number of Elev. In Plaza Level			36.7		34.0

3 Zones

	Total	2 Banks	3 Banks	4 Banks	Decision
Number of Elev. - Zone1	13.3	6.7	4.4	3.3	
		6.7	4.4	3.3	
			4.4	3.3	
Number of Elev. - Zone2	13.3	6.7	4.4	3.3	
		6.7	4.4	3.3	
			4.4	3.3	
Number of Elev. - Zone3	13.3	6.7	4.4	3.3	
		6.7	4.4	3.3	
			4.4	3.3	
Number of Sky lobby	2.0				
Number of Express Elev.	6.7				
	6.7				
Number of Freight Elev.	6.7				
Total Number of Elev. In Plaza Level			33.3		
Decision of Total Number of Office Elevators in Plaza Level					34.0

Hotel

Guideline	Passenger	100.0	units/ 1 elevator
	Express	200.0	units/ 1 elevator
	Service	200.0	units/ 1 elevator
	Freight	200.0	units/ 1 elevator

		Decision
Number of Passenger Elev.	4.0	4.0
Number of Express Elev.	2.0	2.0
Number of Service Elev.	2.0	2.0
Number of Freight Elev.	2.0	2.0
Total Number of Elev. In Plaza Level	4.0	4.0

Residential

Guideline	Passenger	100.0	units/ 1 elevator
	Express	200.0	units/ 1 elevator
	Freight	200.0	units/ 1 elevator

		Decision
Number of Passenger Elev.	4.0	4.0
Number of Express Elev.	2.0	2.0
Number of Freight Elev.	2.0	2.0
Total Number of Elev. In Plaza Level	4.0	4.0

Other Functions

Sky Restaurant & Observatory

		Decision
Number of Express Elev.		2.0
Number of Freight Elev.		2.0
Total Number of Elev. In Plaza Level		4.0

Total Number of Elevators in Plaza Level

46.0	4600.0 sqft

Extra Space in Core (10'x10')

Stairs	2.0	x	200.0	400.0 sqft
Shaft	4.0	x	100.0	400.0 sqft
Mechanical Room	1.0	x	100.0	100.0 sqft
Telephone Room	1.0	x	100.0	100.0 sqft
Corridor	40.0	% of Total Core Area		3733.3 sqft

Appropriate Total Core Area & Dimension at Base

9333.3 sqft	96.6 ft	x	96.6 ft
10000 sqft	100 ft	x	100 ft

Appropriate Base Area & Dimension

The Ratio of Core Area in Base Area 25 %

37333.3 sqft	193.2 ft	x	193.2 ft
40000.0 sqft	200.0 ft	x	200.0 ft

Total Number of Elevators at the Top of Residential

10.0	1000.0 sqft

Extra Space in Core (10'x10')

Stairs	2.0	x	200.0	400.0 sqft
Shaft	2.0	x	100.0	200.0 sqft
Mechanical Room	1.0	x	100.0	100.0 sqft
Telephone Room	1.0	x	100.0	100.0 sqft
Corridor	40.0	% of Total Core Area		1200.0 sqft

Appropriate Total Core Area & Dimension at Top

3000.0 sqft	54.8 ft	x	54.8 ft
3025.0 sqft	55.0 ft	x	55.0 ft

Appropriate Top Area & Dimension

The Ratio of Core Area in Base Area 25 %

12000.0 sqft	109.5 ft	x	109.5 ft
12100.0 sqft	110.0 ft	x	110.0 ft

Figure (101) Base and top area calculation worksheet.
<u>**Ref:**</u> (Sang Min Park n.d.). P.3.

Part 2: Explorations of Geometry (Using Explored Geometry Table)
Selecting base and top geometry and their combination type
Deciding number of points connecting base geometry to top geometry **Figure (102)**.

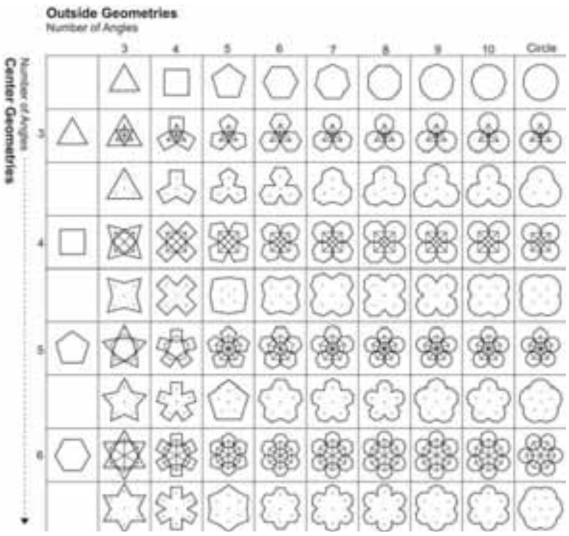


Figure (102) Examples of explored symmetry geometries.
Ref: (Sang Min Park n.d.).P.4.

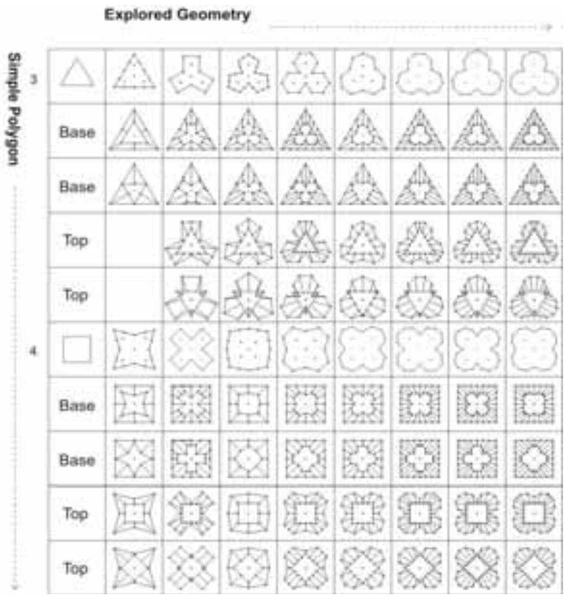


Figure (103) Examples of combinations of base and top geometries.
Ref: (Sang Min Park n.d.). P.4.

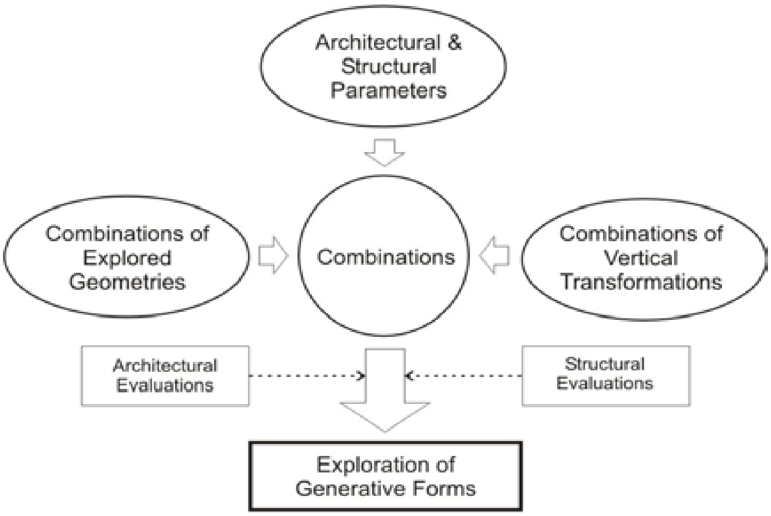
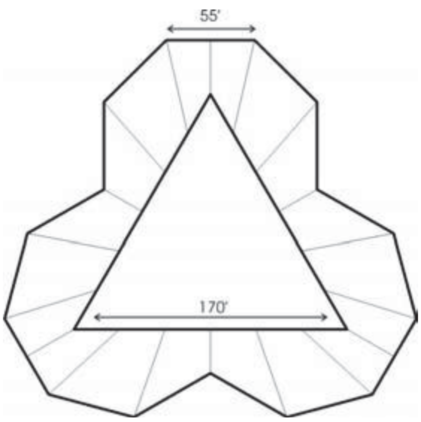


Figure 105 Figure (106) Exploration of Generative Forms
<u>Ref:</u> (Sang Min Park n.d.). P.5.

<u>Part 3</u>: Architectural Model Generation (Using Form Generation Program)
Generating architectural 3D model
Creating building data spreadsheet
Run Form Generation Program
<u>Step 1:</u> Each Function's Necessary Number of Floor Calculation
<u>Step 2:</u> All Floor Plates and Building Data Generation
<u>Step 3:</u> Architectural 3D Model Generation



Base Area: 40.497 ft^2

Top Area : 12.514 ft^2

Figure (107) Example of selected base and top geometries.
<u>Ref:</u> (Sang Min Park n.d.). P.5.

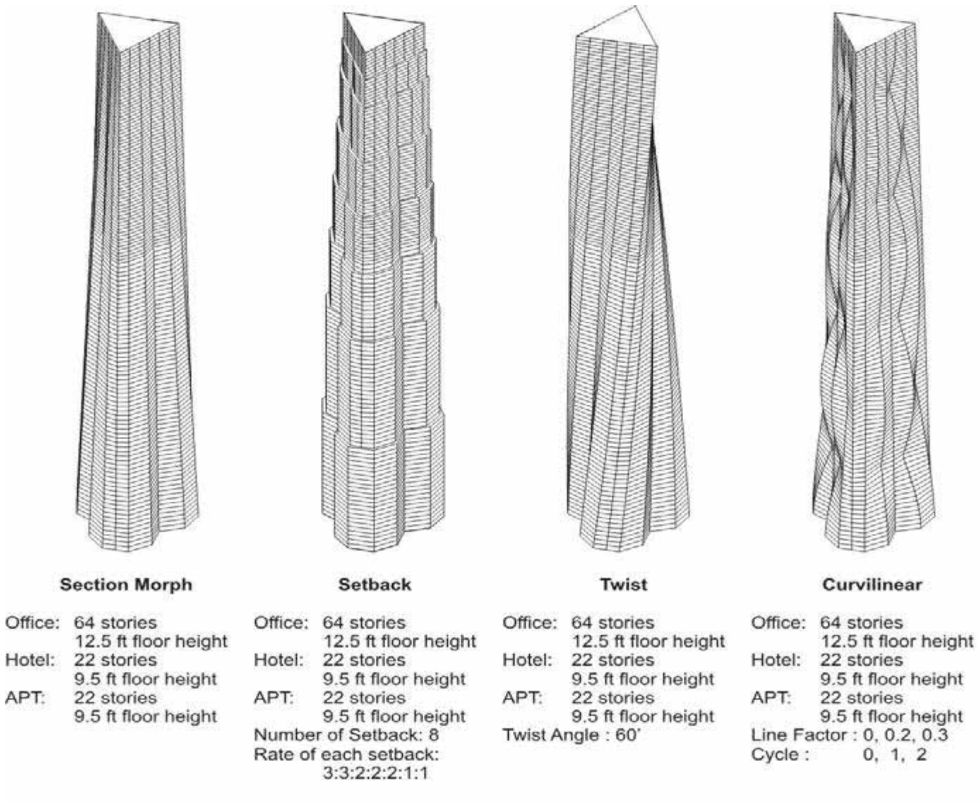


Figure (108) Example of generated forms geometries.
Ref: (Sang Min Park n.d.). P.5.

As example Base and Top geometries are selected as in the form generation was applied through form generation program to be ready for next steps.
Part 4: Structural Model Generation
Generating Structural 3D Model
Creating Structural Input File for Structural Analysis Program
Run Form Generation Program
Step 4: Structural 3D Model Generation and Creating Structural Input Files
Part 5: Mass Model Producing
Preparing Mass Model Making Layout
Run Form Generation Program
Step 5: Mass Model Layout for Laser Cutting
Part 6: Evaluations (Using all output 3D models, data, and mass model) Evaluating Generated Alternatives.

4.8 Tall buildings and sustainability

One of the new approaches in tall building's design is sustainable designs, for example in tall offices; large amount of energy is consumed for the building performance, specially in office spaces and service zones. The most intensive use of energy usually results from the heating or cooling of spaces, 10 percent of the building's energy is consumed by lifts while 20 percent are consumed for lighting. So a careful design can minimize the need for cooling and heating among the year.

Many trends are taken towards a sustainable tall building through several approaches and concepts such as bioclimatic skyscrapers and ecological skyscrapers, some of the ideas to generate a sustainable tall building are.[1]

1. The effective use of passive solar heat and thermal mass of the building.
2. The high insulation level of building.
3. The effective use of natural day lighting through large glass surfaces.
4. The use of double skin façade, this can serve in the reduction of heat loss in winter, and heat gain in summer, because they act as buffer zones between internal and external conditions, also they can help in providing natural ventilation.[2]

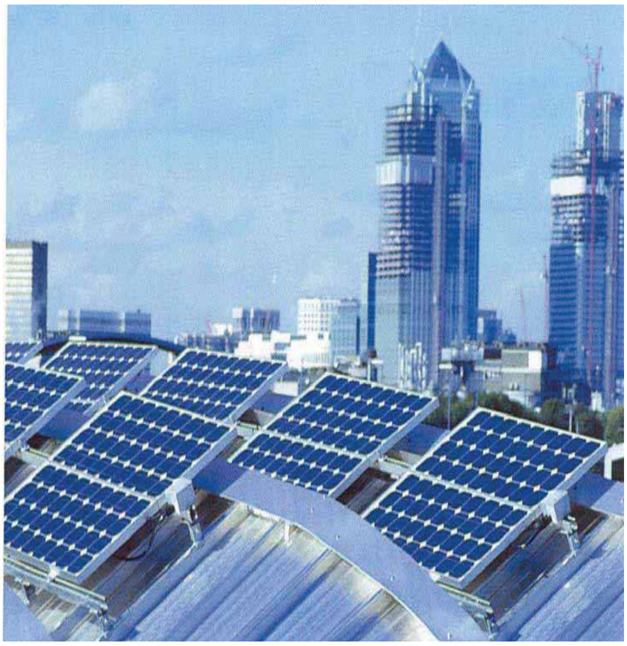


Figure (109) Architectural Design with PV
Ref: (Herbert Giradet March 2002).P.46 & 48.

[1] (Herbert Giradet March 2002).P.6-9.
[2] ibid. P.43

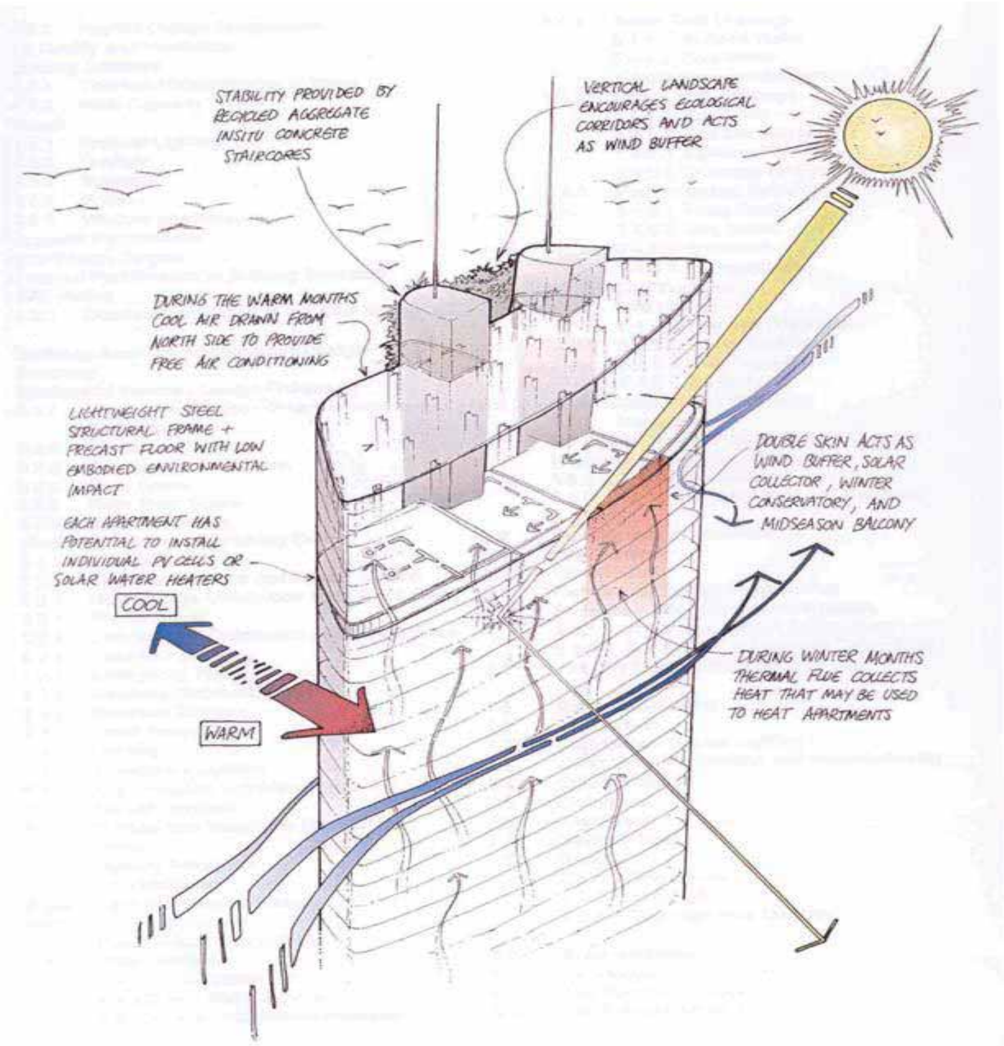


Figure (110) Holloway Circus Tower Principles of Environmental Design
Ref: (Foster 2006).P.42.

5. The design of sustainable operations for tall buildings for example; the use of citigen service and CHP (combined heat and power) that has been highly efficient source of energy, CHP is the simultaneous production of power, heat and sometimes chilled water for air conditioning, CHP avoids transmission losses, because electricity is generated close to point of use, CHP installation are generally 30 percent lower than the levels of rising from conventional power generation techniques.

6. The use of photovoltaic cells (PV) install buildings supply sustainable source of energy[1] through the use of (PV) panels to convert light into energy such as electricity.
7. The creation of internal green sky gardens within buildings.
8. The use of clean sources of energy; such as solar energy and the reduction of CO_2 consumption.

From the well known sustainable towers is the **Commerz Bank by Norman Foster Figure (111).** It was considered to be the world's first ecological office tower.[2]

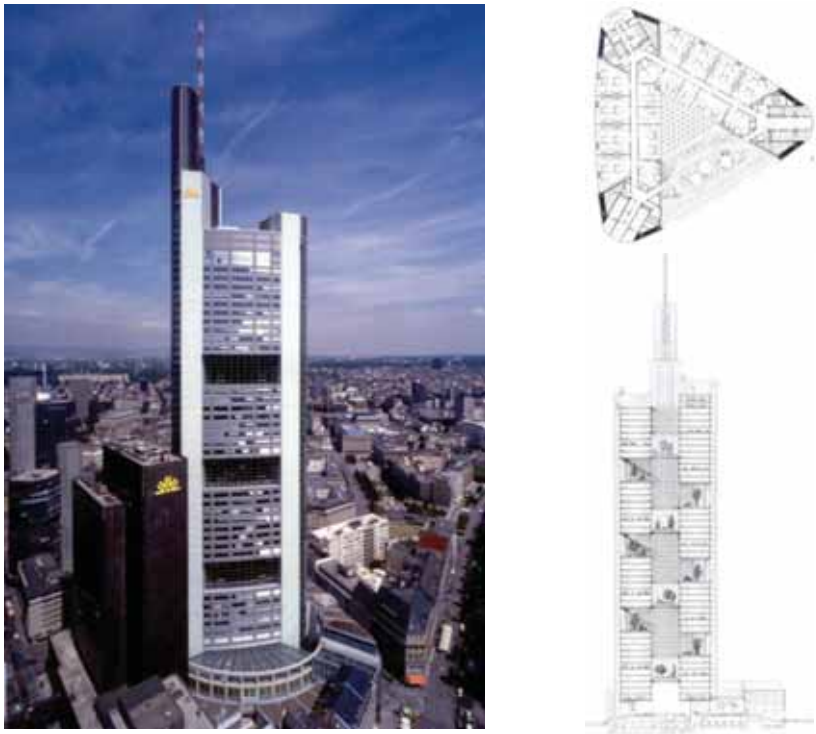


Figure (111) Commerz Bank b Norman Foster
Ref: (Foster 2006).P.208 & 209.

The building uses the idea of natural light and ventilation through the green roof gardens at high levels of the building which represent an ecological solutions to create a suitable green building.

In **Bahrain world trade center Figure (112),** the use of wind turbines reduce between 11 to 15 percent of the total electrical consumption of the building[3].

1 (Herbert Giradet March 2002).P.45.
2 (Foster 2006).P.208
3 ibid..P.180.

Figure (112) Bahrain World Trade Center.
Ref: (Foster 2006).P.181.

4.9 Vertical cities

It is not a new trend to build high, from the ancient time people dreamed of a tower or vertical city that explore the sky; however it was just a dream, until the 20th century when the race of tall building started in north America.

The appearance of tall structures was at the same time parallel to the movement towards modern new cities with a new urban planning and new urban design, cities that look forward for a human quality of life, but the challenge in the design of new cities of today and the future is the accommodation of large populations, while creating a higher quality of life the planning for the increase of population, having in mind that problems such as pollution, urban sprawl, and exploitation on natural resources are non-reversible outcomes of poor planning. [1]

New aspects of design must be taken in consideration such as the reduction of energy consumption specially in automobiles, also by trying to make cities smaller and denser so the power grid will become smaller as a result, and the transfer of electrical energy will be more efficient, the need of automobiles and personal transportation as well will decrease, this will provide a great energy saving and less polluted environment[2].

[1] (Armstrong May, 2008).
[2] (Foster 2006).P.180..

One of the major problems facing any city is the growth, however growth cannot be stopped but can only be controlled, and that's why super tall buildings and mega structures are the likely solutions to the problems that mega cities will face.

Super tall buildings can be designed where the activities of the streets and the city infra structure are extended vertically into its structure, in case of vertical cities or super tall buildings the basic concept for its design will be its performance.

The early history of mega structures started with the industrial revolution; where the concepts of a tall building becoming a city in the sky was produced. Many architects had it as a dreamlike, Le Corbusier, Frank Lloyd Wright and many schools of architecture as well, metabolism, arch gram ….etc, however the dream is now about to become true through the project of **vertical city in Dubai Figure (113)**, it is still a concept but it is about to be achieved.

Super tall structures are constructed in many countries such as, North of America, Asia and it can be a clear proof that one day there can be a real complete verticality.

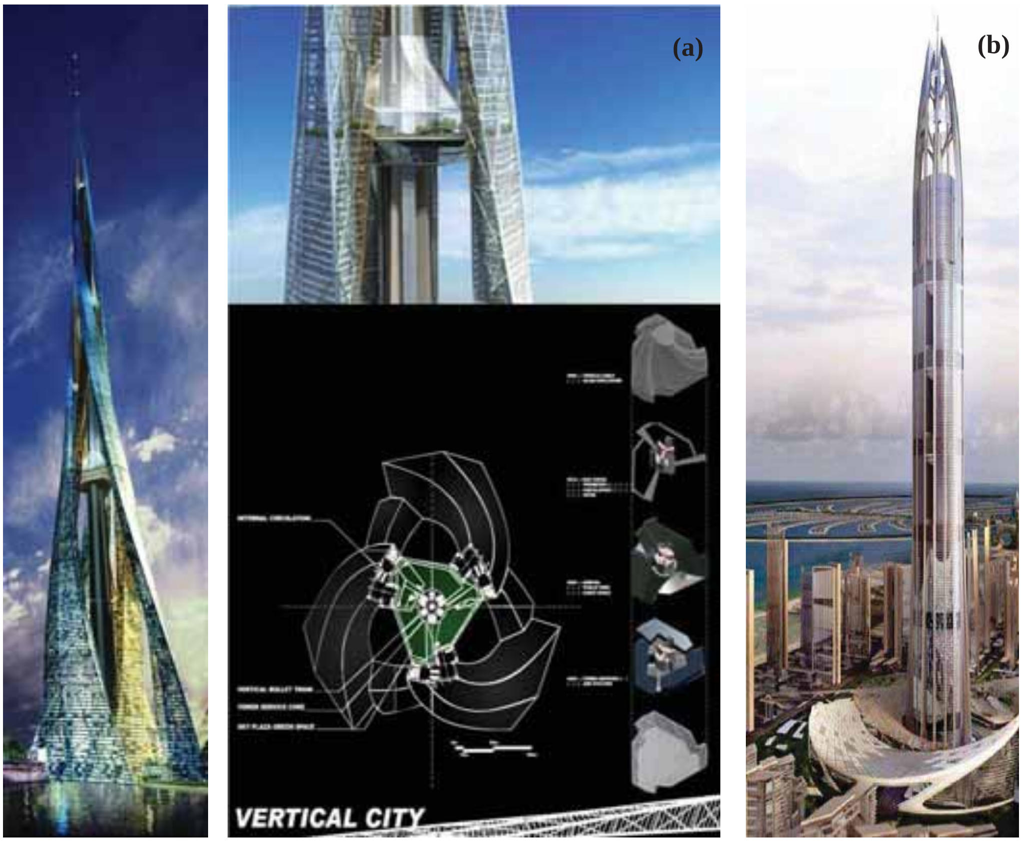
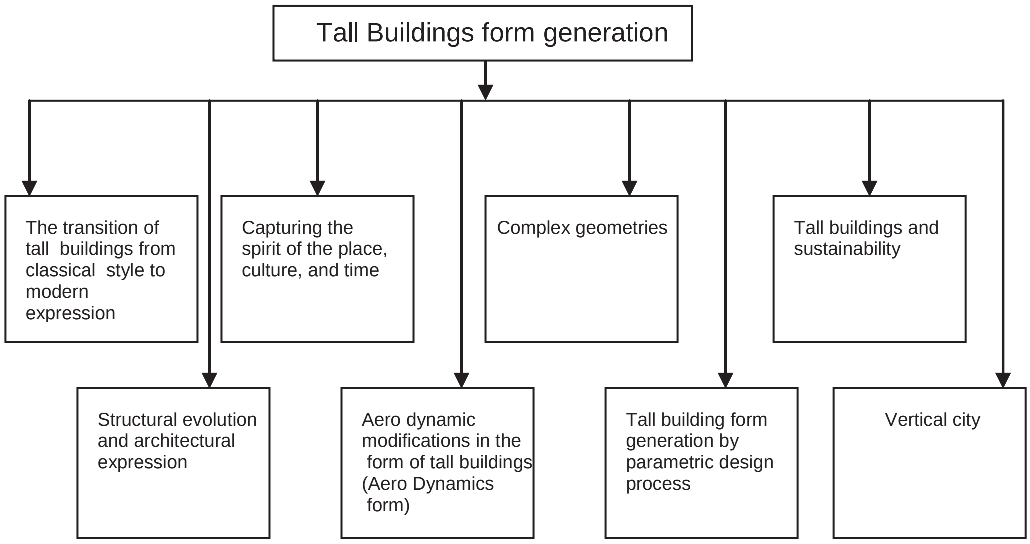


Figure (113) Showing an examples of vertical cities (a)Dubai Vertical City, (b) Nakheel Tower

Ref: (a) http://www.irintech.com , (b) (O'Brien, 2009 Issue II)

Summary

Trends for tall buildings form generation and designs are many, sometimes they can interact, for example in **Swiss Tower**, the use of diagrid as an architectural and structural expression and at the same time to achieve sustainability. However trends for tall buildings form generation are unlimited and will change and increase with time.



Part Three

Case Studies and Conclusion

Chapter Five

Case Studies and Conclusion

CHAPTER FIVE
Case Studies and Conclusion

5.1 Introduction

As mentioned before in the previous chapters, tall building's design trends and forms are multiple ,complicated and renewable in their design process. That is why it represents a challenge for any architect to think of designing an innovative tall structure.

In this chapter, the main objective is to drive the mutual relationship between the trends of the form generation and the structure systems in tall building's design. This will be through diagrams, charts and case studies.

5.2 Case studies

In order to give a clear explanation to the mutual relationship between structure and architecture in tall buildings design, some case are selected.

5.2.1 Methods of choosing case studies

The selection of case studies was based on some points which are:

- The selection of famous and well known tall structures that had a significant effect and impact in tall building's design either due to being among the list of tall structures in the world, as in case of **Burj Dubai (Burj Khaleefa) , Petronas towers** (Twin Towers), **and Taipei 101** or for being famous for their structural or architectural concepts such as in case of **Hearst Tower** or **Swiss Tower.**
- The selection of tall structures that were recently completed or that are under construction.
- The selection of tall structures that are not yet completed that are still in the design stage but follows the rules mentioned in previous chapters ,and that are not still theoretical idea; They are not built yet but their ideas are applicable and there are similar examples constructed.

5.2.2 Methods of case study analysis

Any of the case studies will be analyzed according to the following points.

- Basic information.
  - Location:
  - Architect:
  - Height:
  - Principal Structural material:
  - Other materials:
  - Structure system:
  - Form generation trend:
- Architectural and structural analysis
  - Architectural and structural analysis
  - Architectural concept
  - Function of the building
  - Structure system
- Conclusion

5.2.3 Selected case studies

1. Burj Dubai (Burj AL-Khaleefa).
2. CCTV Tower.
3. Rotating Tower.
4. Turning Torso.
5. Swiss Tower.

5.3 Burj Dubai (Burj Khaeefa) 2003-2010

<u>Location:</u> Dubai, United Arab of Emirates.

<u>Architect:</u> (SOM) Skid More, Owings, and Merill LLPP, Adrian D-smith, FAIA consulting design partners.

<u>Height:</u> More than 700 m.

<u>Principal Structural material:</u> Reinforced concrete.

<u>Other materials:</u> <u>Exterior:</u> aluminum, glass.

<u>Interior:</u> Granite, Stainless Steel, Wood.

<u>Structure system:</u> Bundled Tube

<u>Form generation trend:</u> Capturing the spirit of the place culture and time - Aero-Dynamic design - Sustainable design.

<u>Function of the building:</u> Mixed use

5.3.1 Architectural and structural analysis

5.3.1.1 Architectural concept

The architect searched for elements within the existing context, traditions and culture to find a better motive for the form generation such as onion domes, pointed arches and patterns that are indigenous to the region[1] **Figure (114).**

"The form is geometric in plan, starting with three branches and three pods. The specific shape of these branches modular in nature and in function, and organic, and biomorphic in form, the form can be found in flower petals, leaves, and seeds, in animals such as birds, and sea creatures including crustaceans. The overall composition is a vertical object reduced and transformed by spiral reduction of branch lengths until it reaches its central shaft, This point the shaft peels away to reveal a triptych configuration that erodes in a spiral manner until a single spire remains. The resulting impression is organic and plant-like; this typology is indeterminate in its size and can be expanded vertically by adding modules to its base or continuing to divide the spire element" [2]

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[1] (Smith 2007). P.204.
[2] ibid.

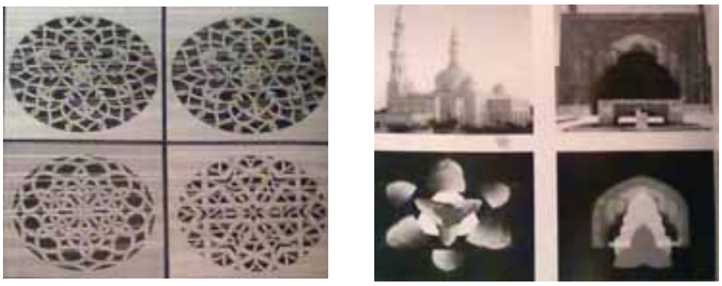


Figure (114) Concept inspiration
Ref: (Smith 2007)

5.3.1.2 Function of the building

The building is a mixed used. It contains offices, residential units, hotels and a great underground parking; the following sketch explains the divisions of **Burj Dubai**[1] **Figure (115).**

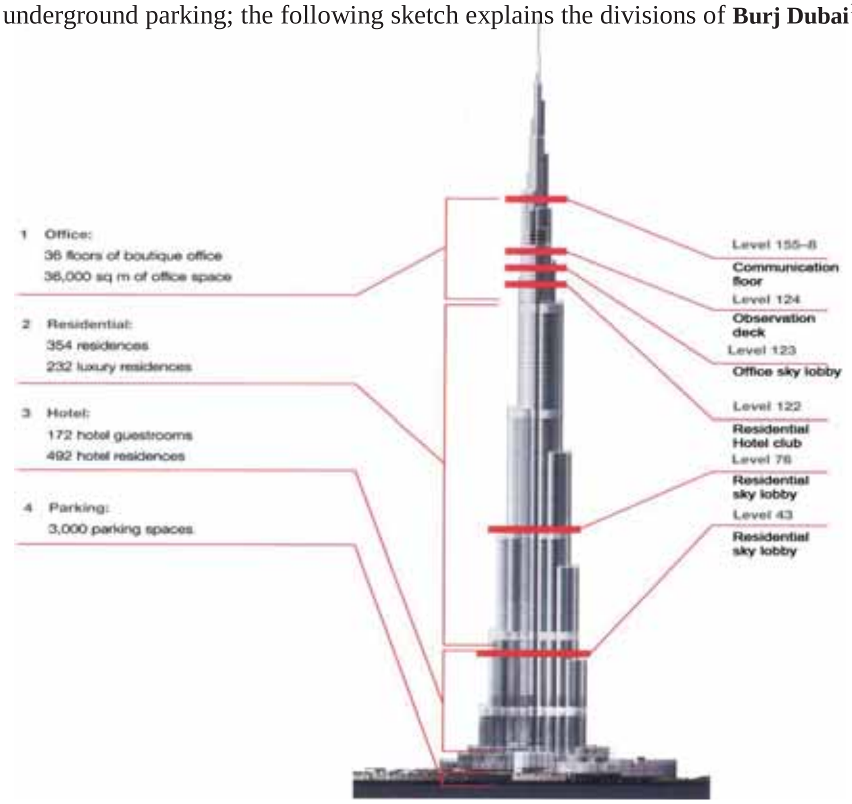


Figure (115) Function of the building
Ref: (Smith 2007)

[1] (Smith 2007). P.228.

The building will feature an innovative condensate collection system. The hot and humid outside, which will combine with the cooling requirements of the building causing a great amount of condensation and moisture from air, then water will be collected and used for the irrigation of the land suspended planting around the tower providing around 15 million gallons of supplemental water per year[1].

5.3.1.3 Structure system

The form is treated as a bundled tube structure having its form varied by decreasing the number of tubes and its size as the structure grows vertically.

The choice of this form served in many issues such as overcoming the vortex shedding phenomenon by its variation in form **Figure (116).**

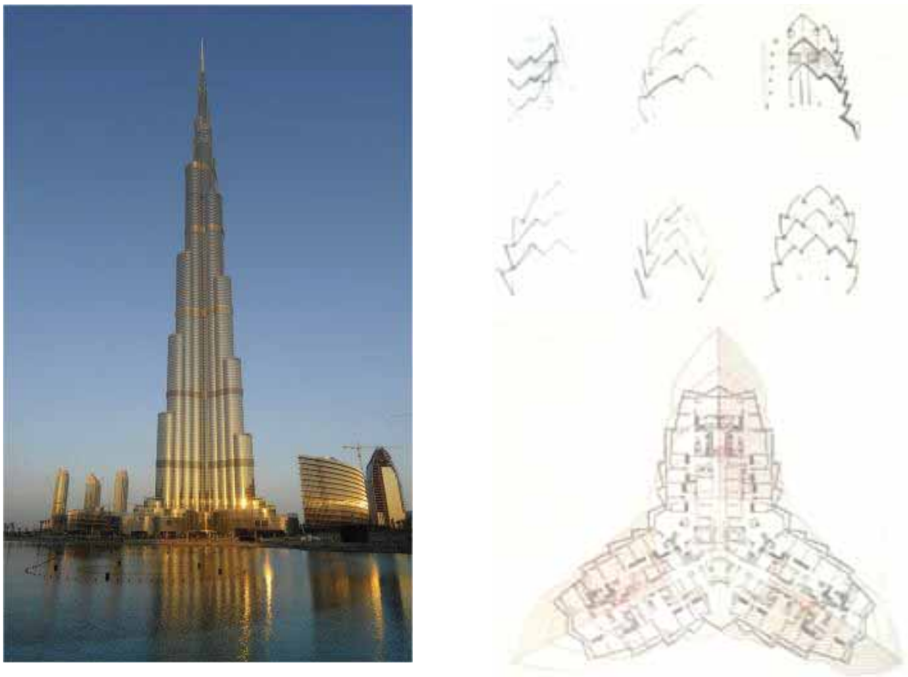


Figure (116) Showing the structure system of burj Elkhaleefa
Ref: http://zollotech.com

The structure of this tower is modular with a central hexagonal core and three branches having 120 degrees from each other integrated at the core as seen. Attached to these branches a well-like columns having 9 m spacing between each, they simply drop off as each branch is setback. That is way the designer was capable of avoiding complex and costly structural transfer [2].

[1] (Smith 2007). P.214.
[2] ibid. P.212.

The building form shape was tested several times through wind tunnel test and the form was modified until the designers reached the best possible form and orientation **Figure (117).**

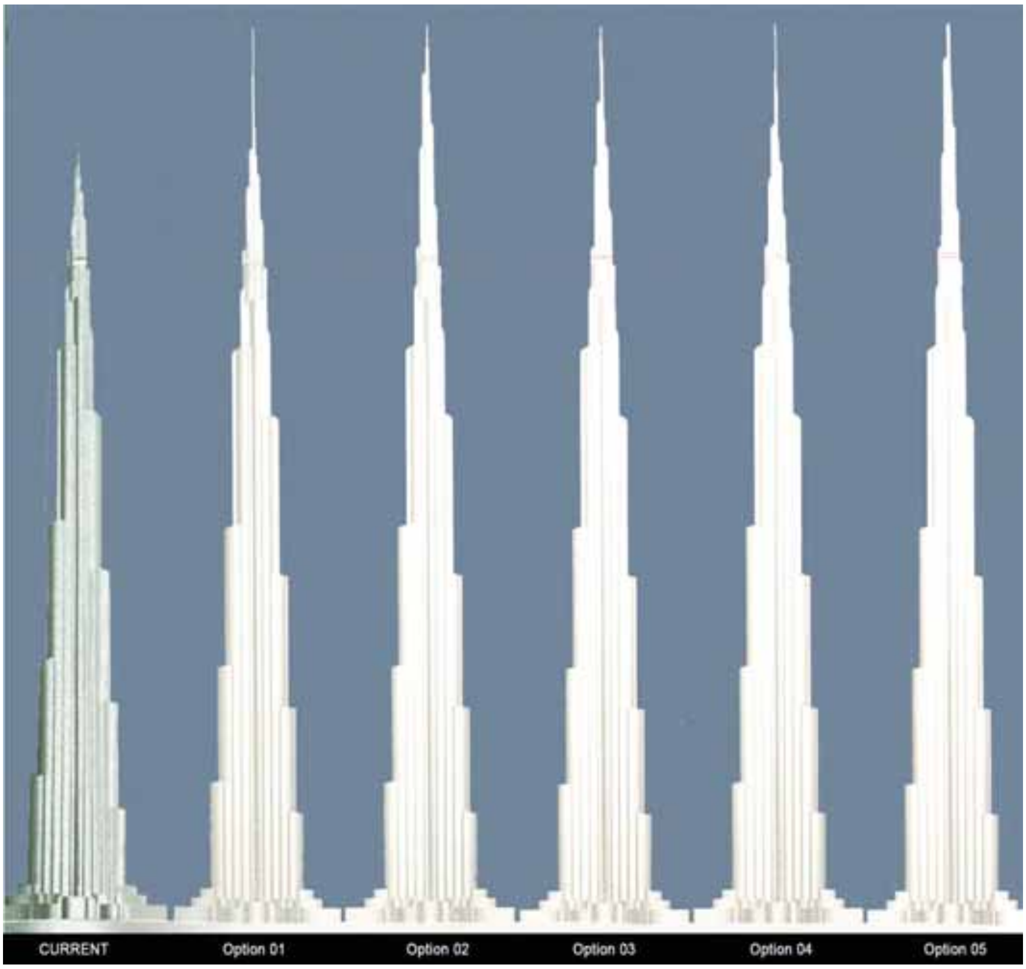


Figure (117) Burj Dubai (Burj Khaeefa) proposals
Ref: (Smith 2007)

5.3.2 Conclusion

Tower of Dubai is an example of a new treatment to bundled tube system, that is used again to create the tallest structure in the world in 2010 after it was used before in **Sears Tower,** also it is a representation to culture and tradition in Dubai.

5.4 CCTV Headquarters 2003-2008

Location: Beijing, China.

Architect: Rem koolhaas's practice office for metropolitan architecture (OMA) Arup, East of China architecture and design institute (ECADI).

Height: 239 m tall.

Principal structural material: Steel + Steel reinforced concrete (SKC).

Other materials: Curtain wall.

Interior:

Structure System: Braced Tube + Dia- grid

Form generation trend: integrating architectural and structural form in tall building design-Aero-dynamic design-Parametric design.

Function of the building: China Central Television.

5.4.1 Architectural and structural analysis

In 5 August 2003 in a discussion at Tsighua University **Rem Koolhaas** said "*Who says that structure should not be reinvented?! Who says that reinventing structure cannot be creative?*" on these words **Rem Koolhaas** based his design[1].

5.4.1.1 Architectural concept

"The client stipulated in the competition brief that the facility should all be housed on one site, but not necessarily constrained to one building. In his architectural response, however OMA decided that by doing just this it should be possible to break down the ghettoes, that trend to form a complex and compartmentalized process like the making of TV programmes and create a building, whose layout in three dimensions would force all of those involved. The creative people, the producers, the technicians, and the administrators - to mix and produce better end - product economically and efficiently.

The winning design thus combines administration and offices, news and broadcasting, programme production and services –the entire process- in a single loop of interconnected activities. The specific of structure evolved in tandem with the specifics of the building as they in turn evolved, a hot able example being the placement of double height studios, with in the towers and base, which significantly influenced the structural form[2]".

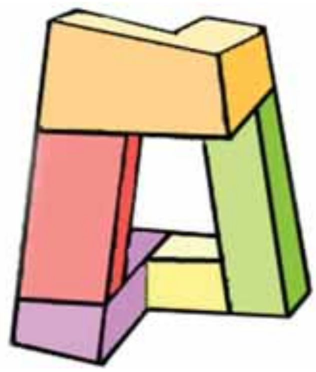
1 (Contributors, CCTV Headquarters, Beijing, China:Structural engineering design and approvals 2/2005).P.03.
2 ibid.

The architectural form of the tower is simply a base of nine stories carrying two leaning towers that slope at 6 degrees in each direction and a nine to 13-stories over hang suspended 36 stories in the air[1].

5.4.1.2 Function of the building

As mentioned before it is china central television it includes **Figure (118)**:

1. Administration and offices.
2. News and broad casting.
3. Programme production and services.



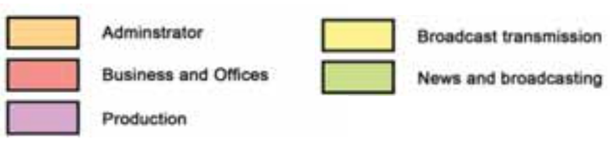
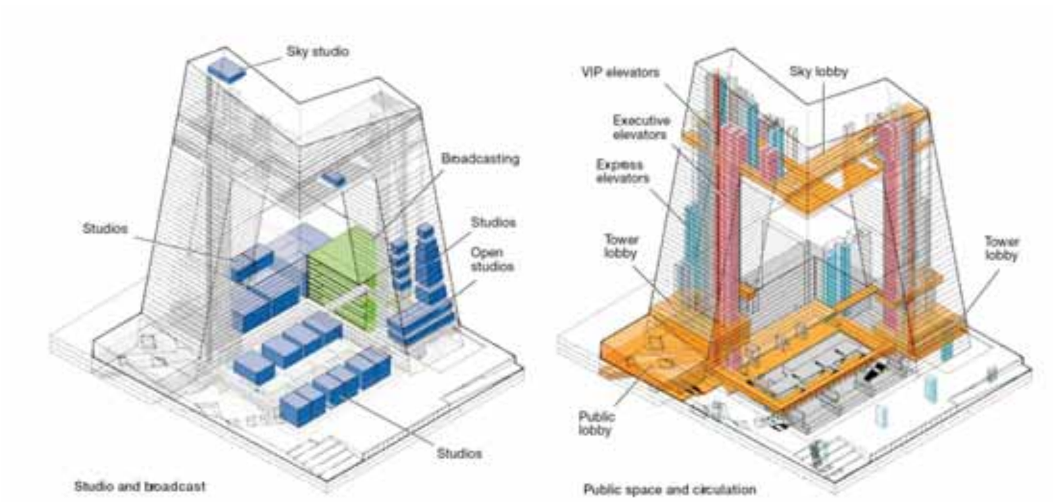


Figure (118) The sketch showing programme distribution.
Ref: (Contributors, CCTV Headquarters, Beijing, China:Structural engineering design and approvals 2/2005). P.4.

The following diagrams explain the 3d configuration of the tower **Figure (119)**.



1 (Contributors, Case Study: CCTV Building - Headquarters & Cultural Center 2008).P.15.

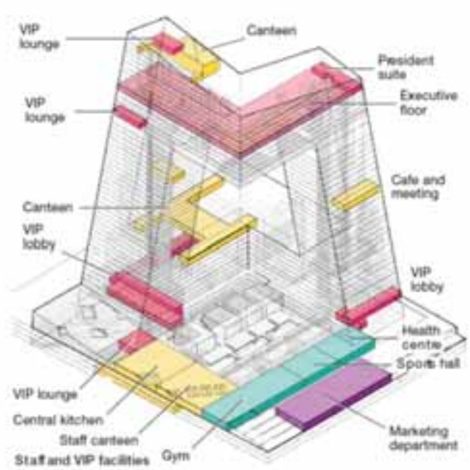


Figure (119) The functions and layout within the CCTV building.
Ref: (Contributors, CCTV Headquarters, Beijing, China:Structural engineering design and approvals 2/2005). P.4.

5.4.1.3 Structure system

"Prior to connection, the two towers would move independently of each other due to environmental conditions, in particular wind and thermal expansion and contraction. As soon as they were joined, therefore the elements at the link would have to be able to resist the stress as caused by these movements".[1]

Simply it is a new treatment to both dia-grid and braced tube, it is the continuous tube through the two towers each is a leaning tube, connected to each other from base, to create a continuous braced tube, and the tube is fully braced from all sides of the façade **Figure (120)**.

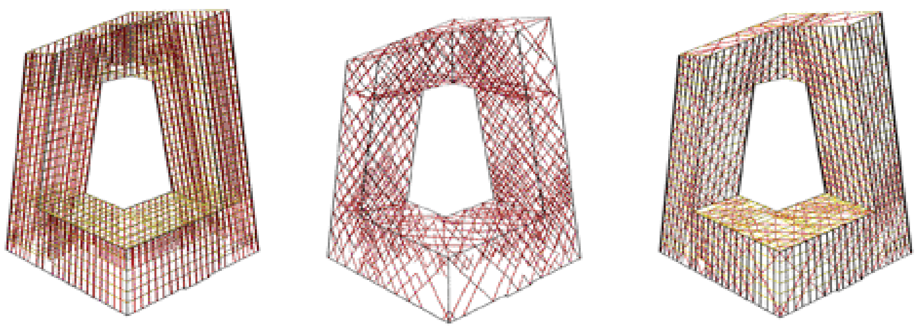


Figure (120) Principles of the tube structure: regular grid of columns and edge beams + patterned diagonal bracing = braced tube system.
Ref: (Contributors, CCTV Headquarters, Beijing, China:Structural engineering design and approvals 2/2005). P.

[1](Contributors, Case Study: CCTV Building - Headquarters & Cultural Center 2008).P.14.

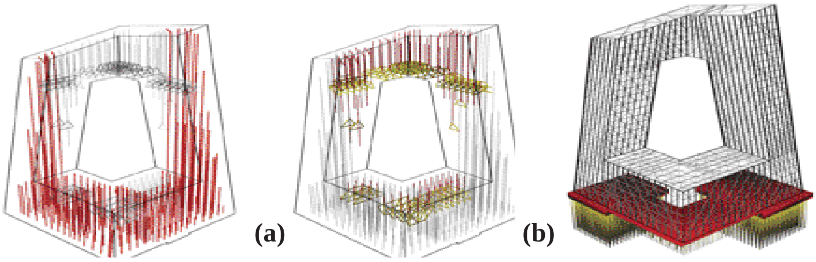


Figure (121) (a) Internal columns starting from pile cap level, (b) Internal columns supported on transfer structures, (c) The foundation system.
Ref: (Contributors, CCTV Headquarters, Beijing, China:Structural engineering design and approvals 2/2005). **P.5.**

Vertical cores oriented and stepped so that they can always sit within the foot print of the sloping towers, also the floor plates of the towers are supported by many vertical columns and due to the leaning, it is not possible to continue the vertical column lines from top to bottom, this was treated by creating a two story deep system of transfer trusses also the overhanging floors are supported by vertical columns that are also transferred to the external tube[1].

The use of parametric design was evolved in the structural design of the tower as many packages of software were used to deliver the CCTV structural design[2].

The design of diagonal bracing at the beginning was to be as regular diagonal steel braces, however the preliminary analysis showed that the forces in the braces are not constant, but they vary along continuous tube. This load to an optimization process in which the brace pattern was modified by adding or removing diagonals, depending on the strength and stiffness requirements of the design[3] **Figure (122)**.

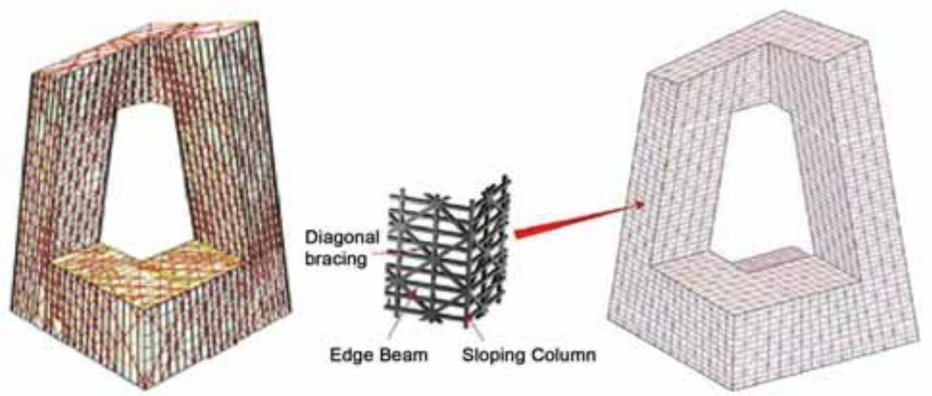


Figure (122) The use of parametric design in specifying t used structure system.
Ref: (Contributors, Case Study: CCTV Building - Headquarters & Cultural Center 2008). P.15.

[1] (Contributors, Case Study: CCTV Building - Headquarters & Cultural Center 2008).P.15.
[2] (Contributors, CCTV Headquarters, Beijing, China:Structural engineering design and approvals 2/2005). P. 05,06 & 07.
[3] ibid.

One of the major problems facing CCTV Tower was how to construct the overhang part that's why a study mode was made up and alternatives were sketched to find out the way to construct it.

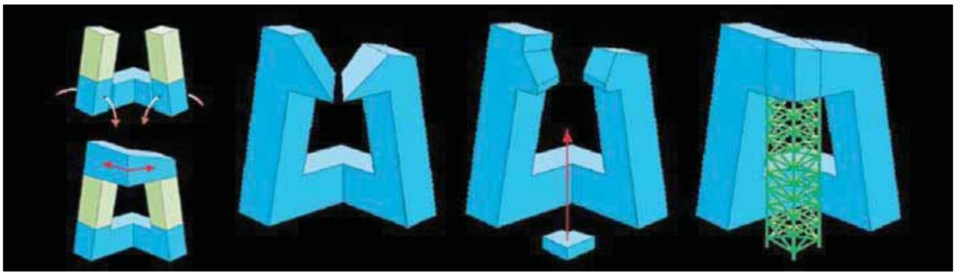


Figure (123) Alternative methods of constructing the Overhang
Ref: (Contributors, Case Study: CCTV Building - Headquarters & Cultural Center 2008). P.20.

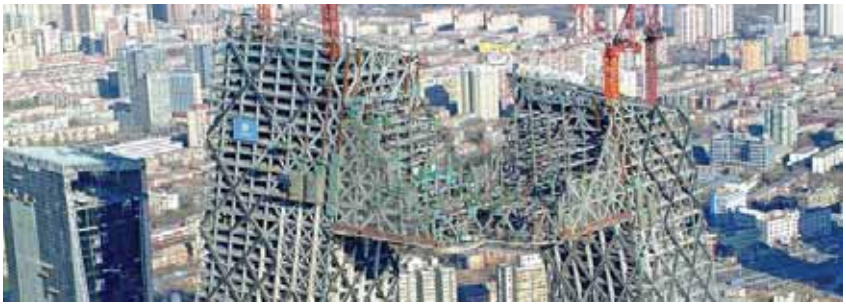


Figure (124) The Overhang before connection
Ref: (Contributors, Case Study: CCTV Building - Headquarters & Cultural Center 2008).P.22.

5.4.2 Conclusion

CCTV Tower posed many technical changes to overcome it is a development of the braced and dia-grid structures together, in addition to that, it is distinctive example for the representation of structure on the façade or the structural and architectural integration.

Figure (125) Shake table test model
Ref: (Contributors, Case Study: CCTV Building - Headquarters & Cultural Center 2008). P.19.

5.5 Rotating tower of Dubai (still a proposal)

Location: **Dubai, United Arab of Emirates**

Architect: **Dr. Arch. David H.Fisher.**

Height:

Principal structural material: **reinforced concrete + steel (composite)**

Other materials: Exterior: **Pre - fabricated units**

Interior:

Structure system: **core with cantilever**

Form generation trend: **Sustainability through (dynamic architecture)**

Function of the building: **Residential Building**

5.5.1 Architectural and structural analysis

5.5.1.1 Architectural concept

This building can be classified under the name of a new term which is dynamic architecture; David H.fisher says "the idea of dynamic architecture was born with the desire to have buildings that adjust themselves to life, that are part of nature. In fact, our building in each floor rotates separately, change their shape continuously and never look the same, I can call them (buildings designed by time, shaped by life) imagine a sky scraper that can revolve according to tenant's needs and whims, allowing them to decide their own height exposition and view" that's why he insisted that the buildings should be a sustainable building due to their nature, so they are made of natural sustainable materials for energy saving also the dynamic tower can produce wind energy that can be used as a clean source of energy.[1]

The dynamic tower is not only an iconic tower, that is not the only aim, it is the last aim but the real main aims is the environment, performance and quality of life, David fisher considers the architectural buildings as a sculptured forms with large scale but he says that they are the shell around our space that's why they should satisfy users need and he stated that the most of these need can be under six commands he named them six commands of architecture and the dynamic tower undergoes those commands which are:[2]

[1] (D. A. Fisher 2008). P.1,2&3.
[2] ibid.

1. Economical feasibility.
2. Functionality.
3. Environmentally sound.
4. Quality and engineering.
5. Maintenance.
6. Design.

The idea of the dynamic tower started from the rotation of floor plates around a central core to see the view around to allow the sun, to make the house part of nature.[1]

Also as we mentioned before the dynamic tower undergoes the six commands as follow:

1- The economical feasibility

Through the prefabrication of units, this can provide a cost saving up to 20% if compared to old traditional method not only that but also this help in reducing people working on site which means less risk of human casualties and time of construction as a result will decrease.

Prefabricated units can provide high quality control, low cost of local and easy monitoring of time.

2- Functionality

Space has a new meaning, it became flexible and dynamic no more fixed location and orientation, space can easily be designed to fit within users needs and can change by the change of their needs easily **Figure (126).**

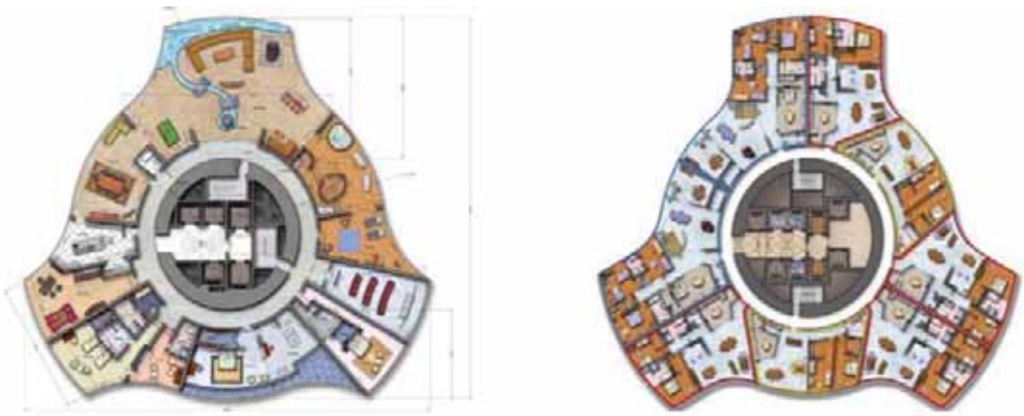


Figure (126) An illustration of how a floor of the Rotating Tower can be turned into various apartments
Ref: (D. A. Fisher 2008) .P.10 & 11.

1 (D. Fisher 2008). P.1-7.

3- Environmentally sounds

First of all the construction site will become smaller smart, ecological and safer due to the new method of construction, no more energy loss and consumption but instead clean sources of energy for the building and the surrounding site through wind turbines or photovoltaic panels **Figure (127).**

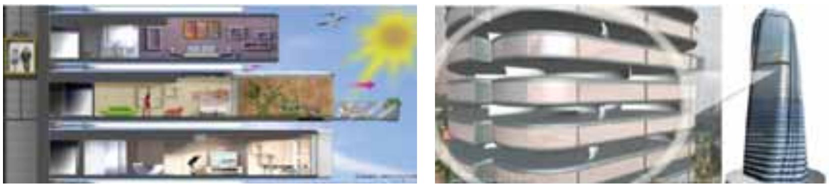


Figure (127) the figure shows the pre-fabricated units and the connection between them in addition to wind turbines detail and PV panels
Ref: (D. Fisher 2008). P.5 & 8.

4- Quality and engineering

The quality control will make the design capable of having all terms of quality in design, finishing material, energy saving, energy generating, ecological treatments and even in life quality.

The rotating tower will be the first skyscraper produced according to an industrial process, the central concrete will be built on site using traditional techniques, and the rest of the building which is around 90% will be prefabricated and transported to the building site as to be connected to the central core, considering that each floor of the tower consists of factory –made modules- that will arrive at the building site with electrical, plumping, air conditioning system ready for use. David call this method as Fisher method, as a result this will decreases the total cost for construction saving up to 20% compared to traditional method and considering number of workers in site, it will be reduced from 2000 in traditional method up to 90 in this new method.[1]

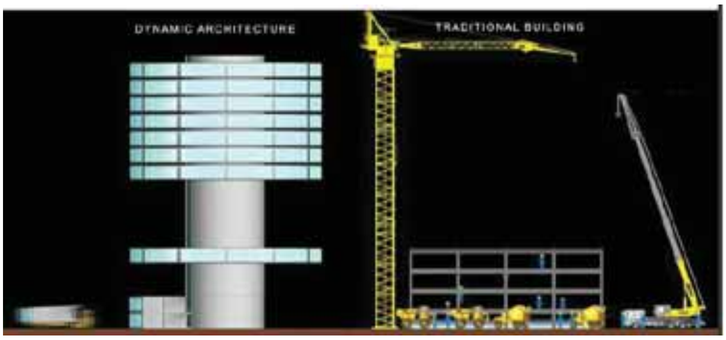


Figure (128) The figure shows the difference between construction by using traditional method and using rotating tower construction method.
Ref: (D. Fisher 2008). P.7.

1 (D. Fisher 2008). P.1-7.

5- Maintenance

Easy maintenance will be provided because each unit is separated from neighbor units, also there is a distance between each unit and the unit below which serve in easier maintenance treatment, and also contains the wind turbines **Figure (129)**.

Figure (129) Detail for the pre-fabricated unit attached to the core
Ref: (D. Fisher 2008). P.5 –Edited by the researcher.

5.5.1.2 Structural idea

It is a very simple idea it is a central reinforced concrete core connected to cantilevered rotating floor plates, there is a limited power of about a 4 KW required to rotate a floor, the drive system is situated in the base of each floor so as not to be seen but at the same time it allows easy maintenance when required.

These fabricated units are made of light weight materials, steel structures, aluminum cladding for easier transportation.

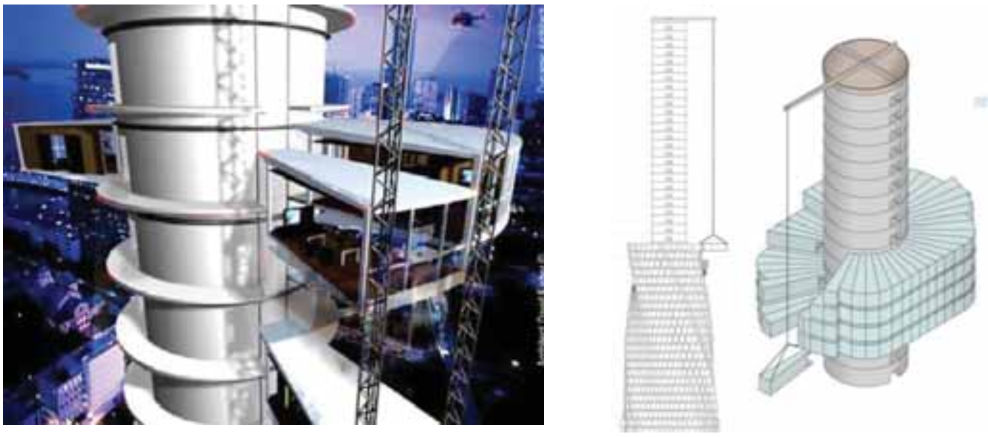


Figure (130) An illustration of how the single modules are assembled around the central core of the Tower.
Ref: (D. Fisher 2008). P.5.

5.5.2 Conclusion

Rotating tower is an era of dynamic sustainable architecture with less energy consumption better life quality and easier structure system and construction methods (see chapter 4).

5.6 The Turning Torso (2005)

Location: Malmo, Sweden

Architect: Santiago Calitrava

Height: 190 m height

Principal structural material: concrete

Other materials: steel + aluminum cladding, lime stone, oiled oak floors.

Interior:

Structure system: Exoskeleton + Core with cantilever

Form generation trend: complex geometry (twisting form)

Function of the building: residential

5.6.1 Architectural and structural analysis

5.6.1.1 Architectural concept

"**Johny Orback**, at the time managing director of Swedish residential cooperative HSB Malmo, first saw calatrav's sculpture as an image submitted with the architect's entry for the Oresund bridge competition in June 1999. The sculpture at this time called twisting torso was formed form cubes twisting through 90^{o} from top to bottom, echoing the form of a body, Orbak met with Calitrava in Zurich to convince him to design a building based on this concept, the result, Turning Torso, is a high-rise structures of nine cubes, Twisting Tower and surrounding area[1]"

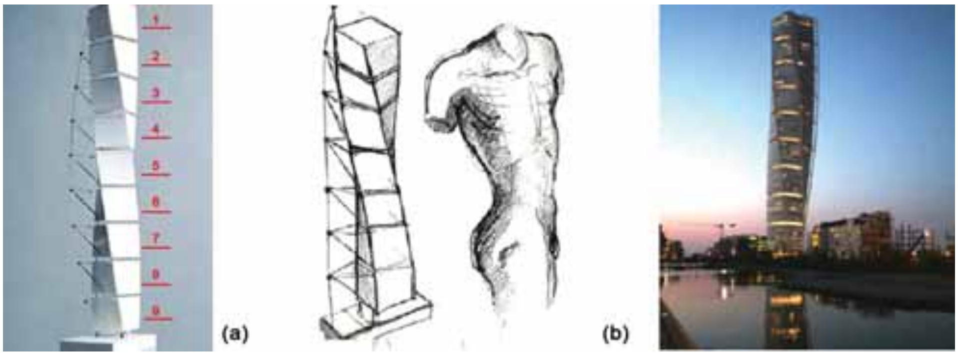


Figure (131) (a) Nine twisting cubes, (b) Architectural concept
Ref: (a) (Tryggestad 2006). P.8. - http://www.scribd.com

[1] (Cox 9/2004). P.4.

5.6.1.2 Function of the building

The tower is designed to be a twisting residential skyscraper of nine cubes; each individual cube contains five stories with large variety of residential apartment size[1]. It represents a new residential and service concept, the first twelve floors are for commercial use in addition to office sections, above these twelve floors there are 197 apartments with areas of 45 and 190 m^2, finally the last two upper floors are designed by Santiago Calitrava as exclusive conference facilities[2].

Figure (132) Examples of offices
Ref: (From Twisting to Turning Torso 2006). P.8.

Figure (133) Examples of residential apartments
Ref: (From Twisting to Turning Torso 2006). P.9.

5.6.1.3 Structural concept

It is a concrete shear wall core carrying cantilevered floor plates twisting around the core and supported with an outside steel spine, so this system is a combination of both Exoskeleton and core structures but mainly, it is a core with cantilever structure The basic function of the steel spine is to reduce the wind displacement also it acts as a reinforced truss[3].
The study model shown in **Figure (134)** shows the structure and the twisting form.

1 (Cox 9/2004). P.4.
2 (From Twisting to Turning Torso 2006). P.8.
3 (Henriksson 2006).

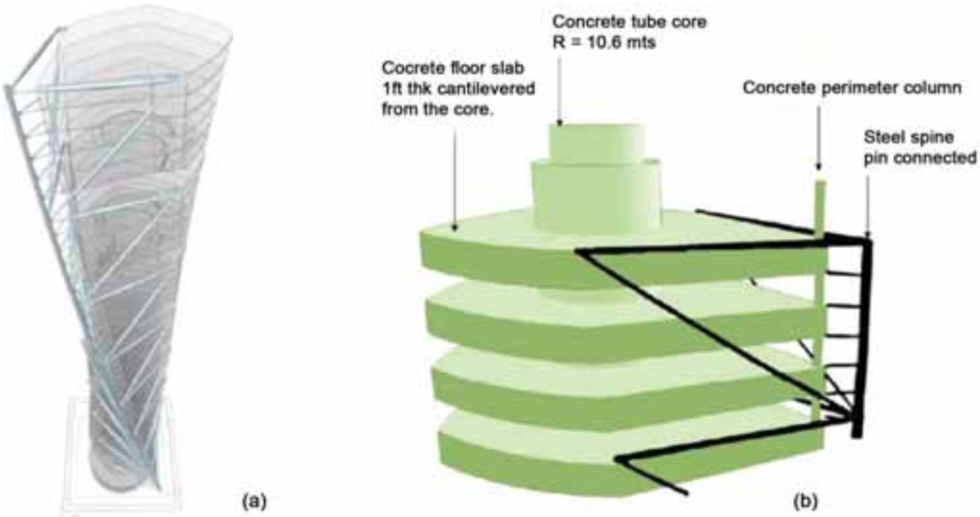


Figure (134) Structural concept of turning torso tower. (a) study model, (b) Detail.
Ref: (a)http://www.scribd.com - (b) (charul mehta n.d.). P.4

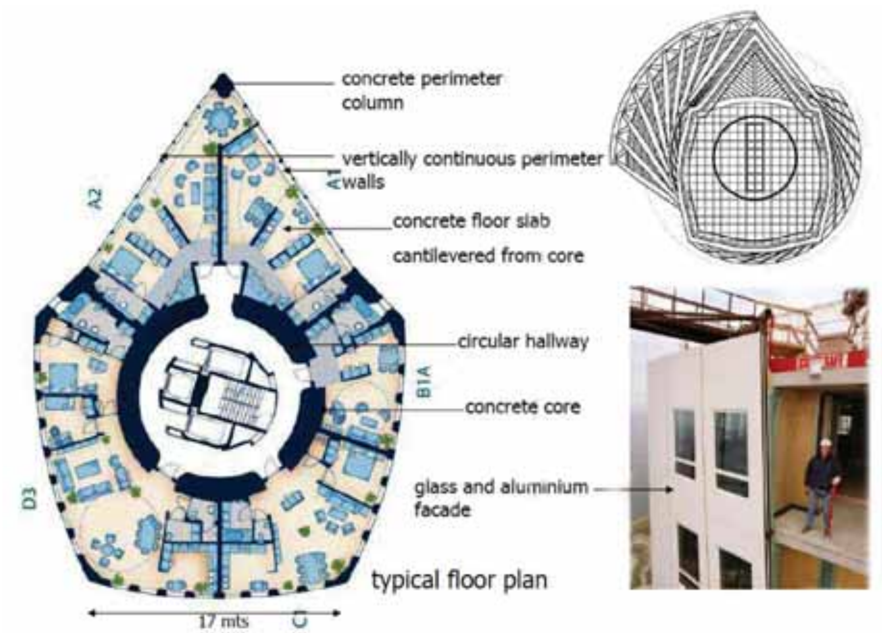


Figure (135) Typical floor plan showing the structural concept of the tower.
Ref: (charul mehta n.d.). P.6.

The system was constructed by using a self climbing slip forms. Which the steel spire was erected using air driven which is administrator to avoid corrosion for steel. It was treated by an anti-corrosion paint.

The construction of turning torso is based on the construction of the core, and then a self climbing slipped form, while the steel spine was erected using air-driven winches as shown in **Figure (136).**

Figure (136) Construction process
Ref: (Cox, 9/2004). P. 7

5.6.2 Conclusion

It is a nine cubes rotating around a central concrete core with the help of an Exoskeleton steel spine to create a twisting residential tower named the turning torso.

5.7 Swiss Re Building 2004

Location: **London, England**

Architect: **Norman Foster**

Height: **40 stories tall**

Principal structure system material: **steel**

Other materials: **curtain wall**

Interior:

Structure system: **Dia-grid**

Form generation trend: **Sustainable -ecological building**

-Aero-dynamic form

Function of the building:

5.7.1 Architectural and structural analysis

5.7.1.1 Architectural concept

The Swiss Re Building is the first ecological building design in London, and being in the heart of London financial district among a cluster of tall buildings, its form can add a unique character to London's skyline[1].

"The form of Swiss Re Building is achieved by a circular plan that widens as it rises from its base and then tappers towards its peak. This allows the floors that occurs towards the middle of the tower to offer more floor space, the tapering of the tower also allows less of the sky to be obstructed[2]"

The form of Swiss Tower is suitable for wind resistance than extruded form as shown in **Figure (137)**. The performance and sustainability through the new innovative design of Swiss Re Building is achieved through the integration between form and floor plates, the typical floor plate is not a complete circle but as shown in **Figure (138)**, **Figure (137)**, it is has six triangular cuts and by rotating each floor with a five degrees a spiral cavity is then created, it has multi functions which are[3]:

1- Providing natural day lighting to interact man and nature.

2- The use of sky gardens to bring spatial quality.

3- Providing natural ventilation and reducing CO_2 by using natural systems to control the climate inside the building.

[1] (G.Bridwell), pp. 107-114.
[2] ibid.
[3] (Peter Beerens).

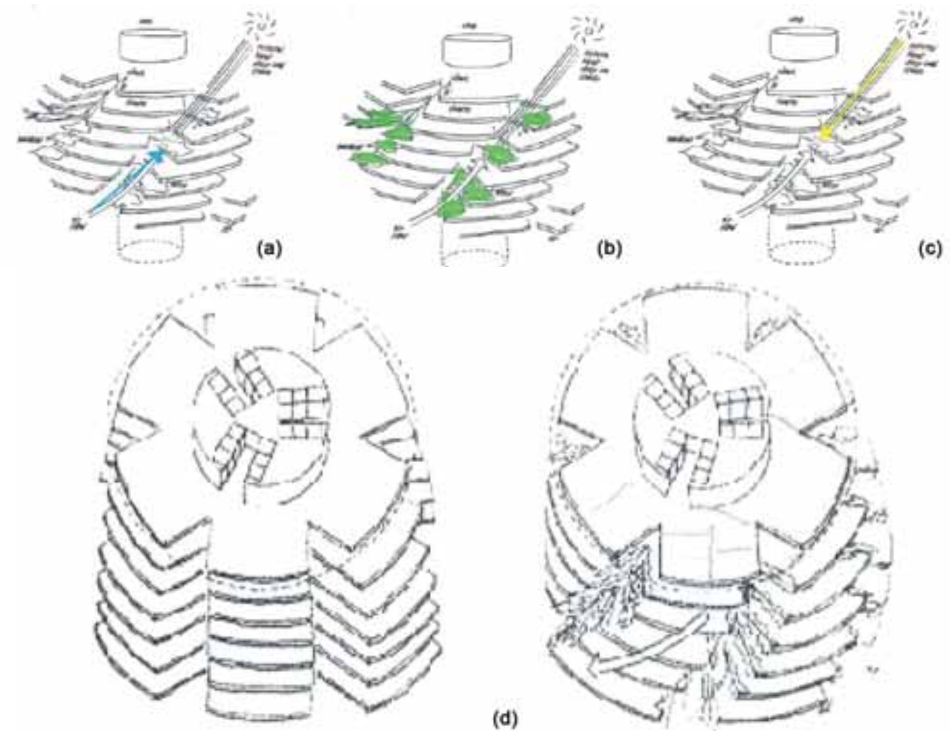


Figure (137) The integration between the form and the environmental concept. (a) Day light, (b) Sky gardens, (c) Ventilation (d) the 5^{o} rotation in floor plan
Ref: (Peter Beerens) - (Bridwell). P.110.

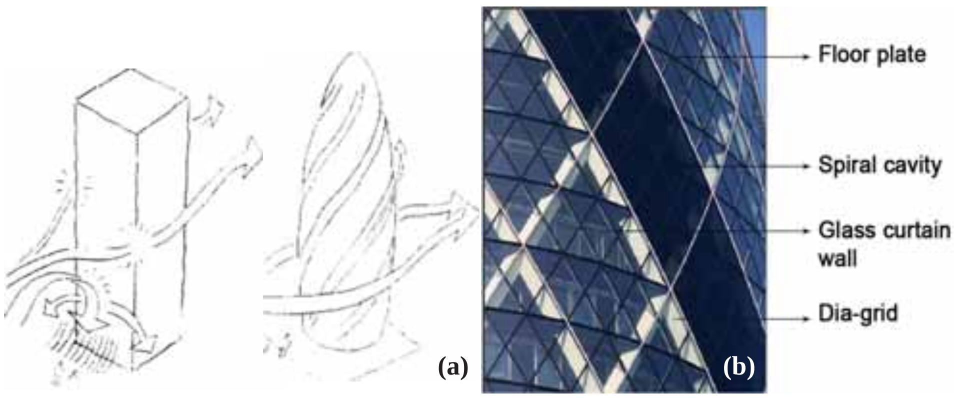


Figure (138) Showing the integration of the form with wind
Ref: (a) (Bridwell). P.109. - (b) http://www.30stmaryaxe.com/ Edited by the researcher.

5.7.1.2 Function of the building

Swiss Re Building acts as a new headquarter for the Swiss Reinsurance Company. So it is an office building, the lower floors are accessible for local communities, while the upper floor is designed to be a restaurant and mezzanine level in the restaurant will offer a full 360 degree panorama over the city[1] (Figure (139).

Figure (139) Restaurant at the upper floor of Swiss Re Building

Ref: http://arts.guardian.co.uk/greatbuildings/interactive/0,,2184617,00.html

In Figure (140-b) the building section shows the 5^o rotation, the restaurant at the upper floor, and ground floor at the base of the building.

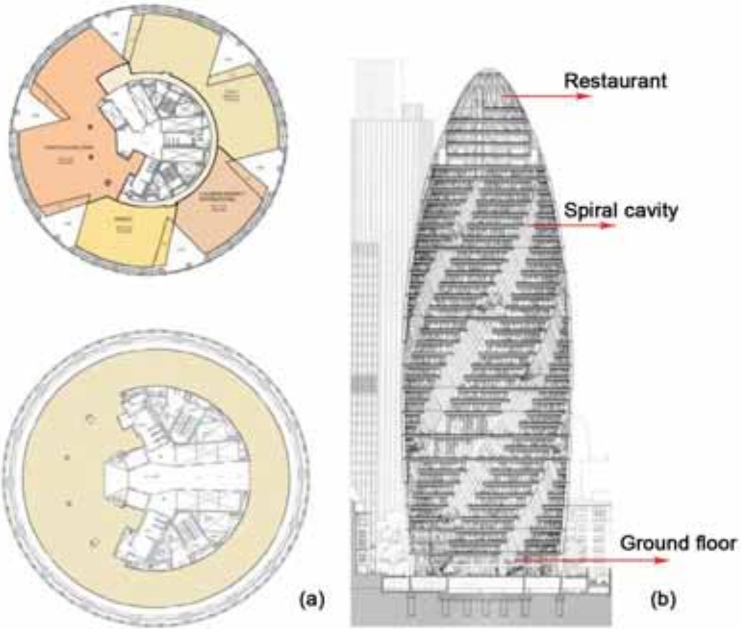


Figure (140) (a) Typical floor plan, (b) Section

Ref: (a) http://www.30stmaryaxe.co.uk/accomm.asp - (b) (Bridwell). P.109.

1 (G.Bridwell), pp. 107-114.

5.7.1.3 Structural idea

The structural design of Swiss Re building is an innovative design, it is a dia-grid structure of a central core having the dia-grid bracing on its perimeter, the core will act only as a load bearing component and will be free from diagonal and bracing while the perimeter dia-grid will be a grid of diagonally interlocking steel pieces.

Figure (141) Structural idea. (a) Steel dia-grid, (b) Floor plates, (c) Core
Ref: (Bridwell). P.114.

Figure (142) Construction process of Swiss Re building
Ref: (Bridwell). P.113.

5.7.2 Conclusion

Swiss Re Building is the first ecological sky scrapper in London, its structure is a central core having a dia-grid structure on the exterior perimeter of the building with six triangular cuts for natural daylight and ventilation.

5.8 Conclusion

according to case studies and the previous chapters , it was found that the structural idea and the architectural concept has a great influence on each other, sometimes the concept of the structural form stars with a structural idea and some other times it starts with a form generation trend, but basically the tall structure is a form made-up of a structure system

5.9 Absolute form

According to the analysis and the study- mentioned in chapters (2), (3) and (4) -on the forms of the tall buildings, it was found that, the absolute form with no regards to the structural system can be classified into three major groups as follow:

- **Simple Box Extruded forms (group 1).**

  They are the typical profiles to most of the tall structures; it can take the shape of a cube or cuboids cladded with curtain walls or any type of cladding according to the design

- **Aero-dynamic modified form (group 2).**

  They are forms design specially to overcome lateral forces due to wind either by their form shape and design or through some modifications on the designed form(see chapter 4)

- **Complex geometry forms (group3).**

  They are forms having complex shapes and profiles through leaning, twisting tapering or any kind of modifications that make the form a complex one see chapter (4).

  The following diagram represents the three different types(three groups) **Figure (143).**

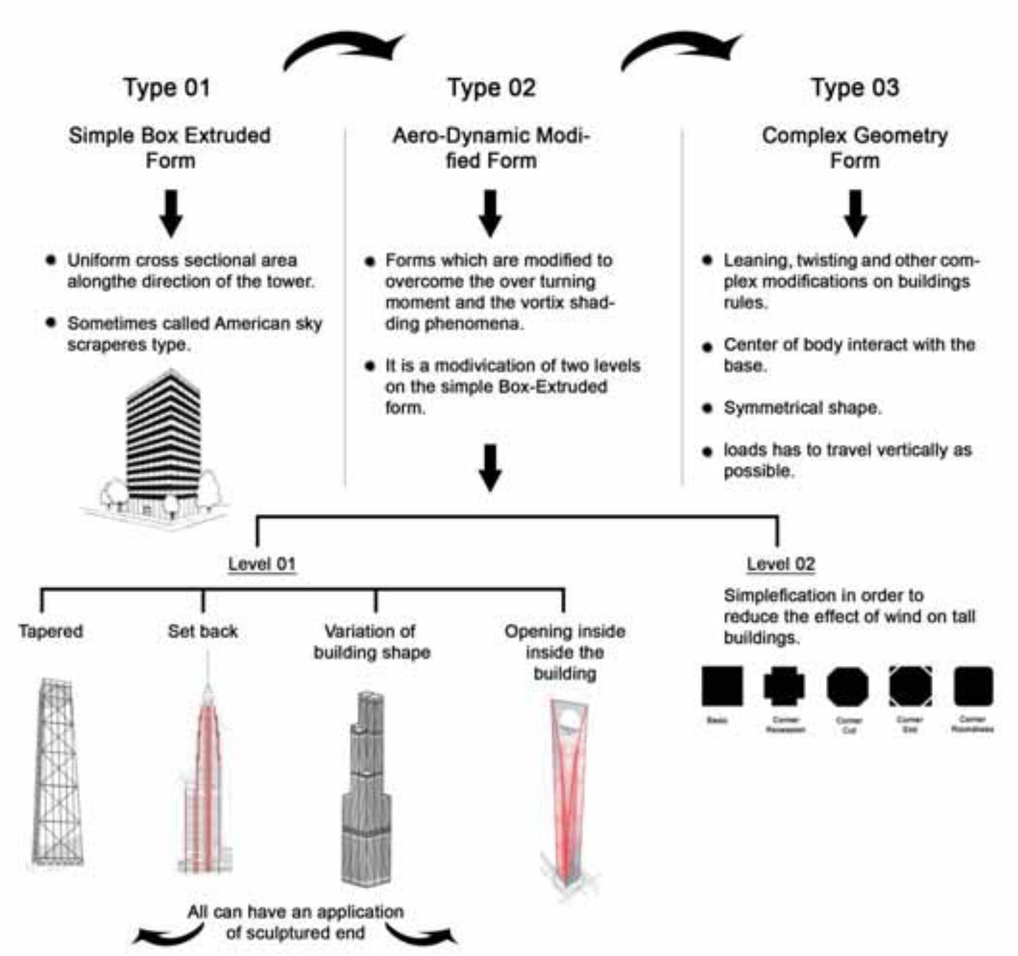


Figure (143) Diagram showing the 3 main types of absolute forms of tall buildings.

5.10 Structure systems in tall buildings design

As studied in chapter (3), there are two major types of structures -according to the arrangements of structural components inside and outside the building- which are interior and exterior structures. Most of the time there is an interaction between these systems; to generate at the end the tall structure in its last form, the first diagram **Figure (144)** explains the different types of structure systems as mentioned in chapter (3), while the second diagram **Figure (145)** explains some of the interaction between systems.

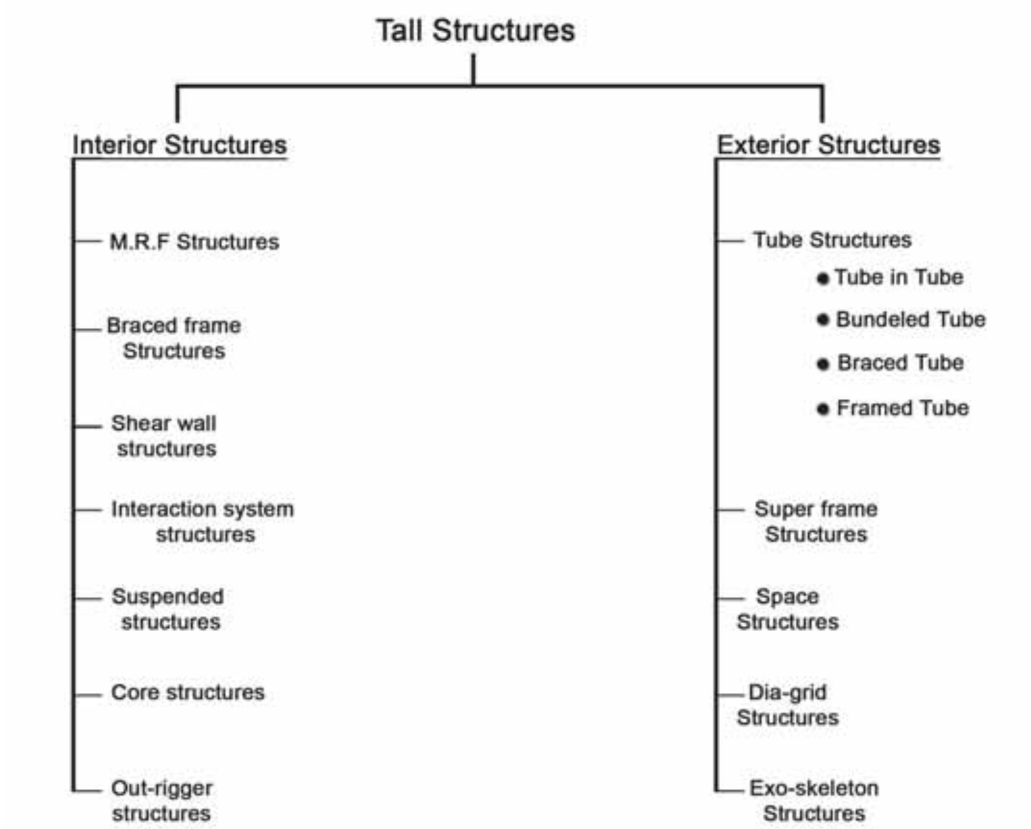


Figure (144) Diagram explaining types of structures

Through the study of the types of interior and exterior structures we can find that they are a mix of organization of main lateral load resisting elements. So in the second diagram we can find the interaction between structure systems and components as follow.

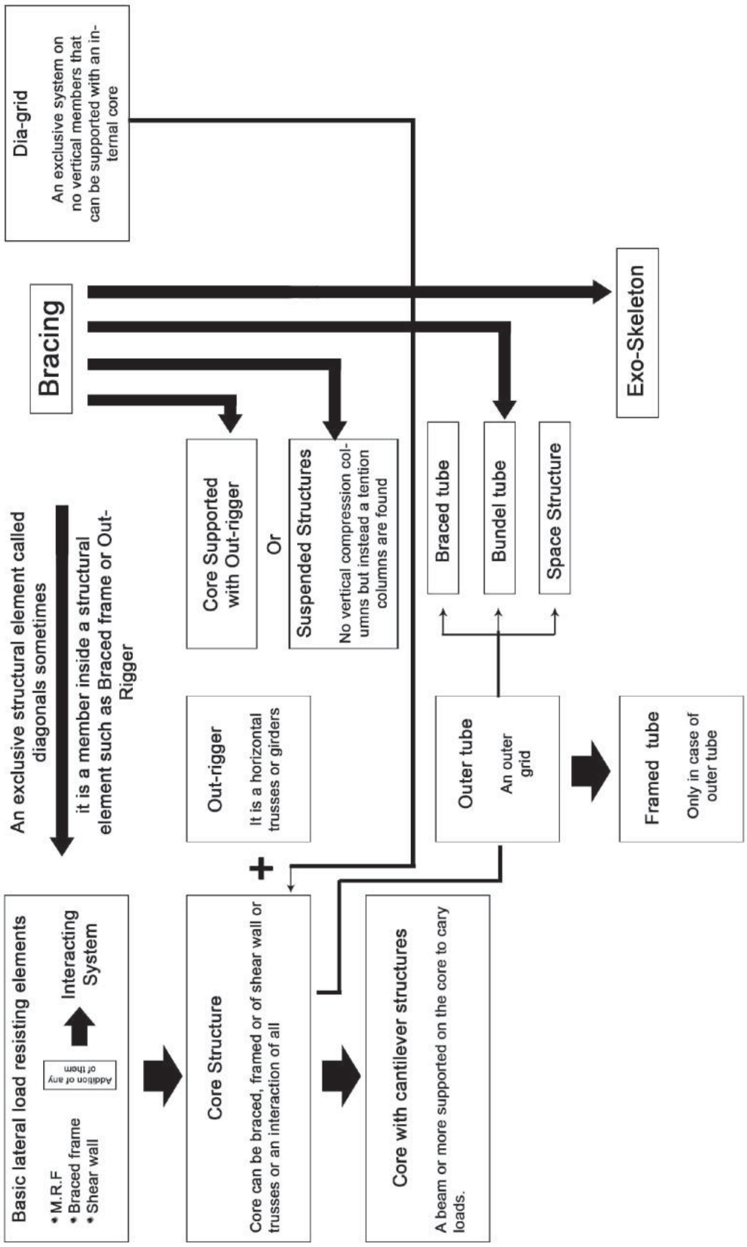


Figure (145) Diagram showing the interaction between different structure systems.

The second diagram explains that the primary lateral load resisting elements are the M.R.f, the braced frame and the shear walls, some of them includes members called braces which are used for bracing as in case of braced frame structures see chapter (3), however when combining these primary elements together a third interactive system is generated, and as mentioned before, these systems are inside the tall structure mainly inside the core so they can be called core structures.

Core structures can be single with a cantilever beam; to give a core with cantilever systems or it can be added to an exterior tube; to give a tubular structures including tube in tube, bundled tube, and braced tube structures, but when a core is supported with an out-rigger two basic structures are found, out-rigger structures and suspended structures see chapter (3). Core can be also be added to some structures such as dia-grid structures to give more stiffness to the tall buildings.

5.11 Structural and architectural mutual integration in tall building design

5.11.1 Any tall structure consists of some basic parts or elements:

- The core
- Outer skin
- Floor plate

5.11.1.1 The core

It is the main element inside the tall building; it contains the services, elevators, stairs and structural elements

5.11.1.2 The outer skin

It is the representation of the architectural form, finishing material, outer structure and the architectural style for tall building

5.11.1.3 Floor plate

It represents the shape of the floor plan. By varying the floor plate size, shape and direction, complex geometry forms are generated. Floor plates help to transfer loads down to the base.

5.11.2 The choice of suitable structure

It is clear that the structure and architecture in tall buildings are interlocked together in same locations within the tall structure. So in order to choose a suitable structure of a specific form, the architect must study the characteristics of the structure system to get use of its advantages.

For example in case of twisted forms the choice of a tubular system would not be effective due to the presence of an outer tube which will obstruct the form from being twisted. So the architect at first has to define the form needs, then to choose the suitable system. The following diagram explain the process of form generation of a twisted form **Figure (146).**

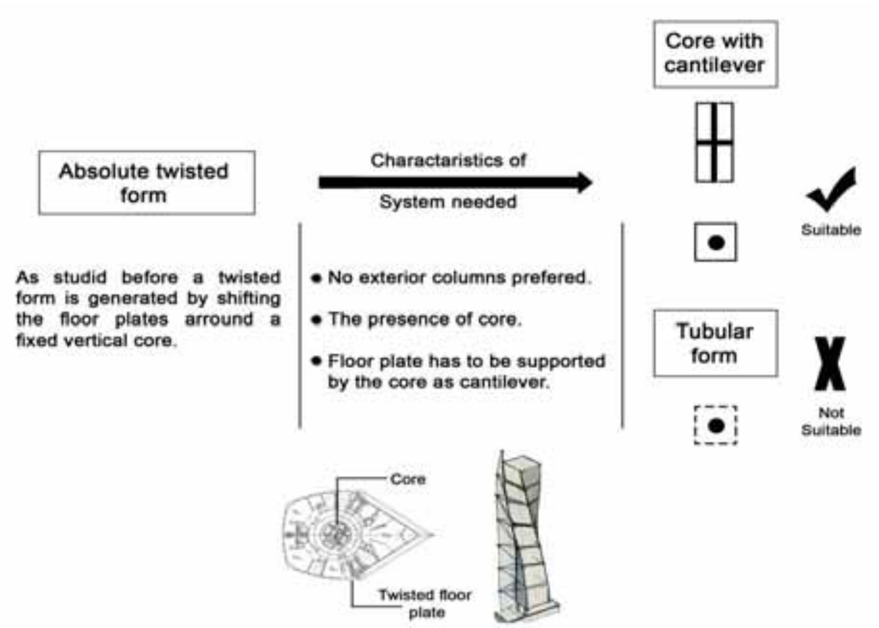


Figure (146) Diagram explain the process of form generation of twisted form

5.11.3 The choice of the structural representation

Sometimes the architect chooses a special system, to have a specific architectural representation. The current trends choose to represent the structural members on the outer skin as in bracings which are the most widely used elements to represent structural members on the outer skin such as in out-rigger and dia-grid structures or in braced tube structures. Hearst Tower, Swiss Tower, John Hancock Tower, and Bank of china are good examples of using bracing structures **Figure (147).**

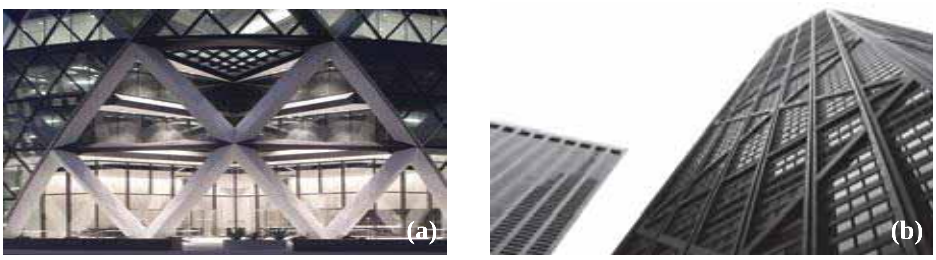


Figure (147) An examples of using bracing structures, (a) Swiss Tower, (b) John Hancock Tower
Ref: (a) http://www.google.com.eg - (b) http://www.trekearth.com

Some other times, architects insist on hiding the structural elements; to give a false expression such as in the towers of the second half of the 19th century and the first half of the 20th century, or to use a complete curtain wall façade as a modern representation to the tall structure **Figure (148)**.

Figure (148) (a) Classical wall bearing expression although the system is not a bearing wall, (b) Modern curtain wall expression.
Ref: http://www.ontarioarchitecture.com

5.11.4 The choice of the construction material

Steel is excellent for framing long span floors, due to its light weight, small member size if compared to concrete, it can provide better flexible spaces and can be quickly erected. On the other hand concrete is so expensive in tall buildings due to the presence of large members and its heavy weight if compared to steel, although it does not provide higher limits for tall buildings.

Members size and shape in case of concrete are different from those in case of steel, so in architectural representation a concrete tall structure is different in most cases than a similar steel tall structure of same height and same chosen structural system. For example in braced tube the steel expression of the façade in John Hancock tower is different from that in tower of concrete braced tube. Similarly in dia-grid, concrete dia-grid-provide thick members, if compared to those of steel dia-grid structures **Figure (149).**

Figure (149) Detail showing the difference between Dia-grid construction case of steel and concrete, (a) Steel, (b) Concrete.
Ref: http://www.designaddict.com

The choice of the construction material, either steel or concrete or a composite system, will define somehow the expression of the architectural form.

Table 3: A comparisons between Steel and Concrete structures

Steel structures	Concrete structures
• Provide greater heights on some systems. • Small member size. • Faster in construction. • Most economic in case of tall buildings.	• Provide less height in the same system. • Large member size • Slower in construction. • Less economical in case of tall buildings.

RECOMENDATIONS

1. Design of tall buildings should include several disciplines specially in the step of concept developing.

2. The architect and the structural engineer should choose the suitable form and structure system to fit with the concept.

3. Tall buildings form should have a degree of performance and sustainability.

4. Tall buildings forms should respect aspects of aero-dynamic design.

5. Architects with the help of structural engineers should look further for new concepts and new methods for developing current trends and structures for tall buildings.

6. Tall buildings should be more dynamic

7. Tall buildings should be much more easier in construction.

8. Tall buildings design should evolve some solution to urban problems such as in case of vertical cities.

9. Parametric design should be involved in the design process of tall buildings as much as possible.

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