POTENTIALS AND LIMITATIONS OF SUPERTALL BUILDING STRUCTURAL SYSTEMS: GUIDING FOR ARCHITECTS

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ABSTRACT

POTENTIALS AND LIMITATIONS OF SUPERTALL BUILDING STRUCTURAL SYSTEMS: GUIDING FOR ARCHITECTS

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In the past, the forms used in design were restricted but currently freedom in the design of supertall buildings has significantly increased, along with a contemporary widening of the form spectrum in design. Owing to the advancements particularly in architectural design methods and innovations in computer technologies, today's supertall buildings could be realized with exceedingly daring forms that are almost never found in their predecessors.

Increasing demand for "iconic" supertall buildings in new urban developments - challenging race for inserting the most extraordinary tall building among big metropolis' thorough the world in their urban silhouettes, and contemporary architect's enthusiasm for creating unconventional building forms - has begun to define the state of the architecture of today's skyscrapers.

Contemporary approaches in supertall building design sometimes bring about exaggeration of aesthetic concern in architectural design, which can pose adverse outcomes in structural design because of the inadequacy or lack of an advance level of interdisciplinary collaboration, specifically between architectural and structural designers.

In other words, abovementioned attitude may cause the problems in the structural design addressed after the architectural form articulation, which unavoidably limits the structural design role to solving the issue rather than handling the structural architectural design together. On the other hand, it must be known that the structural costs of tall buildings can constitute up to nearly 30% of the total construction cost and increase significantly with height.

The architects of today who design supertall buildings must be aware of the fact that some forms, especially unconventional ones, could be put into practice with only certain types of structural systems in order to catch the feasibility and efficiency in structural, aerodynamic, technical and of course last but not least financial/economic concerns. Because of these reasons, the architects inevitably must have profound knowledge of potentials and limitations of supertall building structural systems.

Consequently, today, the role of the architect in the development of supertall buildings' form has become progressively a major concern. Such a role presents the architect with an even greater challenge to realize the conceptual ideas as not only visually pleasant, but also as viable from the structural and constructional points of view.

Keywords: Supertall building, Structural systems, Architectural form

ÖZ

SÜPER YÜKSEK BİNALARDA TAŞIYICI SİSTEMİN POTENSİYEL VE SINIRLILIKLARI: MİMARLAR İÇİN TASARIM KILAVUZU

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Geçmişte, tasarımda kullanılan formlar sınırlı iken günümüzde süper yüksek bina formlarındaki özgürlük, tasarımdaki form yelpazesinin genişlemesiyle önemli ölçüde artmıştır. Günümüzün süper yüksek binaları, mimari tasarım yöntemlerindeki gelişmeler ve bilgisayar teknolojilerindeki yenilikler sayesinde daha önce neredeyse eşine hiç rastlamamış meydan okuyucu formlarla hayata geçirilmektedir.

Büyük metropollerde ikonik süper yüksek binaya talebin artması, şehir siluetinde en sıradışı binayı inşa etme yarışı ve günümüz mimarlarının konvansiyonel olmayan bina formlarını gerçekleştirme hevesleri günümüzün süper yüksek bina mimarisini tanımlamaya başlamıştır.

Güncel yaklaşımların beraberinde bazen estetik kaygıların mimari tasarımda sınırlarının zorlanması gelebilmektedir ki bu da özellikle mimari ve strüktürel tasarımda olması gereken yüksek işbirliği yetersizliği veya eksikliğinden kaynaklı istenmeyen sonuçlar doğurabilmektedir.

Diğer bir deyişle, yukarıda bahsedilen tutum mimari form artikülasyonundan sonra yapılan strüktürel tasarımda sorunlara neden olabilmekte ki bu da mimari ve strüktürel tasarımın bütünleşik yapısını kaçınılmaz olarak sınırlandırmaktadır. Öte yandan bilinmelidir ki yüksek yapılarda strüktürel maliyet toplam maliyetin yaklaşık %30 unu oluşturmakta ve bu maliyet yükseklikle birlikte önemli ölçüde artmaktadır.

Günümüzün süper yüksek bina tasarlayan mimarları farkında olmalıdır ki bazı formlar özellikle konvasiyonel olmayanlar, strüktürel, aerodinamik, teknik ve ekonomik verimlilik açısından ancak belli strüktürel sistemlerle gerçekleştirilebilir. Bu sebepler yüzünden mimarlar süper yüksek bina strüktürel sistemlerinin potansiyel ve kısıtlarını bilmelidir.

Sonuç olarak, bugün, mimarların süper yüksek formunun gelişimindeki rolü giderek artmaktadır. Bu çeşit bir rol daha büyük bir zorlukla beraber mimarların fikirlerini sadece görsel olarak çekici kılmak yerine strüktürel ve inşai bakış açılarından da değerlendirme gerekliğini beraberinde getirmiştir.

Anahtar kelimeler: Süper yüksek bina, Taşıyıcı sistem, Mimari form

To My Parents

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INTRODUCTION

1.1 Research problem

Throughout history, human beings have built tall monumental structures such as temples, pyramids and cathedrals to honor their gods. Human beings have always been struggling to push the limits of nature in their age-old quest for height, from the legendary Tower of Babel in antiquity - purportedly designed with the aim of reaching heaven - to today's tallest building. Skyscrapers of today are monumental buildings too, and are built as symbols of power, wealth, prestige, pride, and national recognition as well.

At the beginning of the 20^{th} century, tall buildings were generally designed as offices, and achieved an important position as a "distinguished space" in the history of American urban architecture. These buildings emerged as a response to the rapidly growing urban population, with the aim of meeting the demand for office units to be positioned as closely as possible to one another.

Architects' creative approaches in their designs for tall buildings, the shortage and high cost of urban land, the desire to prevent disorderly urban expansion, the effort to create a skyline concept, and factors such as concerns for a cultural identity and for prestige have driven the increase in the height of buildings.

While tall buildings were designed mainly in box forms throughout the 19th and 20th centuries, their architectural forms have experienced dramatic changes in the second half of the 20th century owing to the demand for iconic buildings in growing cities.

Today's tall buildings are designed with the aid of structural analysis, advanced computer technologies, and digital design methods. They are built with exceedingly daring architectural and structural designs that are almost never found in their predecessors in unconventional forms, such as cylindrical, curvilinear, aerodynamic, leaned, twisted, tilted, shapes and *etc.*

With the beginning of the 21st century, a number of unconventional forms can be seen throughout the Middle Eastern and Asian cities, which are now the leaders of supertall building construction throughout of the world. Such approaches have manifested in an outstanding creation of supertall building typologies, where contemporary tall building forms today are emerging with an increasing degree of geometrical variation and complication facilitated by the new methods of design and means of construction, combined with the extensive use of the computer in architectural modelling and structural analysis (Vollers, 2008).

At this point, special structural systems, developed for supertall buildings must be underlined, when it is thought that because of the inefficiency of structural forms, inadequate knowledge about material properties, and limited architectural design methods, they were unable to be constructed.

In supertall building design, continuation of growing tendency to overstate aesthetics and style, sometimes could result in less attention to structural design. In other words, this attitude requires that the form undergo a subsequent rationalization process and may cause the problems in the structural design addressed after the architectural form articulation.

This approach unavoidably limits the structural design role to solving the issue rather than integration of the structural design with the architectural design. Such a passive approach could enable a building to stand upright but it will not solve the problems about architect's enthusiasm and formal, technical, financial issues.

The structural costs of supertall buildings can constitute up to 30% of the total construction cost and increase noticeably with height (Almusharaf and Elnimeiri, 2010). In contemporary architectural design of supertall buildings, search for an exotic form emerges as a dominating tendency, but this tendency generally results in costly construction (Elnimeiri and Almusharaf, 2010).

Consequently, the architects designing contemporary supertall buildings must be aware of the fact that unconventional forms could be satisfied with only certain types of structural systems that unavoidably affect the architectural features as in the case of

- *WTC Twin Towers* (New York, 1972),
- *John Hancock Center* (Chicago, 1969), and
- *Willis Tower* (Chicago, 1974)

as milestones in the history of skyscrapers. Because of these reasons, the architects inevitably must have profound knowledge of potentials and limitations of supertall building structural systems as a prerequisite to achieving structurally sensitive/integrated architectural forms.

1.2 Research Objectives

The primary goal of this study is to furnish aid to people involved with the implementation of supertall building by establishing valuable data that could be used as criteria for development, planning and design of supertall buildings.

The purpose of this study is to propose a design guideline, which can direct architects, during the early/schematic design phase. The awareness about potentials and limitations of supertall building structural systems leads in developing their original supertall building forms that are "sensitive" to the structural design. In order to achieve this goal, the following research objectives have been identified:

- Studying and identifying the various design considerations, in particular architectural and structural design considerations that directly influence the development of the architectural form of supertall buildings. The focus in this research will be placed on the architectural form and structural systems.
- Establishing, as applicable to the research objective, the sets of design parameters to be encoded within the proposed guideline.
- Creating a set of structural and aerodynamic performance criteria pertaining to supertall buildings.
- Studying, evaluating, and selecting the most suitable structural system of supertall building for the intended architectural form.
- Establishing a design guideline for the architect in order to adjust and improve simply the morphological analysis of form based on structural and aerodynamic performance criteria rather than only subjective visual judgments.

1.3 Scope of the Research

The study addresses the quest for the design guideline directing architects to develop structurally and aerodynamically viable supertall building forms. Creating a synergy between form and structural performance will be the major focus of this study.

The process is intended for use in the early/schematic architectural design stage, during which the architectural form is not yet well articulated. It will comprise the generation architectural forms toward structurally & aerodynamically sound and constructible solutions. Such processes will involve interaction on the part of the architect and will require direct cooperation among the architectural (formal), aerodynamic, and structural design considerations until a balance is reached and a final acceptable form is developed.

The design guideline proposed in this study will be limited to the supertall buildings, namely the buildings with over 300m or 75-story height and above, that represents the supertall buildings with completed and under construction status.

In this study, for the topics related with both *tall building* and *supertall building* at the same time - for example in background research, lateral loads *etc.* - *"(super)tall building"* will be used as a subject terminology. On the other hand, in this research, *"tall building"* is used for general expressions; while *"supertall building"* is used for the issues related to the buildings with over 300m or 75-story height and above.

The research will deal mostly with architectural and structural, and also aerodynamic design parameters. While building form and core planning (core type) as architectural design parameters and structural systems as structural design parameters will be discussed in depth, other architectural and structural issues like lease span, floor-to-floor height, slenderness (aspect) ratio, sustainability, and structural materials will only be considered on a generic level in this study.

Site constraints and zoning codes/laws are out of the scope. Structural analysis also will not be considered in this study. The problems related to construction techniques, fabrication processes and façade engineering will be out of the scope, too.

Architects who are well suited to use the proposed design guideline are interested in the relationship between the architectural and structural form, and have a solid attention in exploring revolutionary yet structurally & aerodynamically sound and constructible supertall building forms. They have realistic awareness of the structural systems of supertall buildings and also appreciate structural rationale and aesthetics.

The main readership of the research is intended to be architects, structural engineers, their trainees, and researchers. In addition, the dissertation has been written to be accessible, as far as possible, to general readers interested in supertall buildings by using plain language.

1.4 Research Significance

This study will attempt to establish a close connection between the architectural form and structural design of supertall buildings within a design guideline. The guideline is expected to yield a morphological analysis of supertall building form directly related with structural design considerations.

The proposed design guideline is also expected to have noteworthy implications for education and professional practice of supertall building design, since it intends to inspire the architects' thinking processes for engagement of structural systems and to inspire designers for developing forms based on the impact of different geometry on structural and aerodynamic performance.

The aim is to analyze formal expression for particularly contemporary supertall building design, sometimes which could be determined merely by formal and/or functional design concerns instead of structural and aerodynamic performance that directly affects early stage of architectural form development. With such an approach, the architects designing contemporary supertall buildings must be aware of the fact that in particular unconventional/extraordinary forms could be satisfied with only certain types of structural systems in order to catch the feasibility and efficiency in structural, aerodynamic, technical and of course financial/economic concerns. In this way, the great importance of profound knowledge of potentials and limitations of supertall building structural systems for the architects will be comprehended much better.

1.5 Research Methodology

Besides the book of "*Tall Buildings: Structural Systems and Aerodynamic Forms*" (Gunel and Ilgın, 2014), "*METU graduate course of BS 536: Studies of Tall Buildings: Design Considerations*" and *CTBUH database* as main sources, the literature review and background research involve reviewing previous dissertations, research papers from numerous journals, conference proceedings, fact sheets, construction documents, magazines, internet sources, and mailing correspondences to related architectural and structural design offices.

In order to analyze architectural, structural, and aerodynamic design considerations, 91 supertall buildings with completed and under construction status (Appendix-A) have been selected from 286 supertall buildings of CTBUH (Appendix-B).

The main determinant factor for the selection of 91 supertall buildings is the availability of the data demonstrated in the supertall building list (Appendix-A). The difficulty in data collection process has been experienced because of security issues of supertall buildings particularly after the tragedy of *WTC Twin Towers* at September 11th 2001 in the United States.

On the other hand, for the sake of comparison of all structural systems together, the supertall buildings completed after 1980 are included in the sample group for this study. *"Outrigger"* and resulting structural system called as *"outriggered frame system"* were introduced in late 1970s. Outriggered frame system is the latest invented structural system of supertall buildings.

The research will proceed according to five main phases, which are as follows:

a. Background research in briefly manner that traces emergence and historical background of tall buildings shortly from 1880 until the present day and highlights key building examples during the various periods within this timeline.
b. A review of the various architectural, structural and aerodynamic design considerations that directly influence the development of the architectural form of supertall buildings.
c. Making an investigation and then designing charts about the supertall buildings with completed and under construction status, which includes the data of
   - *building form,*
   - *core planning (core type),*
   - *function and*
   - *slenderness (aspect) ratio* as architectural design considerations,
   - structural materials and structural systems as structural design consideration and also aerodynamic design consideration (if exist / if obtained).
d. In the light of the inferences from the charts, a discussion of interrelation analyses of:
   - *completion date and building height,*
   - *structural system and structural material,*
   - *structural system and building form,*
   - *structural system and building height,*
   - *structural system and core planning (core type),*
   - *timeline and structural material,*
   - *building function and building form,*
   - *building location and building form,*
   - *building location and structural system,*
   - *building height and building form,*
   - *building height and building function,*

- *building form and aspect ratio,*
- *structural system and aspect ratio, and*
- *building height and aspect ratio,*

with measurable parameters will be generated to be used as a guideline for supertall building design.

e. The advices will be given for achieving a successful integration to evolve an architecturally pleasing and structurally & aerodynamically efficient supertall building. The intended approach is to yield an innovative work environment where the development of architectural form is directed by instant response on the structural performance as well as formal and spatial design considerations.

1.6 Organization of Dissertation

The research will be organized according to five main chapters, which are as follows:

Chapter 1 provides an introduction to the subject, defines the research problem, identifies the research objectives and scope of the research, and describes the research significance, research methodology, and finally organization of the dissertation.

Chapter 2 reviews definition, emergence and historical background, lateral loads affecting (super)tall buildings, and widely identifies the architectural, structural and aerodynamic design considerations in supertall building development.

Chapter 3 presents a deep investigation about 91 supertall buildings with completed and under construction status, which includes the data of building form, core planning (core type), function and slenderness (aspect) ratio as architectural design considerations, structural materials and structural systems as structural design consideration.

Chapter 3 also contains a parametric study based on all the data collected from the supertall building examples. A set of quantitative interrelation analysis with measurable parameters is performed to show relationship among several design factors. The result demonstrates integrated design considerations to help the decision making in initial design stage in supertall building projects.

Chapter 4 provides structurally and/or aerodynamically adaptive architectural forms based on the data collected.

Chapter 5 presents concluding remarks on architectural and structural, and also aerodynamic design parameters of supertall buildings, highlights the research limitations, addresses the future trends of architectural forms, and proposes directions for future studies.

The research also shows that a careful study of trends in architectural features and structural design of supertall buildings along with an integrated approach considering various design requirements can be an effective method in design of future generation of supertall buildings.

The Appendix-A includes the list of 91 supertall buildings with completed and under construction status". In this list, the information columns are about:

- *building name (official name),*
- *location,*
- *height,*
- *number of floors,*
- *completion date,*
- *architect,*
- *energy label,*
- *photo/image,*
- *tower gross floor area,*

- *average floor area and ground floor area,*
- *function,*
- *typical floor plan,*
- *core dimensions,*
- *lease span,*
- *core planning (core type),*
- *aspect ratio,*
- *structural systems and structural material,* and
- *aerodynamic design considerations*

The Appendix-B presents the list of 286 supertall buildings with completed and under construction status". In this list, the information columns are about:

- *building name (official name),*
- *location,*
- *height,*
- *structural material,*
- *building form, and*
- *building function.*

CHAPTER 2

GENERAL CONSIDERATIONS ON SUPERTALL BUILDINGS

This chapter presents mainly a brief account of design considerations for supertall building development. After definition, emergence and historical background, and lateral loads affecting supertall building parts; the considerations including architectural design considerations, structural design considerations, and finally aerodynamic design considerations will be discussed.

2.1 Definition

"Tall building", "high-rise building", and "skyscraper" are difficult to define and distinguish solely from a dimensional perspective because height is a relative matter that changes according to time and place. While these terms all refer to the notion of very tall buildings, the term "skyscraper" is the most forceful.

The term "high-rise building" has been recognized as a building type since the late 19th century, while the history of the term "tall building" is very much older than that of the term "high-rise building". As for the use of the term "skyscraper" for some tall/high-rise buildings reflecting social amazement and exaggeration, it first began in connection with the 12-story *Home Insurance Building*, built in Chicago towards the end of the 19th century (Harbert, 2002; Peet, 2011).

There is no general consensus on the height or number of stories above which buildings should be classified as tall buildings or skyscrapers. The architectural/structural height of a building is measured from the open-air pedestrian entrance to the top of the building, ignoring antennae and flagpoles.

According to the CTBUH (Council on Tall Buildings and Urban Habitat), buildings of 14 stories or 50 meters' height and above could be considered as "tall buildings"; buildings of 300 meters' and 600 meters' height and above, are classified as "supertall buildings" and "megatall buildings" respectively.

The CTBUH measures the "height to architectural top" from the level of the lowest "significant open-air pedestrian entrance" to the architectural top of the building, including spires, but not including antennae, signage, flag poles or other functional-technical equipment. In this book, this height measurement is used for the "architectural height" of the buildings.

According to the Emporis Standards, buildings of 12 stories or 35 meters' height and above, and multi-story buildings of more than 100 meters' height, are classified as "high-rise buildings" and "skyscrapers" respectively (Emporis Data Standards ESN 18727, ESN 24419).

Tall buildings are defined:

- by structural designers as buildings that require an unusual structural system and where wind loads are prominent in analysis and design, in other words when the lateral loads begin to control the structural design;
- by architectural designers as buildings requiring interdisciplinary work in particular with structural designers, and with experts in the fields of aerodynamics, mechanics and urban planning that affect design and use; and
- by civil engineers as buildings needing unusual and sophisticated construction techniques.

The first use of the word “skyscraper” in the sense of “tall building” was in an article published in 1883 in the journal *American Architect*, appearing as “America needs tall buildings; it needs skyscrapers” (Giblin, 1981).

While Ada Louise Huxtable (1984) emphasizes that tall buildings are symbols of our age and that the words “skyscraper” and “20th century” have an equivalent meaning, César Pelli (1982) defines a skyscraper as a supertall building and highlights the word “super” within this definition as changing according to time and place.
Structures such as *The Eiffel Tower* (Paris, 1889) cannot be classified as skyscrapers because of the lack of a habitable interior space.

In the view of the author of this study, “tall building or high-rise building” is a local concept and “skyscraper or supertall building” is a global concept. To be able to define a tall building as a skyscraper or supertall building, it is not sufficient for it only to be tall in its own region; it is necessary for it to be recognized around the world as a skyscraper or supertall building.

In this context skyscraper or supertall building is distinguished as being higher than tall or high-rise building. In this study, the definition of “supertall building” is based on the buildings with over 300m or 75-story height and above.

2.2 Emergence and Historical Development

Like the Greek temples or the Gothic cathedrals that were the foremost building types of their own ages, skyscrapers have become iconic structures of industrial societies. These structures are an architectural response to the human instincts, egos and rivalries that always create an urge to build higher, and to the economic needs brought about by intense urbanization.

Architects make a contribution to the social and economic changes of the age, reflecting the environment they live in with their designs and creating a development/evolution by developing new building types. In addition, underlying the first appearances of skyscrapers in Chicago was a social transformation triggered by the economic boom of that era and by the increase in value of urban building plots.

The concentrated demand for increasing incorporation in city centers, together with the intensification of business activity and the rise in the values of capitalism, necessitated the creation of a new, unusually high building type which had the large spaces that could meet these demands - and many such buildings were produced using extraordinary forms and techniques.

In the masonry construction technique that was employed before the development of rigid frame systems, load-bearing masonry walls were used structurally, which, although they had high levels of fire resistance, reduced the net usable area because of their excess dead loads and wide cross-sections.

The 64 meters, attained towards the end of the 19^{th} century by the 17-story *Monadnock Building* (Chicago, 1891) (Figure 2.1a), is the highest point that this construction technique was able to reach. The structure used 2.13m thick load-bearing masonry walls at the ground floor, and was the last building to be built in the city using this technique.

(a) (b)

Figure 2.1 (a) Monadnock Building, Chicago, 1891 (www.ctbuh.org);
(b) Home Insurance Building, Chicago, 1885 (www.ctbuh.org)

At the end of the 19th century, beginning with the discovery of the elevator for the vertical transportation system, and structural metal (cast iron which was soon replaced by steel) beam-column framing system, the construction of tall buildings commenced as an American building type owing to innovations and developments in new structural systems, high-strength concrete, foundation systems, and mechanical systems; this continues to drive the race for height in skyscrapers that is spreading across the world.

The *Home Insurance Building* (Chicago, 1885) (Figure 2.1b), designed by engineer William Le Baron Jenney with 12 stories, is recognized as being the first skyscraper. The use of a structural frame in the building won it the title of the first skyscraper, marking a new epoch in the construction of tall buildings, and it became a model for later tall building designs.

After the *Home Insurance Building* (Chicago) in 1885 at 55m, the race to construct the world's tallest building continued with:

- the *World Building* (New York) in 1890 at 94m,
- the *Manhattan Life Insurance Building* (New York) in 1894 at 106m,
- the *Park Row Building* (New York) in 1899 at 119m,
- the *Singer Building* (New York) in 1908 at 187m,
- the *Metropolitan Life Tower* (New York) in 1909 at 213m,
- the *Woolworth Building* (New York) in 1913 at 241m,
- *The Trump Building* (New York) in 1930 at 283m,
- the *Chrysler Building* (New York) in 1930 at 319m,
- the *Empire State Building* (New York) in 1931 at 381m,
- the *One World Trade Center (WTC I)* (New York) in 1972 at 417m,
- the *Two World Trade Center (WTC II)* (New York) in 1973 at 415m,
- the *Willis Tower* (Chicago) in 1974 at 442m,
- *The Petronas Twin Towers* (Kuala Lumpur) in 1998 at 452m,
- the *TAIPEI 101* (Taipei) in 2004 at 508m, and
- the *Burj Khalifa* (Dubai) in 2010 at 828m,

and when 800m was passed at the beginning of the 2000s, heights have been reached that could not have even been dreamed of in engineer William Le Baron Jenney's time. In other words, while 10-story buildings were classified as skyscrapers in the 1890s, about 40 years later the *Empire State Building* (New York, 1931) exceeded 100 stories, and about 100 years later the *Burj Khalifa* (Dubai, 2010) exceeded 150 stories.

Skyscrapers, which were thought previously to be exclusively a North American urban phenomenon, have today entered the skylines of almost all major cities, especially in Asia.

2.3 Lateral loads affecting (super)tall buildings

From the structural point of view, (super)tall buildings, because of their extraordinary height, show a greater sensitivity to wind and earthquake induced lateral loads than low-rise buildings. Estimating those lateral loads which play an important role in the design of tall buildings is more difficult than estimating vertical loads.

Earthquake loads increase according to the building weight, and wind loads increase according to the building height. For this reason, wind loads, while they are generally an unimportant issue in the design of structural systems for low- and mid-rise buildings, play a decisive role in that of tall buildings, and can even be a cause of large lateral drift (sway) that is more critical than that from earthquake loads.

The occupancy comfort takes prominence in the design of structural systems in tall buildings, and it is necessary to limit the building sway. In tall buildings, which can be described as vertical cantilever beams, the maximum lateral top drift caused by lateral loads is expected to be approximately 1/500 of the building height (structural height), according to Bennett (1995) and Taranath (1998), and in limits ranging from 1.5/1000 to 3/1000 according to Smith and Coull (1991).

In this context, the drift index is defined as the ratio of the maximum lateral top displacement of the building to the building height (Δ/H); and the inter-story drift index as the ratio of the lateral displacement of the floor relative to the floor below, to the floor-to-floor height (Δ/h). Generally in wind design of tall buildings, 1/400-500 is commonly preferred as both the drift index and the inter-story drift index.

2.3.1 Wind loads

At first wind loads were ignored because the weight of the construction materials and structural systems used in the first skyscrapers made vertical loads more critical than lateral loads, but over time wind loads became important, as the strength to weight ratio of construction materials and the ratio of floor area to structural weight in structural systems increased and the total weight and rigidity of structures decreased.

Wind speed and pressure increase parabolically according to height, and therefore wind loads affecting tall buildings become important as the height of the building increases. In general, structural design begins to be controlled by wind loads in buildings of more than 40-story (ACI SP-97, 1989).

Today, owing to developments in structural systems and to high-strength materials, tall buildings have increased in their height to weight ratio but on the other hand reduced in stiffness compared with their precursors, and so have become greatly affected by wind. With the reduced stiffness, the sensitivity to lateral drift, and hence the sway under wind loads, increases. The sway, which cannot be observed outside the building or at the lower floors, can cause discomfort to occupants at the higher floors of a building.

2.3.2 Earthquake loads

Earthquakes are the propagation of energy released as seismic waves in the earth when the earth's crust cracks, or when sudden slippage occurs along the cracks as a result of the movement of the earth's tectonic plates relative to one another. With the cracking of the earth's crust, faults develop. Over time, an accumulation of stress in the faults results in sudden slippage and the release of energy. The propagation of waves of energy, formed as a result of seismic movement in the earth's crust, acts upon the building foundations and becomes the earthquake load of the building. In determining earthquake loads, the characteristics of the structure and records of previous earthquakes have great importance. Compared with wind loads, earthquake loads are more intense but of shorter duration.

Earthquakes can occur almost anywhere, and considering that low, medium and high severity earthquakes may occur during the life of a structure located in an active earthquake zone, it is necessary to understand very well the behavior of a structure during an earthquake in order to prevent the disastrous collapses that can occur.

An earthquake's effect or power is measured by the "earthquake's intensity" or "earthquake's magnitude". Accounting for the effects upon living creatures, structures, and the environment in the measurement of an earthquake gives the "intensity" of the earthquake, while using earthquake seismographs (seismometers) to measure the energy released at the center of an earthquake gives the "magnitude" of the earthquake.

The intensity of an earthquake indicates its effect in any given region. The magnitude of an earthquake gives information on its intensity at its center (epicenter). While the measure of magnitude gives only a single value for the magnitude of an earthquake, the measure of intensity gives different intensity values in different regions. The "magnitude" of earthquakes is indicated by the *Richter scale* and their "intensity" is indicated by the *Mercalli scale*.

The lateral inertia forces on a structure created by an earthquake are functions of:

- the magnitude and duration of the earthquake,
- the distance of the structure from the center of the earthquake (epicenter), and
- the mass of the structure, the structural system, and the soil-structure interaction.

The magnitude of the lateral force (F) on a structure formed by the effect of an earthquake depends on the structure's mass (m), the ground acceleration (a) and the structure's dynamic characteristics ($F\ \alpha\ ma$) (Figure 2.2).

The ground acceleration changes according to the characteristics of the earthquake and the ground. Theoretically, in the case of rigid structures and foundations, the acceleration of the structure is equal to that of the ground. In this case, according to Newton's Law, the lateral load (F) affecting a structure is equal to the mass (m) of the structure multiplied by the ground acceleration (a), ($F = ma$) (Figure 2.2a).

This theoretical case does not occur in practice because every structure has certain flexibility. For a structure that deforms due to its flexibility, thus dissipating some energy, the lateral force (F) affecting the structure is less than the product of the mass of the structure and the ground acceleration ($F<ma$) (Figure 2.2b).

As the height of a structure increases, the flexibility also increases and the acceleration is expected to be less than in low-rise structures ($F<ma$); however, for structures whose natural period is close to that of the seismic waves, in earthquakes of long duration, the lateral force (F) affecting the structure may be larger than the mass of the structure multiplied by the ground acceleration ($F>ma$) (Figure 2.2c).

For this reason, the lateral load on a structure caused by an earthquake is a function not only of the mass of the structure and the ground acceleration, but also of the dynamic characteristics of the structure.

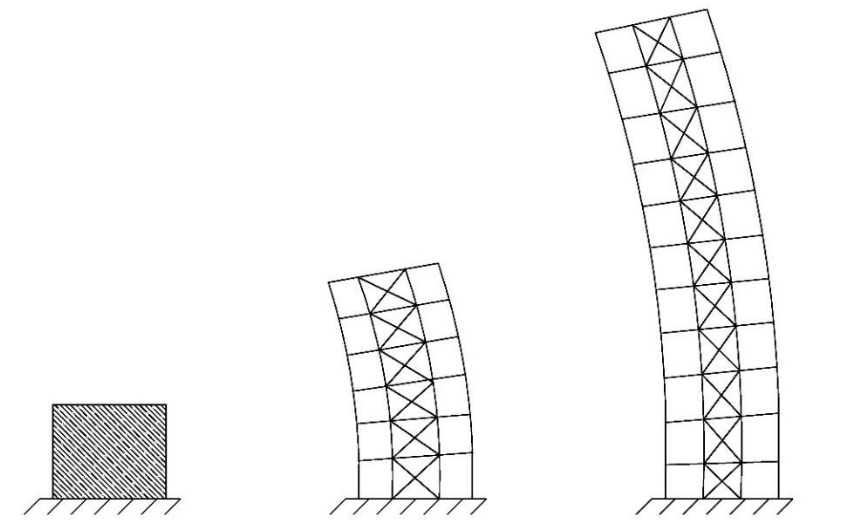


Figure 2.2 The behavior of a building during an earthquake

2.4 Architectural Design Considerations

(Super)tall building design involves many professionals from several disciplines, starting from concept design to construction documents. Because of the requirement of coordination among numerous experts, the entire process become a very complicated issue. For a given building development project, the major responsibility lies with the architect.

This section presents some of the most common architectural design considerations in (super)tall building development. These considerations include function, lease span, floor-to-floor height, core planning, aspect (slenderness) ratio, building form and sustainability. These considerations are interdependent with each other and they affect the overall building design.

There is a definite relationship among abovementioned components. A change in one component or building system will generally result in changes in many others. For example, a variation in floor-to-floor height will change building height, and so the overall architectural, structural, and mechanical costs of the building.

2.4.1 Function

Function is one of the most important architectural design considerations in supertall building development. They are mostly designed to satisfy the occupancy needs which are determined on the basis of the functional requirements. As a main dominant factor that directly affects other design factors, function is of primary concern which requires to be assessed at the early/schematic stages of the architectural design.

Generally, the functional types of (super)tall buildings are divided into single-use and multi-function. Multi-function tall buildings first appeared in the mid-1960s and *Marina City* (Chicago, 1964) is the first multi-function tall building with the concept of “city-within-a-city” (Kim, 2004).

While commercial, office, hotel, residential are considered as major functions; commercial/retail, parking and observatory are considered as supplementary functions in (super)tall buildings. Multi-function (super)tall buildings can be classified into several types according to their complexity: Office with hotel; office with residential; office, hotel and residential (Kim and Elnimeiri, 2004). The combination of these functions usually require a complex building core and user circulation (Park, 2005).

According to CTBUH, “A single-function tall building is defined as one where 85% or more of its total floor area is dedicated to a single use” and “a multi-use tall building contains two or more functions (or uses), where each of the functions occupies a significant proportion* of the total floor area.”

From the structural point of view, hotel or residential function with smaller column space could be located at the bottom of the building, while office or commercial function with wider column space could be located at the top of the building to avoid special condition for transferring loads.

2.4.2 Lease span

Lease span is also one of the most important architectural design considerations in supertall building development. It is defined as the distance between a fixed interior element (the building core wall) and the exterior envelop (window) (Figure 2.3). Lease span generally measured from the dominant side (wider side) of the building.

Lease span depends on the functional requirements and user type. As a measure of occupaiable space established by the core and exterior envelop, lease span is substantial for the interior space planning as well as the entire building's configuration. The total space efficiency depends on the each function’s lease span, but when overall building form is complex other than prismatic, the lease span may not be same on every floor (Park, 2005).

Office and commercial functions utilize longer span, structural floor systems while residential functions utilize relatively smaller span structural systems (Khan and Elnimeiri, 1986).

Generally accepted lease span in practice ranges from approximately 10.67m (35') to 13.71m (45') for office function, approximately 7.62m (25') to 10.67m (35') for residential/hotel function, approximately 9.14m (30') to 12.20m (40') for commercial/retail (Ali and Armstrong, 1995). Office lease span can be larger when single tenant groups occupied floor.

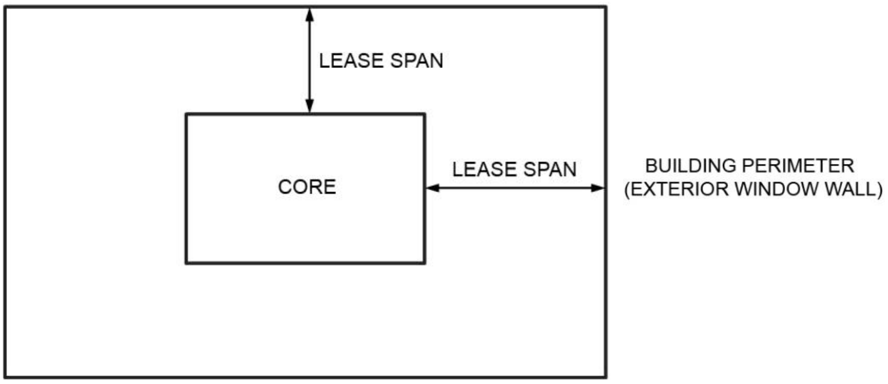


Figure 2.3 Lease span

2.4.3 Floor-to-floor height

Floor-to-floor height is one of the most important architectural design considerations in supertall building development, too. It is defined as the sum of the required ceiling height, the depth of the structural floor system, and the depth of the space required for accommodating the horizontal mechanical and electrical services (Figure 2.4).

Floor-to-floor height has an influence on the overall building economics because of extra cost for many items such as the curtain walls, interior partitions, insulations, vertical pipes and conduits, and more costly foundations due to the extra load of added height, since a small difference in this height, when multiplied by the number of floors, can have a major effect on the building's exterior as well as its structure and thus, its total cost (Choi, 2001).

This dimension has an impact on the overall building energy conservation as it affects the area of the exterior building façade exposed to the outside climate. Reducing floor-to-floor height typically results in a noteworthy savings in overall building bulk and cost.

The most common floor-to-floor height for an office building is approximately 380cm (12'6"), and the range of floor-to-floor height is from approximately 350cm (11'6") to 406cm (13'4"). Ali and Armstrong (1995) emphasize that commercial functions require a variety of ceiling heights ranging between 2.7m and 3.7m; office functions necessitate ceiling heights of approximately 2.5m to 2.7m, while residential and hotel functions require ceiling heights of 2.4m to 2.7m.

Owing to the mechanical and electrical distribution systems, office function requires deeper space than hotel and residential functions. In addition to this, office function also necessitates suspended ceiling system to hide beams, joists, waffle slab, whereas flat plate slab system is more suitable for hotel and residential functions.

The depth of the mechanical system for centralized air handling system and floor structure may take up to almost one-third of overall floor-to-floor height for office function (Kim, 2004). On the other hand, office environment has been dramatically changed to accommodate adequate comfort. Rapid growth of telecommunication and data transmission necessitate extra mechanical space.

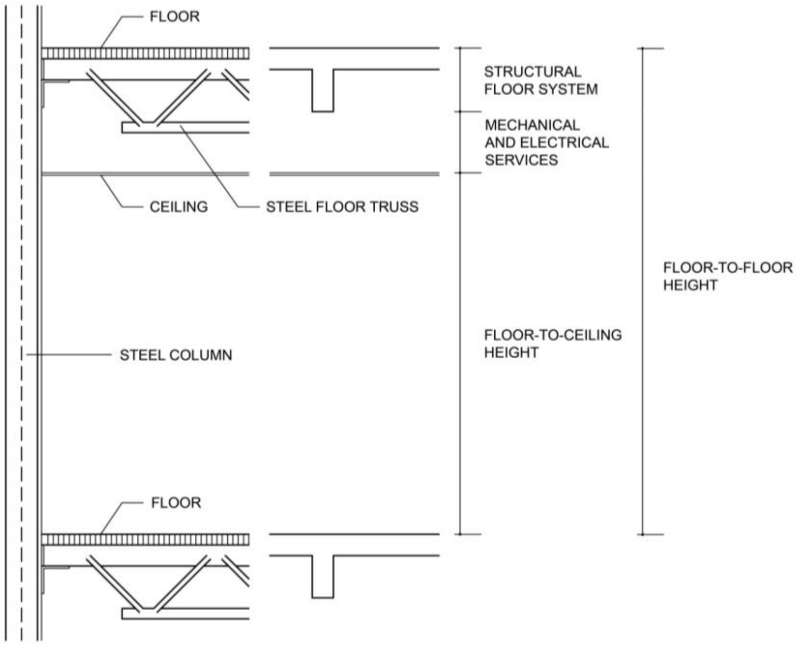


Figure 2.4 Floor-to-floor height (Ali and Armstrong, 1995)

2.4.4 Core planning (Core type)

Core planning is also one of the most important architectural design considerations in supertall building development. A conventional floor planning contains the perimeter zone, interior zone, and core zone. Basically, a core zone, namely service core, is a compact space consisting of elevators, elevator shafts, elevator lobbies, fire-protected lobbies, staircases, vertical mechanical and electrical services, ducts, water pipes, toilets, air handling units, *etc*. (Yeang, 2000). Because of accessibility, ease of keeping in use and some economic reasons, these components of a (super)tall building are always clustered and formed a vertical stem linking the floors (Trabucco, 2010).

As the building height and floor plan size increase, more elevator are needed. Elevator zoning is required for usability of space. This zoning increases handling capacity at expense of interval time. Besides this, separate elevator lobby is required for each zone or each function.

A (super)tall building core is typically allocated in the plan based on structural and space planning requirements. The core size directly influences overall building dimension, total space efficiency and structural behavior as generally a shear walled system is employed in the core.

Core planning is also directly related to the space efficiency of the building. Space efficiency is simply referred as the ratio of rentable area over the gross area and it depends on the core area, namely core planning, of the building. In multi-function building, as the core is usually more complex than these necessary for single-use building, rational combination of functional distribution is very important (Kim, 2004).

From structural point of view, a service core can contribute to tall buildings as the primary structural element like structural core for both vertical and lateral load-resisting systems (Yeang, 2000). Due to the detrimental effect of wind on tall buildings, the service core can be used to provide stiffness, and decrease the top deflection of the building to between the acceptable limits (Yeang, 2000).

From sustainability point of view, service core represents a growing and increasingly important tool to improve the sustainability. Ali and Armstrong (2008) underline the importance of service core in terms of sustainability as *"The service core is a distinctive feature of a tall building and its design plays an important role in the success and sustainability of the whole structure"*.

From building economy point of view, as building height goes up, construction cost of service core becomes curial, covering a large percentage of the total building cost due to its large scale. As the size of the service core is one of the most important factor that determinates the building cost, it should be as minimum as possible in size while still efficiently housing the necessary functions.

The selection of the best arrangement for a specific building differs with the building function, fire regulations and building codes, climatic conditions, architectural design decisions, *etc*. (Yeang, 2000). Vertical circulation system depends on the relation between the service core and the usable areas in floor plan (Beedle *et al.*, 2007). Selecting the suitable arrangement would help to find solution for the objectives of the building (Yeang, 2000).

For instance, if the main objective of the design is a clear internal space, then the end core configuration may be the most efficient solution if the fire escape distances are in the acceptable limits according to the related regulation (Yeang, 2000). As another example, if the issue is about sustainable tall building, the split core can offer a better low-energy performance (Yeang, 2000).

The placement of the core also depends on the occupancy conditions. Whereas single-tenant/use case is the most flexible to decide, for multi-tenant/use case there should be selected a service core type which can provide service for all of the tenants/users (Yeang, 2000).

While Trabucco (2010) basically classifies service cores as central/internal and peripheral/external, Yeang (2000) and Beedle *et al*. (2007) classify them regarding the placement as four generic types of arrangements (Figure 2.5):

- the central core
- the split core
- the end core
- the atrium core

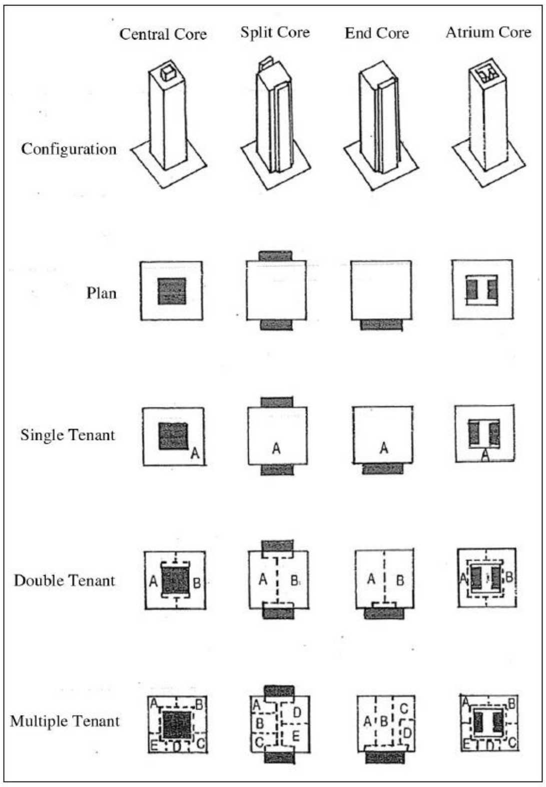


Figure 2.5 The arrangement of generic service core types (Yeang, 2000)

In this research, taking into consideration the studies in the literature (Yeang, 2000; Kohn and Katz, 2002; Trabucco, 2008, 2010) the following classification configuration of the service core is proposed (Figure 2.6):

Some tall buildings utilize more than one core arrangement at the same time. In this case, for the determination of service core type according to proposed classification, first of all, the ratio of dominance has to be checked. If the ratio is equal or more than 75%, the core type is named with the dominant party in this research. For example, if a supertall building employs a central core and a split core arrangement through the building height with ratio of 80% and 20%, respectively, the type is named as central core. In an exceptional case, for instance if the ratios are 60% and 40% or possible combination of these, when naming two types have to be used for the proposed classification.

1- Central core
   a. central
   b. central split

2- Peripheral core
   a. partial peripheral
   b. full peripheral

3- Peripheral split core
   a. partial split
   b. full split

4- External core
   a. attached
   b. detached

5- External split core
   a. partial split
   b. full split

6- Atrium core
   a. atrium
   b. atrium split

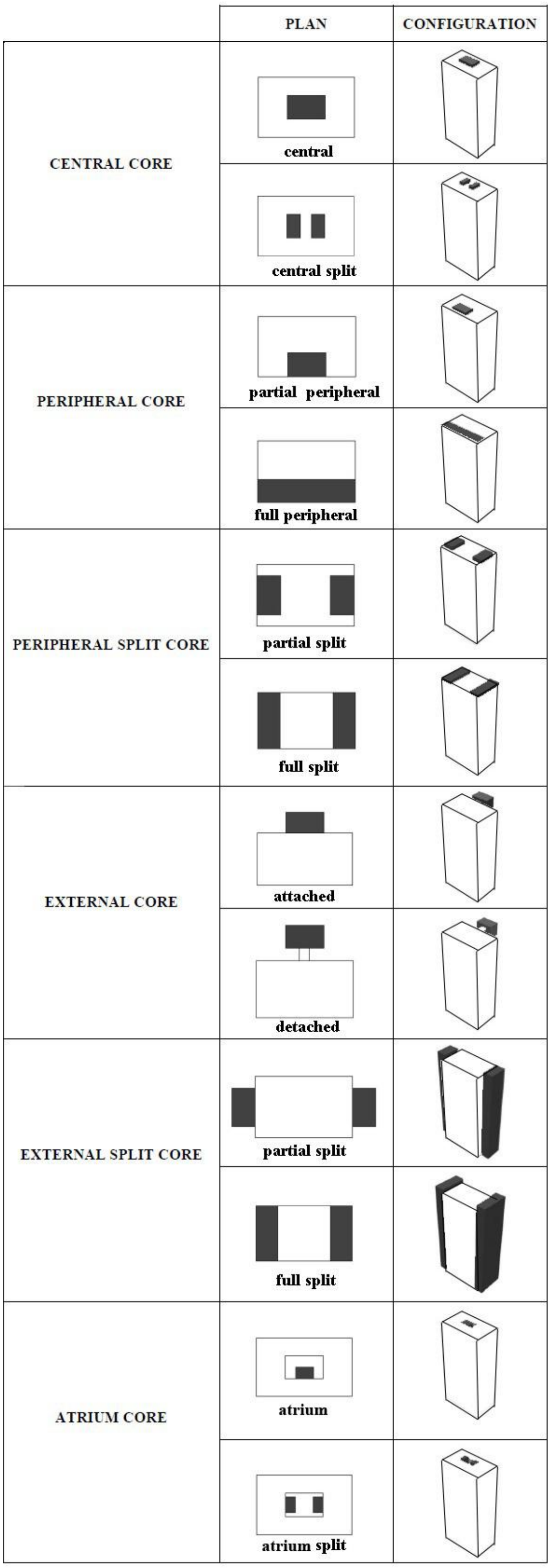


Figure 2.6 Proposed arrangement of service cores

Central core is centrally positioned in the building as in the case of *Two International Finance Centre* (Hong Kong, 2003) (Figure 2.7) and *Bank of China Tower* (Hong Kong, 1990) (Figure 2.8). Owing to the its advantageous of structural contribution, compactness, enabling of openness in the exterior façade for light and views and safety concerns allowing easy access for fire escape, central core becomes the most widely used configuration.

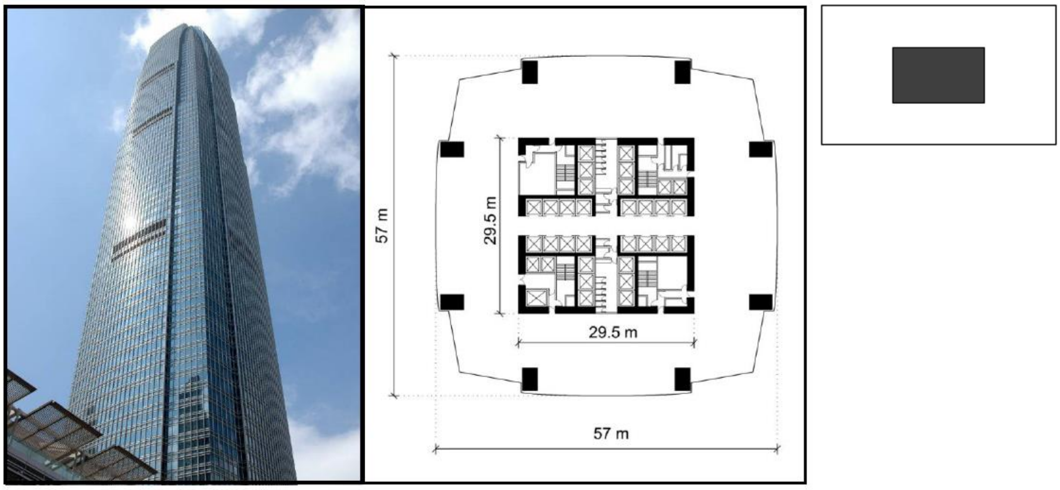


Figure 2.7 Two International Finance Centre, Hong Kong, 2003 (Keskin, 2012)

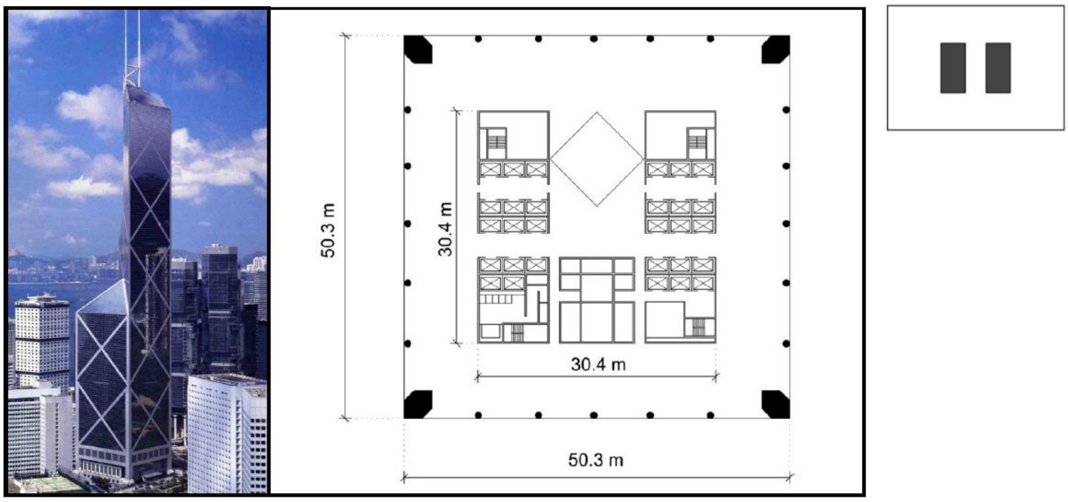


Figure 2.8 Bank of China Tower, Hong Kong, 1990 (Keskin, 2012)

Peripheral core is peripherally positioned in the building as in the case of *Menara Ta1* (Hong Kong, 1989) (Figure 2.9). Owing to the its advantageous of homogeneous workplaces generally planned into one space, environmental performance in terms of acting as a thermal buffer zone in the hot climate enabling natural ventilation and cooling, thus energy saving potential, and for the buildings with smaller floor plates where the central core is a problem due to the inadequacy of floor space for tenancy options or those where poor views or party walls present a tricky, peripheral core becomes more attractive in abovementioned cases. Low effectiveness in the space use because of prolonged circulation path and challenging in acceptable fire escape distance may be counted as drawback of this configuration.

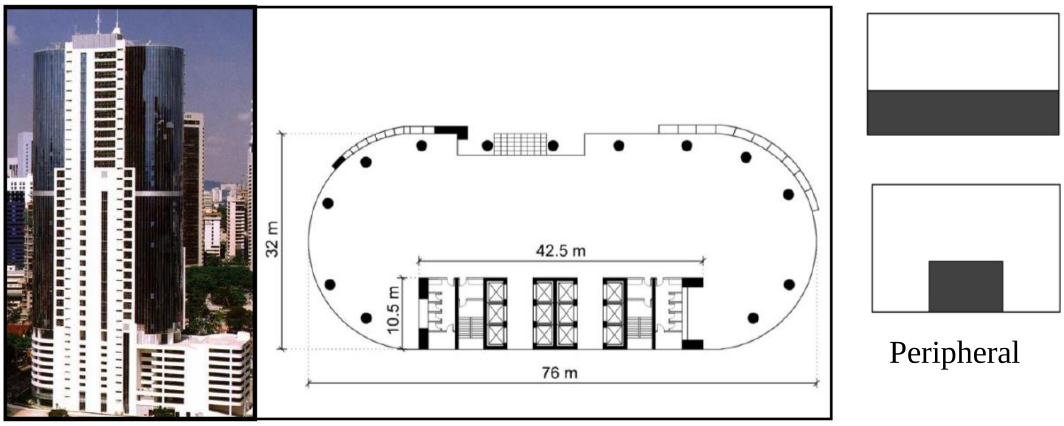


Figure 2.9 Menara Ta1, Hong Kong, 1989 (Keskin, 2012)

Peripheral split core is also peripherally positioned but divided into two or more in the building as in the case of *Commerzbank Tower* (Frankfurt, 1997) (Figure 2.10). In order to overcome problems facing in single core in terms of complicated service requirements and excessive corridor length especially for special design needs of large or long-narrow floor plan, peripheral split core may become preferable option owing to its potential of larger open spaces for atria and/or tenant use.

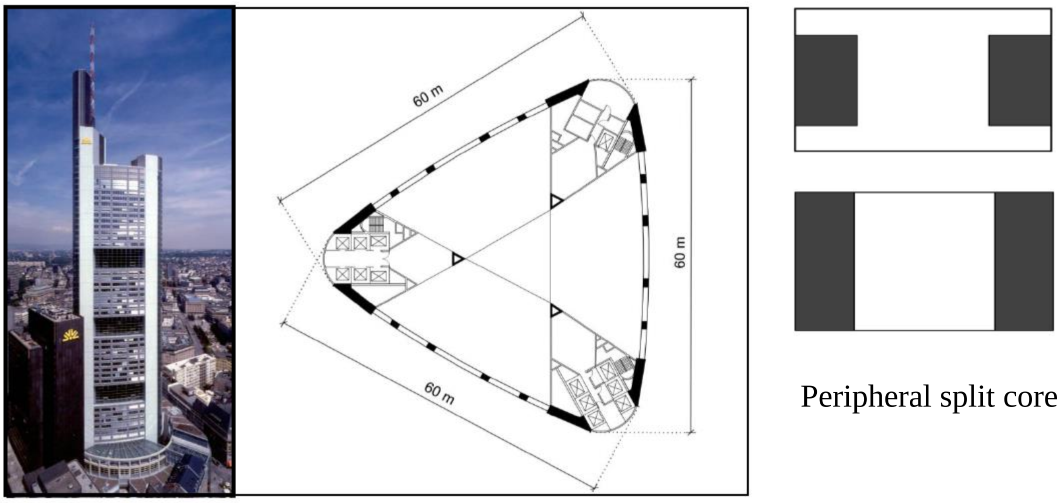


Figure 2.10 Commerzbank Tower, Frankfurt, 1997 (Keskin, 2012)

External core is independently positioned from the building as an isolated component either attached directly or by sky bridge(s) to the building as in the case of *One Bush Plaza* (San Francisco, 1959) (Figure 2.11). As in the case of peripheral core, similarly, environmental performance in terms of acting as a thermal buffer zone in the hot climate enabling natural ventilation and cooling, thus energy saving potential could be evaluated as assets; on the other hand accessibility limitations during emergency and functionality problems about internal space and traffic may be assessed as weakness of external core.

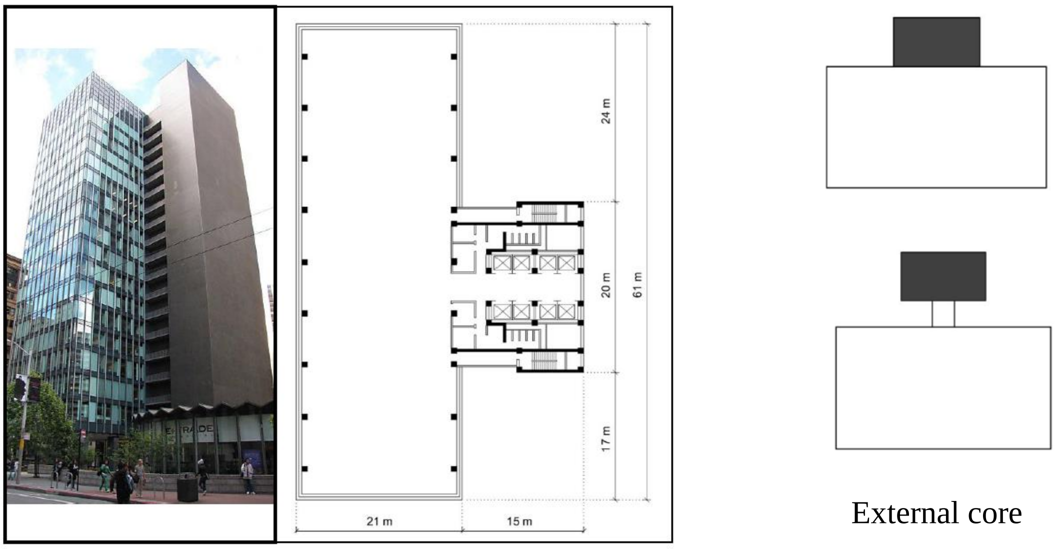


Figure 2.11 One Bush Plaza, San Francisco, 1959 (Keskin, 2012)

External split core is externally positioned but divided into two or more in the building as in the case of *IBM Headquarters Building* (Tokyo, 1989) (Figure 2.12). As in the case of peripheral core, similarly, in order to overcome problems facing in single core in terms of complicated service requirements and excessive corridor length especially for special design needs of large or long-narrow floor plans, external split core might become desirable alternative owing to its potential of larger open spaces for atria and/or tenant use.

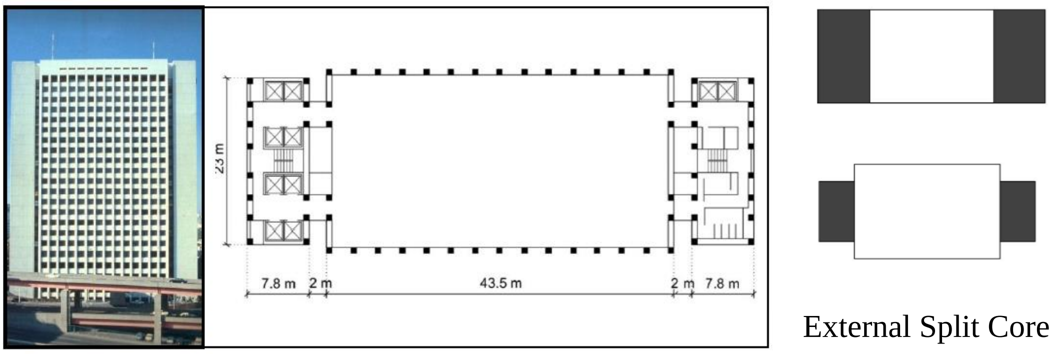


Figure 2.12 IBM Headquarters Building, Tokyo, 1989 (Keskin, 2012)

Atrium core is kind of an improved central core, where there is a combination of advantages of external and peripheral core like natural ventilation and natural lighting, and merits of central core as in the case of *Nakheel Tower* (Dubai, never completed) (Figure 2.13). Its environmental performance in terms of providing daylight and natural ventilation for occupied spaces can be an advantage, nevertheless the requirement of additional fire safety cautions owing to its potential for allowance of fire spread by the chimney effect is a drawback. The atrium core also can be arranged as two or more elements to solve the single atrium core based problems in the case of large or long-narrow floor plans.

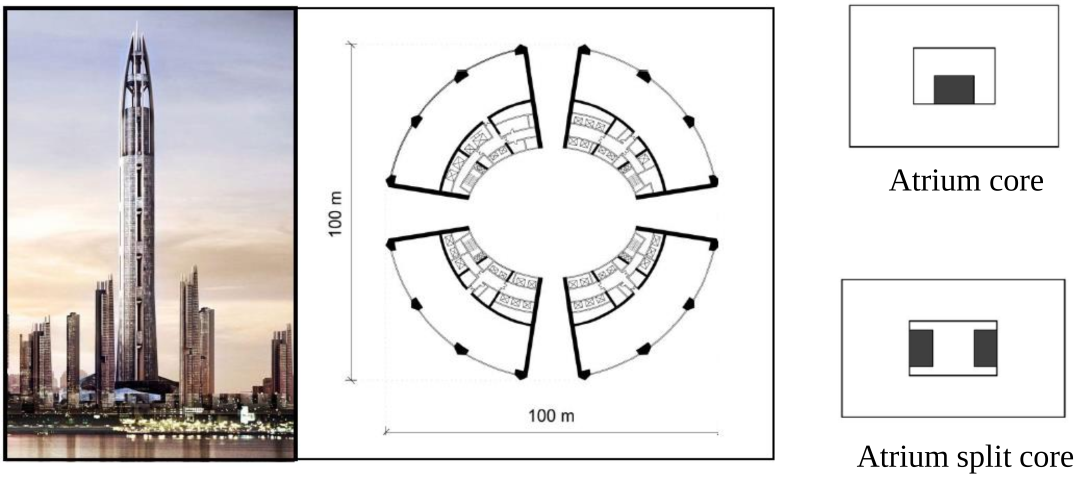


Figure 2.13 Nakheel Tower, Dubai, never completed (Keskin, 2012)

2.4.5 Aspect (slenderness) ratio

Aspect ratio is described as a ratio of the height (H) of the building over the narrow side of the building width (B) (Figure 2.14). It should be noted that the aspect ratio referred to here is that of the structural system.

As super-slender supertalls,

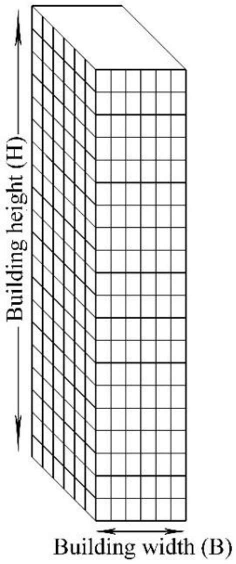
- *432 Park Avenue* (New York, 2015) (Figure 2.15a),
- *Collins House* (Melbourne, under construction) (Figure 2.15b),
- *Highcliff* (Hong Kong, 2003) (Figure 2.15c), and
- *111 West 57th Street* (New York, under construction) (Figure 2.15d)

with their extraordinary slenderness ratio of approximately 1/15, 1/16.5, 1/20 and 1/24 respectively, are the most slender supertall buildings in the world.

In the design of tall buildings, for buildings below 40 stories with height to width ratio (the ratio of the structural height of a building to the narrowest structural width at the ground floor plan, also termed aspect ratio) below 6, the values predicted in the building design codes can be used to determine wind loads.

Because wind loads can change quickly or even suddenly, unlike live and dead loads, in order to estimate the wind load in buildings of more than 40 stories, or that have an aspect ratio of 6 or higher (slender and flexible buildings), or that have unusual forms, dynamic effect of the wind and dynamic building response must be taken into account. In this context, wind tunnel tests are recommended for estimating the wind loads on such buildings.

Under wind load, the overturning moment at the base of a building varies in proportion to the square of the height of the building, and lateral deflection varies as the fourth of the height of the building (Almusharaf, 2011). For supertall buildings with large slenderness ratios, lateral loads typically become dominant, and stiffness rather than strength begins to govern the design.



(a) (b) (c) (d)

Figure 2.14 Slenderness ratio (H/B)

Figure 2.15 (a) 432 Park Avenue, New York, 2015 (S.R: 1/15) (www.ctbuh.org);
(b) Collins House, Melbourne, under construction (S.R: 1/16.5) (www.ctbuh.org);
(c) Highcliff, Hong Kong, 2003 (S.R: 1/20) (www.ctbuh.org);
(d) 111 West 57th Street, New York, under construction (S.R: 1/24) (www.ctbuh.org)

2.4.6 Building form

Supertall building forms have been evolving toward encouraging various architectural styles through the exploration for new morphological schemes owing to the digital tools and techniques utilized during the design process.

Contemporary trends also search for extraordinary form treatments of building forms to improve the performance by minimizing the outer façade/floor surface ratio to decrease material use/cost/energy consumption; or by optimizing wind flow or activate wind generators more effectively. The main aim at the end of these profound analysis is to satisfy sophistication, aesthetic, structural efficiency, building economy and environmentally consciousness in the design of complex shaped buildings.

A proposed scheme by Vollers (2008) categorizes non-orthogonal (super)tall buildings based on the overall shaping of their respective volumes (Figure 2.16). The work attempts to involve most typical forms of (super)tall buildings today.

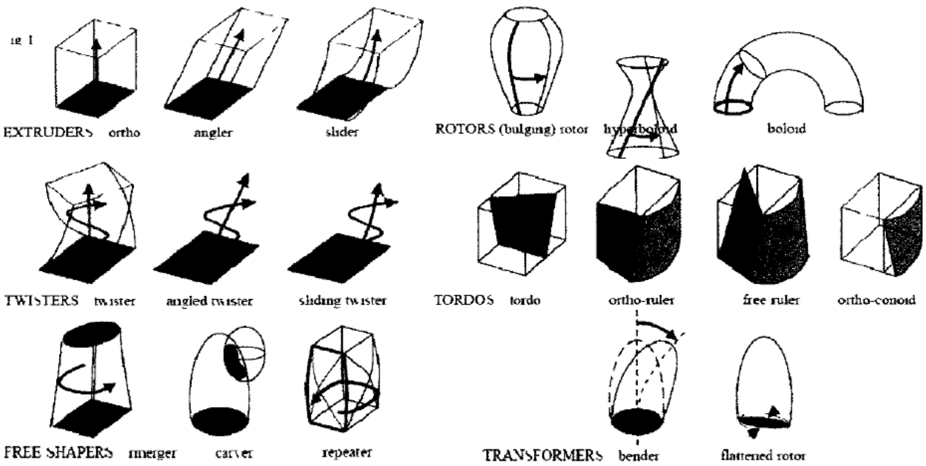


Figure 2.16 Morphological scheme for shaping of tall building volumes (Vollers, 2008)

A typical supertall building could be divided into 3 sections: *top/head*, *main body/tower*, *base* (Figure 2.17). Tripartite design concept originating in the late 19th century, best exemplified in *Chrysler Building* (New York, 1930), suggests that a skyscraper should have a distinct top (crown), middle (shaft), and base (podium) (Al-Kodmany and Ali, 2016). In the following, three main sections of supertall building viewed vertically are discussed briefly.

- ***Base*** This section is seen from street level and may rise to a height of five to ten stories depending on the depth of the open space in front of the supertall building. Interfacing with the urban settings, this part the supertall building is a critical determinant of the building's contextual quality (Architectural Record, 1974). The "base" configuration has a minor effect on the urban ecology because of its low height, while it has major effect on the scale, definition of the street, and of course "humanizing" image of the building (Ali and Armstrong, 1995).
- ***Main body/tower*** This section extends from the building's base upward. The "main body/tower" configuration is the most critical in changing the quality of interaction between the building and eco-environmental conditions like the air movement in its surroundings and in perceiving of building scale (Ali and Armstrong, 1995).
- ***Top/head*** This section generally has a reduced footprint and so thus it has a lesser impact on the eco-environmental condition of the building compared to the main body/tower section. In very rare occasions it has the same or bigger footprint compared to the rest of the building (Ali and Armstrong, 1995). The "top/head" highlights building's own identity, and is perfectly formed by formal influences of both the lower sections and the city's skylines (MacMillan and Metzstein, 1974).

In this research, building forms are classified essentially based on the *main body/tower* configuration. *Base* section is totally ignored in the classification. *Top/head* section is taken into consideration when generating subclasses.

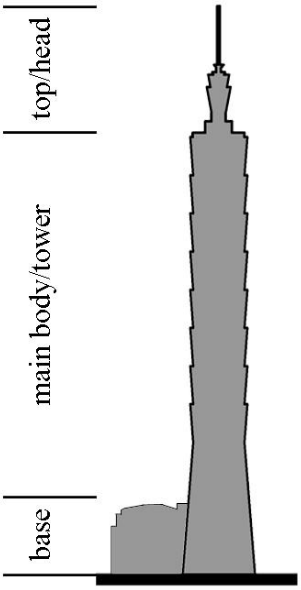


Figure 2.17 Sections of a typical supertall building

In this research, taking into consideration the studies in the literature (Vollers, 2008; Sev and Tugrul, 2014; Al-Kodmany and Ali, 2016 and like) the following classification proposed by the author based on the contemporary supertall building form (both orthogonal and non-orthogonal) configuration:

- Simple/extruded forms
  - Simple/extruded forms with architectural top
  - Articulated simple/extruded forms (with architectural top)
- Leaning/tilted forms
- Tapered forms
  - continuous tapered
  - non-continuous tapered
- Setback forms
- Twisted forms
- Free forms
  - Sculptural free forms
  - Modulated & unmodulated and repetitive free forms
  - Amorphous free form

Simple/extruded forms

This category refers to buildings with *simple/extruded form* whose two ends are similar, equal, and parallel figures, whose sides are identical, and whose axle are fully vertical, namely perpendicular to the ground. In additıon to this, they have an identical floor profile repeated through the entire height of the building as in the case of

- *WTC Twin Towers* (New York, 1972) (Figure 2.18a) and
- *432 Park Avenue* (New York, 2015) (Figure 2.18b).

The buildings in simple form with some minor but visible/striking at the supertall building scale, façade articulations like projections or recessed, cut corner and so on through the building height are named as *"articulated simple/extruded forms"* as in the case of *Aon Center* (Chicago, 1973) (Figure 2.18c).

Simple forms could have some minor architectural modification/articulation particularly on the building head/top. Such kind of simple forms are called as "*simple/extruded forms with architectural top"*.

Numerous supertall building forms utilize both articulation and architectural top at the same time in their simple forms, named as "*articulated simple/extruded form with architectural top*" as in the case of

- *Makkah Royal Clock Tower* (Mecca, 2012) (Figure 2.18d),
- *Princess Tower* (Dubai, 2012) (Figure 2.18e), and
- *23 Marina* (Dubai, 2012) (Figure 2.18f).

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

Figure 2.18 (a) WTC Twin Towers, New York, 1972 (www.ctbuh.org);
(b) 432 Park Avenue, New York, 2015 (www.ctbuh.org);
(c) Aon Center, Chicago, 1973 (www.ctbuh.org);
(d) Makkah Royal Clock Tower, Mecca, 2012 (www.ctbuh.org);
(e) Princess Tower, Dubai, 2012 (www.ctbuh.org);
(f) 23 Marina, Dubai, 2012 (www.ctbuh.org)

Leaning/tilted forms

This category refers to buildings with *inclined form*. Buildings have traditionally been constructed vertically, namely orthogonal to the ground. When a building is constructed in a tilted form, it is classically an indication of some serious problems occurred to the building as in the case of *Tower of Pisa* suffering from differential settlements (Moon, 2015a).

Today, nevertheless, the buildings with tilted forms are intentionally designed to generate more dramatic architecture as in the case of

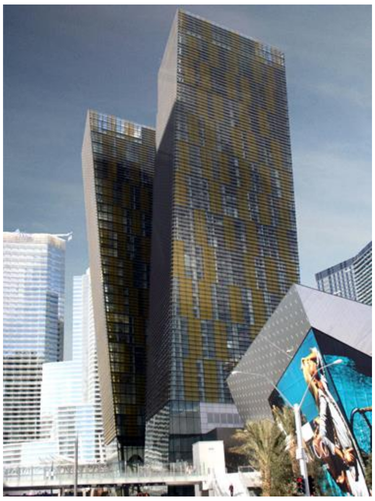
- the 26-story, 114m high *Puerta de Europa Complex* (Madrid, 1996) with an inclination of 15° (Figure 2.19a),
- the 36-story, 165m high *Capital Gate Tower* (Abu Dhabi, 2011) with an inclination of 18° (Figure 2.19b),
- the 37-story, 137m high *Veer Towers* (Las Vegas, 2010) with an inclination of 5° (Figure 2.19c), and
- *Signature Towers* (Dubai, proposed) (Figure 2.19d),

which are the most remarkable examples of leaning tall buildings of the contemporary era. Leaning profile can be either linear (Figure 2.19a) or non-linear (Figure 2.19b). Some leaning forms with non-linear profile can be categorized as free forms, too (Figure 2.19b).

The structural performance of a tilted tall building is dependent upon its structural system and angle of tilt. Tall buildings with tilted form are subjected to significant initial lateral deformations due to eccentric gravity loads (Moon, 2014; Moon, 2015a).

Gravity-induced lateral displacements increase as the angle of tilt increases. Surprisingly, compared to the tubular structures, the outriggered frame system provides somewhat greater lateral stiffness for tilted forms owing to the triangulation of the major structural components (Moon, 2014; Moon, 2015a; Choi *et al.*, 2017).

(a) (b)



(c) (d)

Figure 2.19 (a) Puerta de Europa Complex, Madrid, 1996 (www.ctbuh.org);
(b) Capital Gate Tower, Abu Dhabi, 2011(www.ctbuh.org);
(c) Veer Towers, Las Vegas, 2010 (www.ctbuh.org);
(d) Signature Towers, Dubai, proposed (www.zaha-hadid.com)

Tapered forms

This category refers to buildings with *tapering effect* by reduced floor plans and surface areas through the height into either linear or non-linear profiles. Namely, in the tapered form the floor plan dimensions are reduced constantly as the building rises. Pyramidal form can be accepted as the most basic type of tapered form with the first example as the ancient pyramids in Egypt. However, they are not considered to be a building because of the absence of occupied floors.

Tapered form variations may be generated by using tapering effect, where the floor's profile size is scaled while its proportions are preserved as in the case of

- *John Hancock Center* (Chicago, 1969) (Figure 2.20a),
- *Shanghai World Financial Center* (Shanghai, 2008) (Figure 2.20b), and
- *One Word Trade Center* (New York, 2014) (Figure 2.20c).

The taper profile can be either

- linear as in the case of *John Hancock Center* (Chicago, 1969) (Figure 2.20a) or
- non-linear as in the case of *Chase Tower* (Chicago, 1969) (Figure2.20d).

Tapered forms also can be divided into two groups: *continuous tapered*, namely tapering effect continuously through the building height as in the case of *John Hancock Center* (Chicago, 1969) (Figure 2.20a) and *non-continuous tapered*, namely tapering effect interrupted through the building height *Ping An Finance Center* (Shenzhen, 2017) (Figure 2.20e) and *Lotte World Tower* (Seoul, 2017) (Figure 2.20f).

Compared to prismatic forms, tapered forms provide many advantages for structural systems for tall buildings. Owing to greater building width, tapered forms demonstrate more resistance shear and overturning moments resulting from lateral loads than prismatic forms (Moon, 2015a).

Tapered forms can be often more desirable architecturally for multi-function tall buildings to accommodate different function by offering various lease span opportunities as in the case of *John Hancock Center* (Chicago, 1969) (Figure 2.20a) (Abalos and Herreros, 2003).

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

Figure 2.20 (a) John Hancock Center, Chicago, 1969 (www.ctbuh.org);
(b) SWFC, Shanghai, 2008 (www.ctbuh.org);
(c) One World Trade Center, New York, 2014 (www.ctbuh.org);
(d) Chase Tower, Chicago, 1969 (www.ctbuh.org);
(e) Ping An Finance Center, Shenzhen, 2017 (www.ctbuh.org);
(f) Lotte World Tower, Seoul, 2017 (www.ctbuh.org)

Setback forms

This category refers to buildings with *recessed horizontal sections* through the height of the building. Namely, in the setback form, the overall plan dimensions are reduced it at certain levels as the building rises.

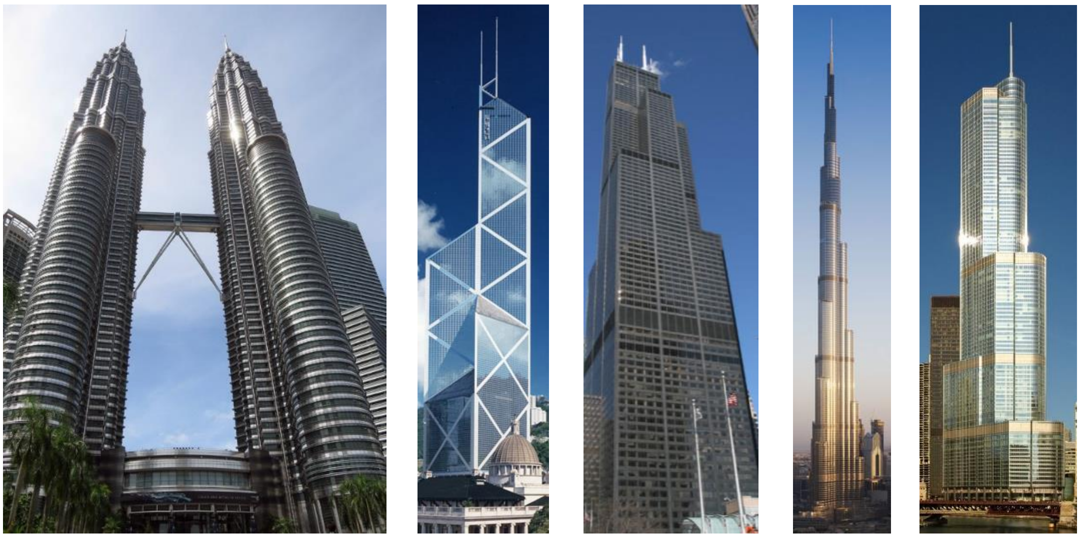
- *Petronas Twin Towers* (Kuala Lumpur, 1998) (Figure 2.21a),
- *Bank of China Tower* (Hong Kong, 1990) (Figure 2.21b),
- *Willis Tower* (Chicago, 1974) (Figure 2.21c),
- *Burj Khalifa* (Dubai, 2010) (Figure 2.21d), and
- *Trump International Hotel&Tower* (Chicago, 2009) (Figure 2.21e)

are the remarkable examples of supertall buildings with setbacks.

The masterpieces from 1930s such as *Empire State Building* (New York, 1931) and *Chrysler Building* (New York, 1930) also utilized progressive setbacks of the base, main body and top in order to satisfy zoning laws to diminish the shadow on neighboring buildings.

Setbacks can be more desirable architecturally for multi-function tall buildings to accommodate different function by offering various lease span opportunities as in the case of tapered forms. Owing to this reason, setback solutions seem to be more popular, although they present structural problems at the setback location.

Structurally, the number of setbacks and their rates should be carefully considered with transferring beam, transferred column, column setback distance, and locations. On the other hand, setbacks cause the upper parts of the building to be narrower than the lower parts to meet structural needs for wind resistance and functional requirements for different user types mentioned above.



(a) (b) (c) (d) (e)

Figure 2.21 (a) Petronas Twin Towers, Kuala Lumpur, 1998 (www.ctbuh.org);
(b) Bank of China Tower, Hong Kong, 1990 (www.ctbuh.org);
(c) Willis Tower, Chicago, 1974 (www.ctbuh.org);
(d) Burj Khalifa, Dubai, 2010 (www.ctbuh.org);
(e) Trump International Hotel&Tower, Chicago, 2009(www.ctbuh.org)

Twisted forms

This category refers to buildings with *progressively rotating floors* or its façade as they multiply upward along an axis by inputting a twist angle. Typically, but not always, each plate is shaped similarly in plan and is turned on a shared axis a consistent number of degrees from the floor below. A spectacular diversity of textures, view angles, and ripple effects results from these manipulations, making these "twisters" some of the world's most iconic buildings - and in many cases, aerodynamic.

Utilization of twisted forms for tall buildings is a recent architectural phenomenon. Twisted forms employed for contemporary tall buildings can be understood as a reaction to rectangular box forms of modern architecture (Moon, 2015a).

The basic group in this category is the "*linear twist"*, which is a result of rotating each floor in relation to the one below it according to a constant value as in the case of

- *Turning Torso* (Malmö, 2005) (Figure 2.22a),
- *Cayan Tower* (Dubai, 2013) (Figure 2.22b), and
- *Evolution Tower* (Moscow, 2016) (Figure 2.22c).

Twisted form variations could be generated also by applying either a taper, called as "*tapering twisted form"* as in the case of

- *Lakhta Center* (St. Petersburg, under construction) (Figure 2.22d) or

a deformer to the linear twist, called as "*non-linear twist form"* as in the case of

- *Chicago Spire* (Chicago, never completed) (Figure 2.22e).
- *Diamond Tower* (Jeddah, under construction) (Figure 2.22f) and
- *Al Majdoul Tower* (Riyadh, 2017) (Figure 2.22g)

  are also specular examples of twisted form.

From structural point of view, twisted forms are not advantageous. If diagrid-framed-tube, trussed-tube or outriggered framed systems are employed for twisted tall buildings, lateral stiffness of these systems decreases as the rate of twist increases (Moon, 2010; Moon, 2015a).

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

Figure 2.22 (a) Turning Torso, Malmö, 2005 (www.ctbuh.org);
(b) Cayan Tower, Dubai, 2013 (www.ctbuh.org);
(c) Evolution Tower, Moscow, 2015 (www.ctbuh.org);
(d) Lakhta Center, St. Petersburg, under construction (www.ctbuh.org);
(e) Chicago Spire, Chicago, never completed (www.ctbuh.org);
(f) Diamond Tower, Jeddah, under construction (www.ctbuh.org);
(g) Al Majdoul Tower, Riyadh, 2017 (www.ctbuh.org)

Free forms

This category refers to buildings with *free forms* which is out of the abovementioned forms. Free forms may emerge with various design inspirations and objectives by the architects, engineers and owners as well. For instance in order to decrease the wind loads on the structure and achieve structural efficiency, aerodynamic forms emerge, to produce changeable outlooks instead of a constant one, dynamic forms are designed; and to incorporate cultural motifs to the design, regional or cultural forms are created.

According to Ali and Moon (2007), *Willis Tower* (Chicago, 1974) (Figure 2.47a) and *One Magnificent Mile* (Chicago, 1983) (Figure 2.47b) can be stated as the first examples of free forms, by the introduction of bundled-tube system.

In this study, the following classification is based on the configuration of the free forms:

- *Sculptural free forms* as in the case of
  - *Al Hamra Tower* (Kuwait, 2011) (Figure 2.23a),
  - *Almas Tower* (Dubai, 2008) (Figure 2.23b),
  - *CCTV Headquarters* (Beijing, 2012) (Figure 2.23c), and
  - *Tour Phare* (Puteaux, proposed) (Figure 2.23d);
- *Modulated & unmodulated and repetitive free forms* as in the case of
  - *TAIPEI 101* (Taipei, 2004) with bamboo shape (Figure 2.24a),
  - *Evergrande IFC 1* (Hefei, under construction) (Figure 2.24b), and
  - *Jin Mao Tower* (Shanghai, 1999) (Figure 2.24c);
- *Amorphous free form*s as in the case of
  - *Eton Place Dalian Tower 1* (Dalian, 2016) (Figure 2.24d),
  - *Burj Mohammed Bin Rashid* (Abu Dhabi, 2014) (Figure 2.24e), and
  - *Federation Towers - Vostok Tower* (Moscow, 2016) (Figure 2.24f).

(a) (b) (c) (d)

Figure 2.23 (a) Al Hamra Tower, Kuwait city, 2011 (www.ctbuh.org);
(b) Almas Tower, Dubai, 2008 (www.ctbuh.org);
(c) CCTV Headquarters, Beijing, 2012 (www.ctbuh.org);
(d) Tour Phare, Puteaux, proposed (www.ctbuh.org)

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

Figure 2.24 (a) TAIPEI 101, Taipei, 2004 (www.ctbuh.org);
(b) Evergrande IFC 1, Hefei, under construction (www.ctbuh.org);
(c) Jin Mao Tower, Shanghai, 1999 (www.ctbuh.org);
(d) Burj Mohammed Bin Rashid Tower, Abu Dhabi, 2014 (www.ctbuh.org);
(e) Federation Towers - Vostok, Moscow, 2016 (www.ctbuh.org);
(f) Eton Place Dalian Tower 1, Dalian, 2016 (www.ctbuh.org)

2.4.7 Sustainability

Promptly growing cities all over the world are creating an extraordinary stress on material and energy sources. As a leading energy consumer, a supertall building does not usual conjure images or sustainable design. Huge energy consumption of supertall buildings makes architects and engineers search for new, constructive systems, technologies, and building materials.

A great number of scientific developments have been introduced in supertall buildings in recent years. It allows extending the use of renewable energy and the efficient use of resources. A new generation of supertall buildings is integrating new technological advances with innovative design approaches to yield more energy-efficient, sustainable and habitable buildings named as “vertical garden cities”.

As a consequence of the enormous weight exposed to huge amount of wind forces, the structure of a supertall building costs much more than of a conventional building (Beedle *et al*., 2007). Above from the amount of material used in the process, the special technologies used to build up the building cause a significant increase in price (Gonçalves and Umakoshi, 2010).

Addition to the fact above, Yeang and Powell (2007) claim that when compared to other building types, supertall buildings use up at least three times more energy and material to construct, to operate and to demolish. Namely, when the buildings are getting taller, operational costs are getting higher with the necessity of more complex systems. This matter has become more significant over the past few decades, having led to much study on cheaper, and more environment friendly and energy-efficient technologies.

Above all, as one of the most basic passive sustainable strategies, which works with the environment to eliminate undesirable heat or cold and take advantage of sun and breezes, the *sustainable settlement* plays a vital role for end product of all planning exercises, the architectural layouts should be well integrated with the sun path charts and the orientations of openings in order to minimize solar heat gain and maximize air flow. Therefore, an appropriate orientation may offer thermally indoor conditions besides physical and psychological comfort in any settlement at lesser energy demand.

Sustainable design of supertall buildings generally depends on system solutions in structural, mechanical, electrical, transportation networks, façade, natural lighting, and ventilation, heating & cooling systems. The ingenuity of the sustainable architecture would be expressed in striking the balance between the systems and spatial relations among functional, social or economic requirements. At that point, the connection between (super)tall buildings and their infrastructure related to energy, transportation networks, heating and cooling systems, water & waste distribution are need to be taken into consideration in terms of sustainable design.

Firstly, from structural point of view, as a building's height increases, the required amount of structural material to resist lateral loads increases drastically. So, an appropriate and efficient structural system selection especially for a supertall building with complicated forms, through integrative design studies in conjunction with various building systems, is a very vital initial step for the sustainable design. For example, when the primary structural members are located over the building's perimeter, the system's efficiency can be maximized as in the case of *Bank of China Tower* (Hong Kong, 1990) with trussed-tube system (Figure 2.21b). Compared to buildings of the same height and area, the *Bank of China Tower* (Hong Kong, 1990) used 40% less steel (Ali and Armstrong, 1995).

Architects and engineers have started to work on sustainability of super(tall) buildings due to the increased conscious about the negative effect of them on environment (Elnimeiri and Gupta, 2008). By the last two decades, a growing group of professionals searches for a suitable way for super(tall) buildings to meet or reduce the energy demand of them (Wood, 2007).

Since key principle of sustainability is to diminish or exclude use of natural sources beyond the rate at which they can naturally regenerate, this clearly could be accomplished through efficient use of resources and indeed energy. A far better step is to rely on true sustainable sources of material and power from sun rays, wind power, geothermal power and so forth.

As true sustainable sources, particularly sun rays and wind power, offer a great potential in terms of cooling & ventilation and electricity generation for tall buildings owing to very large surface area for sun utilization and extraordinary height for wind harness (Elbakheit, 2008). Because of their astonishing height, tall buildings can benefit from high level of wind speeds.

Building façade/envelope is one of the most substantial components that make a supertall building sustainable as it is the first line of interaction of the building with natural forces. Its integration through both passive and active design strategies to decrease energy consumption and contribute in energy generation with gradually growing trend gains greater emphasis today.

As an innovative and encouraging trends in the design of (super)tall buildings, which challenge traditional typologies and are adapted for specific climatic conditions, in particular for *bioclimatic skyscrapers*, which has a key feature of the adaptability in their natural environment, building envelope becomes a forefront concept in terms of the thermal balance (Generalova *et al*., 2017).

At abovementioned concept, using double facades in different climatic conditions with account of their interaction with other technological, constructive and planning elements, for example, passive and active solar control systems, landscaping, smart control systems of temperature and humidity are the key elements for the climate adaptation and energy saving features (Holdsworth, 2005; Balzannikov, 2007; Vavilova, 2010; Lotfabadi, 2014; Wood, 2014).

Utilization of *newly developed building materials* is also one of the critical approach of green building especially in terms of façade design. *New insulation materials* enabling more energy conservation and less energy loss could be used with better effectiveness in (super)tall buildings to advance the green performance and environmental credential. Besides this, *new glazing materials* with improved visual and thermal properties might be combined with photovoltaic cells, and so these materials satisfy both the function of glazing component and electricity generation.

Natural ventilation is another important issue for green building design, especially when employed as a cooling principle in extreme hot or cold climates. Many of vernacular architecture examples exist with features such as wind catchers, underground cooling, fountains, cross ventilation, internal courtyards, and stack effect devices.

Day lighting is also significant topic and has also evolved noticeably in the few past decades. Many invented to channel natural light deep into interiors, which are deprived from normal windows or means of natural light.

One of the recent development in building automation services and networks is the development of monitoring station for all building services. Although it is in its infancy, it has great potential for managing, controlling, optimizing, and monitoring building services especially for supertall buildings.

Foster's *Commerzbank Tower* (Frankfurt, 1997) (Figure 2.25a) is an early but outstanding example, where many of these key principles mentioned above were together, vertical circulation, naturel ventilation, day-lighting from façade curtain walls and atrium, and air conditioning are incorporated in a central core. These measures resulted in lowered energy consumption and operational costs noticeably.

The most recent examples of sustainable tall buildings, where there is an integration of architectural design and environmental technologies in a more functional and elegant way, are

- *COR Building* (Miami, project pending) (Figure 2.25b) with its well-balanced transparent-opaque skin and wind turbines blend in the skin of the building,
- *Bahrain World Trade Center* (Manama, 2008) (Figure 2.25c),

- *Pearl River Tower* (Guangzhou, 2009) (Figure 2.25d), and
- *Shanghai Tower* (Shanghai, 2015) (Figure 2.25e) with double skin façades

helping in reduction buildings' energy consumption and wind loads applied to the building (Oesterle et al., 2001). Wood (2007) states that these types of design strategy is the way of creating prosperous ecofriendly tall buildings which fulfill both sustainability and presence.

(a) (b) (c) (d) (e)

Figure 2.25 (a) Commerzbank Tower, Frankfurt, 1997 (www.ctbuh.org);
(b) COR Building, Miami, project pending (Gunel and Ilgın, 2014);
(c) BWTC, Manama, 2008 (Gunel and Ilgın, 2014);
(d) Pearl River Tower, Guangzhou, 2009 (www.ctbuh.org);
(e) Shanghai Tower, Shanghai, 2015 (www.ctbuh.org)

What is more, in the past two decades, several rating systems also called of building environmental assessment methods (BEAMs) / eco-labeling, in many parts of the world have been implemented (i.e. LEED from USA, BREEM from UK *etc*.) to assess the physical properties of building materials against the environmental performance for building interior and ultimately against the global environmental wellbeing. Operation system of these methods depends on giving points to each relevant aspect, and concluding with an overall score to label the sustainability level of the related building (Yıu-Ching, 2005). The assessment criteria or the percentage of a criterion may show a discrepancy for different BEAMs.

2.5 Structural Design Considerations

Structural systems in the early 20th century buildings were basically designed to resist vertical loads. Today, owing to developments in this field and to high-strength materials, with the increase in the height of buildings and the decrease in their weight, wind and earthquake induced lateral loads have become the primary loads, especially in supertall buildings, and have begun to pose more of a threat than before. As a result, for structural engineers, providing the strength to resist lateral loads in tall buildings, whether wind or earthquake induced, has become an essential input in the design of new structural systems.

Since a supertall building is feasible by the structure itself, the structural system is the most important design parameter. Many planning consideration are dependent upon the structural system for their proper performance. The selected structural system has an effect on not only building's exterior aesthetics but also on its interior space planning.

As the height of buildings increases, the choice of structural system decreases. While the choice of structural system in low-rise buildings is considerable, the alternatives in choice of a structural system become restricted by limitations imposed by the height of buildings. Therefore, especially in supertall buildings, architectural and structural design should be considered together.

Structurally, tall buildings have different design conditions compared to low-rise buildings. Due to their height and slenderness, tall buildings are extremely susceptible to wind and seismic loads. The main design characteristics of tall building structures can be summarized as follows (Zhang, 2001):

- The lateral load (wind and seismic loads) has become the critical factor for tall buildings, however the vertical load is also a very significant factor. This is because the axial force and bending moment caused by the vertical load is only linearly proportional to the height of the buildings, but the axial force and overturning moment caused by the horizontal load increases as the square of the height of the building.

- For tall buildings, the axial deformation of the vertical members has a large effect on the member internal force, the lateral displacement and also the length of the pre-cast member.
- The lateral displacement becomes the control index for the design of the structural system and the major member dimensions. Under a uniform lateral load, the lateral displacement is proportional to the height of the building by four times. Controlling the maximum lateral displacement is part of the serviceability requirement in order to prevent both human discomfort (due to high acceleration of the structure) and damage to main structural members, as well as partitions and other non-structural members.
- The durability design of the high-rise structure is more important than that of a low-rise structure since tall buildings are more slender than low-rise buildings. Sufficient durability guarantees that the structure has adequate deformability after it has entered the plastic deformation stage under seismic load.

Although there is no exact methodology for the determination of suitable structural system and the best possible solution differs for each particular case, according to Ali and Armstrong (1995), the most significant factors for the selection of appropriate structural systems can be summarized as follows:

- Design lateral loads (mainly wind and/or earthquake induced)
- Serviceability performance criteria
- Construction methods
- Local conditions (material, labor, common practices)
- Soil conditions and related foundation system
- Building function and occupancy types
- Building form
- Aspect (slenderness) ratio
- Architectural, structural, mechanical needs
- Economics

Obviously, the structural system for supertall buildings is the major area of research. The structural system developed with an optimization process among function, aesthetic, structural material and many other criteria while realizing ideal building performance. Potentials and limitations related to the height, form, and aspect ratio for the supertall buildings is determined by the structural system.

This section presents a brief account of structural design considerations in tall building development. These considerations include structural materials and structural systems.

While structural systems will be discussed in depth, structural materials will only be considered on a generic level in this study. These considerations are interdependent with each other and they affect the overall building design.

2.5.1 Structural Materials

According to CTBUH:

> *"**Steel tall building**: Both the main vertical/lateral structural elements and the floor systems are constructed from steel. Note that a building of steel construction with a floor system of concrete planks or concrete slab on top of steel beams is still considered a 'steel' structure.*
>
> ***Concrete tall building:** Both the main vertical/lateral structural elements and the floor systems are constructed from concrete.*
>
> ***Mixed-Structured tall building:** Utilizes distinct steel and concrete systems, one on top of the other. Steel/concrete indicates a steel structural system located on top of a concrete structural system, with the opposite true of concrete/steel.*
>
> ***Composite tall building:** A combination of both steel and concrete components are used together in the main structural elements. Examples include buildings which utilize: steel columns with a floor system of concrete*

beams; a steel structure with a concrete core; concrete-encased steel columns; concrete-filled steel tubes; etc"

According to Gunel and Ilgın (2014) and the author as well taking as a basis the columns, beams, shear trusses (braces), shear walls, and outriggers that are the elements of the main vertical and horizontal structural systems, buildings can be categorized as being reinforced concrete buildings where these elements are made of reinforced concrete, or as steel buildings where these elements are made of steel.

The author can define composite buildings as: those in which some structural elements are made of reinforced concrete and other structural elements are made of steel; and/or those in which some structural elements are made of both structural steel and concrete together.
Buildings can be classified on the basis of the materials used in their structural systems as:

- Steel
- Reinforced concrete
- Composite

2.5.2 Structural Systems

The set of tall building structural systems has developed over time, starting with rigid frame systems, and with the addition of shear-frame, mega column (mega frame, space truss), mega core, outriggered frame, and tube systems, it has made much taller buildings possible.

For "tall buildings" of 40 stories and below, "rigid frame systems", "flat plate/slab systems", "core systems", and "shear wall systems" are used. For "supertall buildings" over 300m high or 75 stories, the necessity for an economic and efficient structural system satisfying both the structural safety, and serviceability (occupancy comfort) to be limited to a maximum lateral drift due to lateral loads of approximately 1/500 of the building height, reduces the choice of structural system (Bennett, 1995; Taranath, 1998). For this reason, for buildings of more than 40 stories, “shear-frame systems”, “mega column systems”, “mega core systems”, “outriggered frame systems”, and “tube systems” are used.

Rigid frame systems economically do not have sufficient resistance against lateral loads in buildings over 25 storeys because of bending on columns that causes large deformations. In this case, the total stiffness and so the economical height of the building can be increased by adding vertical shear trusses (braces) and/or shear walls to the rigid frame to carry the external shear induced by lateral loads (Figure 2.26).

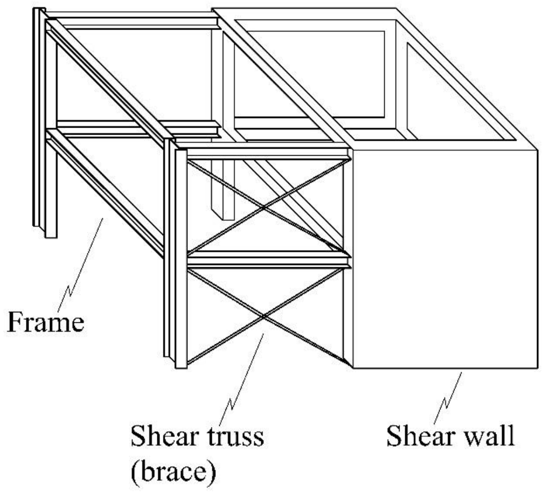


Figure 2.26 Rigid frame, shear truss (brace), and shear wall

This interactive system of frames and shear trusses and/or shear walls is called the “shear-frame system”, and is quite effective against lateral loads (Figure 2.27). In this context, shear-frame systems can be divided into two types:

- Shear trussed frame (Braced frame) system (Figure 2.27a)
- Shear walled frame system (Figure 2.27b)

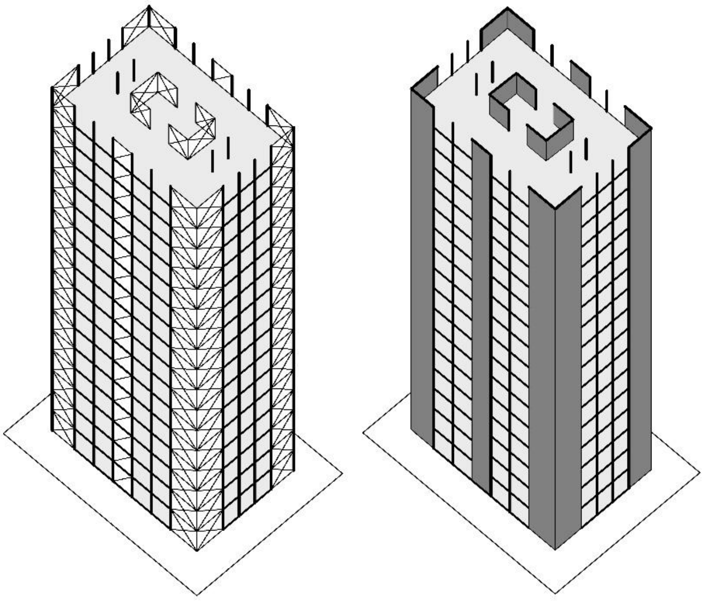


Figure 2.27 (a) Shear trussed frame (braced frame) system,
(b) Shear walled frame system

Today, for lateral bracing of supertall buildings, many structural systems and classifications are currently used in practice, and discussed in the literature (Smith and Coull, 1991; Taranath, 1998). However, the terms used for structural systems in the literature are different than each other though that is the same structural system. In this study, these systems are categorized based on the structure's resistance to lateral loads according to Gunel and Ilgın (2014).

Supertall building (namely 300 meter's height or greater) structural systems:

- Mega core systems
- Mega column (Mega frame, Space truss) systems
- Outriggered frame systems
- Tube systems
    - Framed-tube and diagrid-framed-tube systems
    - Trussed-tube systems
    - Bundled-tube systems

The number of floors that can be reached efficiently and economically by structural systems for tall buildings and supertall buildings is discussed in the literature (ACI SP-97, 1989; Gunel and Ilgın, 2014; Smith and Coull, 1991; Taranath, 1998). In this study, Table 2.1 is proposed according to Gunel and Ilgın (2014).

Table 2.1 Supertall building structural systems and the number of floors they can reach

Tall building structural systems, and tentatively the number of floors they can reach efficiently and economically	10	20	30	40	>40	>75
Rigid frame systems	■	■	■			
Flat plate/slab systems with columns and/or shear walls	■	■	■			
Core systems	■	■				
Shear wall systems	■	■	■	■		
Shear-frame systems (shear trussed / braced frame and shear walled frame systems)	■	■	■	■	■	
Mega core systems	■	■	■	■	■	■
Mega column (Mega frame, Space truss) systems	■	■	■	■	■	■
Outriggered frame systems	■	■	■	■	■	■
Tube systems	■	■	■	■	■	■

2.5.2.1 Mega core systems

Mega core systems consist of reinforced concrete or composite core shear walls with much larger cross-sections than normal, running continuously throughout the height of the building (Figure 2.28). Since the mega core can resist all vertical and lateral loads in this system, there is no need for columns or shear walls on the perimeter of the building. In mega core systems, floor slabs are cantilevered from the core shear wall (Figure 2.28a).

Mega core systems can also be used with strengthened cantilever slabs (Figure 2.28b). In this case, floor slabs are supported by the core shear walls and discontinuous perimeter columns. Perimeter columns are supported by strengthened cantilever slabs repeated on some stories. Strengthened cantilever slabs protrude from the core, and are strengthened in order to support the load coming from the stories above.

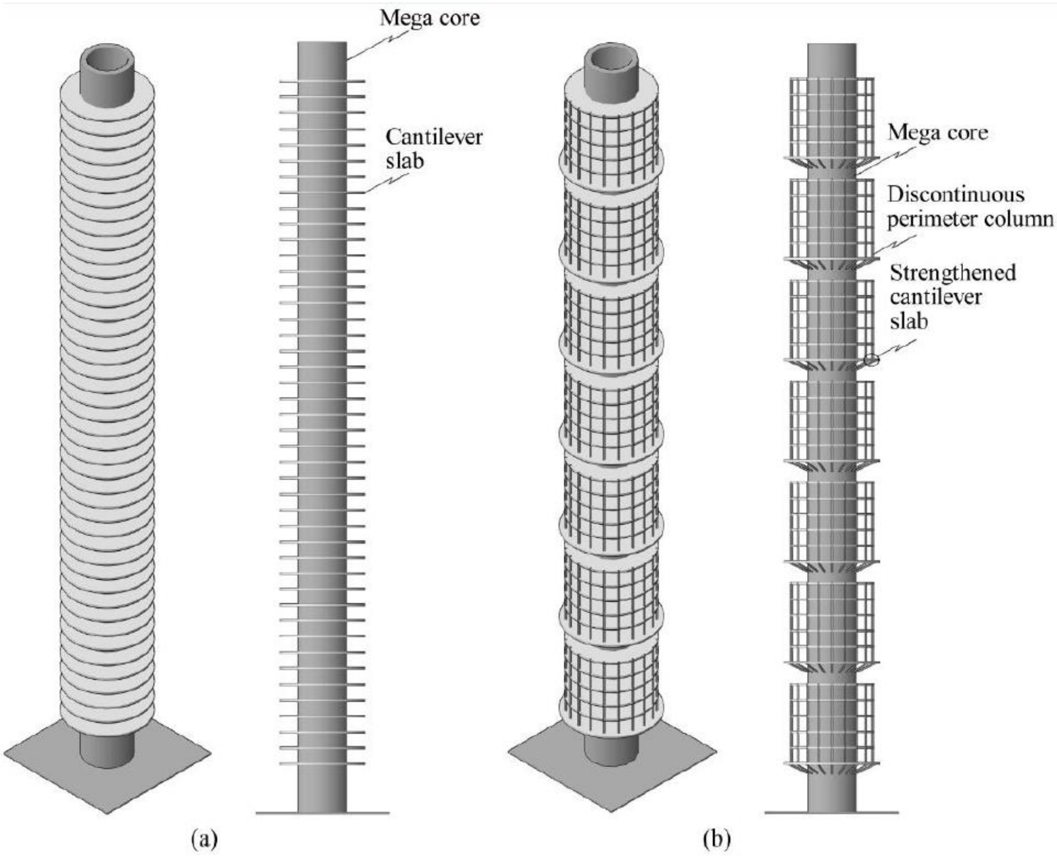


Figure 2.28 Mega core system: (a) cantilever slab, (b) supported cantilever slab

Mega core systems efficiently and economically provide sufficient stiffness to resist wind and earthquake induced lateral loads in buildings of more than 75 stories. Some examples of tall buildings using the mega core system with reinforced concrete structural material include:

the 57-story, 190m high *HSB Turning Torso* (Malmö, 2005) (Figure 2.29) which has a reinforced concrete core shear wall having circular cross-section with an external diameter varying between 15.6 to 11.4m (from bottom to top) and thickness varying between 2.5 to 0.4m (from bottom to top), and

the 36-story, 300m high *Aspire Tower* (Doha, 2006) (Figure 2.30) which has a reinforced concrete core shear wall having circular cross-section with an external diameter varying between 18 to13m (from bottom to top) and thickness varying between 2 to 1m (from bottom to top).

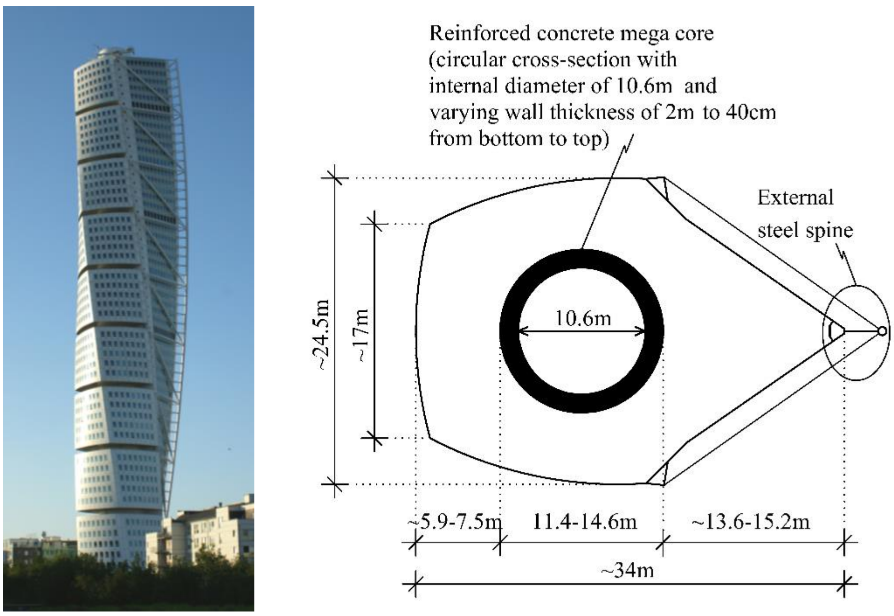


Figure 2.29 HSB Turning Torso, Malmö, 2005 (Gunel and Ilgın, 2014)

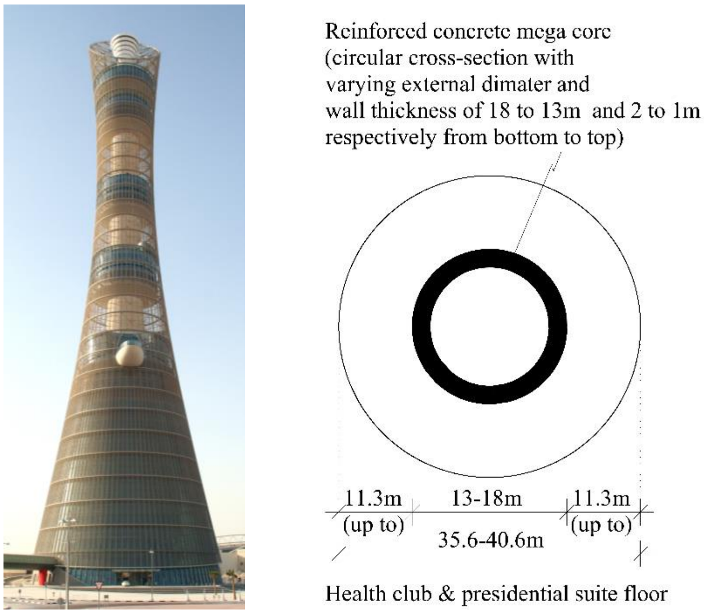


Figure 2.30 Aspire Tower, Doha, 2006 (Gunel and Ilgın, 2014)

2.5.2.2 Mega column (mega frame, space truss) systems

Mega column systems consist of reinforced concrete or composite columns and/or shear walls with much larger cross-sections than normal, running continuously throughout the height of the building. In this system, mega columns and/or mega shear walls can resist all the vertical and lateral loads (Figure 2.31).

In mega column systems, horizontal connections are of primary importance. Due to the probable insufficiency of floor slabs acting as rigid floor diaphragms, to support this behavior of restraining the columns laterally, belts, vierendeel frames, and mega braces are used. In this way, all external mega columns and/or shear walls are connected together to participate in the lateral stiffness of the structure (Figure 2.31).

Belts and vierendeel frames consist of at least one story depth horizontal shear trusses or shear walls that located at least two or more levels throughout the height of the building as in the case of the *Commerzbank Tower* (Frankfurt, 1997) (Figure 2.25a), which has 6 mega shear walls connected with vierendeel frames. Mega braces are multi-story diagonals that placed continuously throughout the height of the building (Figure 2.31).

According to the author, mega column systems, in their function and appearance, can also be named as “mega frame systems” (Figure 2.31); likewise, in some cases where there are mega braces supporting the mega columns, being reminiscent of a three dimensional truss, they can also be named as “space truss systems”.

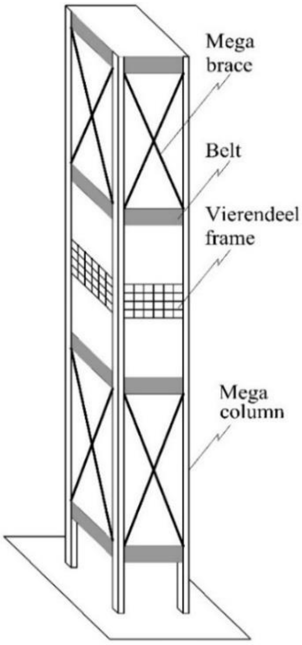


Figure 2.31 Mega column system

Figure 2.32 The Center,
Hong Kong, 1998
(www.ctbuh.org)

Mega column systems efficiently and economically provide sufficient stiffness to resist wind and earthquake induced lateral loads in buildings of more than 75 stories. Some examples of tall buildings using the mega column system with composite structural material include:

The 73-story, 346m high *Center* (Hong Kong, 1998) (Figure 2.32), which has 12 composite mega columns, of which the largest have square cross-sections of 2.5×2.5m at the ground floor.

Mega columns can also be used solely to provide large spaces at the building entrance, as an aid to the main structural system for the levels above the entrance, without running continuously throughout the height of the building. As the number of mega columns at the entrance is much lower than the number of columns on the upper stories, the structural transition between them is achieved using deep transfer beams.

In such cases, the cross-sectional dimensions of the column at the entrance are large enough for it to be classified as a "mega column", but the structural system cannot be classified as a "mega column system".

The 63-story, 283m high *Cheung Kong Centre* (Hong Kong, 1999), which has an outriggered frame system and 8 composite mega columns at the ground floor with 2.5m diameter circular cross-sections, is one of the most remarkable example of this case.

Mega columns, in cases where they run continuously throughout the height of the building, can be used with an outriggered frame system or a tube system. In such cases, when they are used for a purpose such as reducing the number of columns, the structural system cannot be classified as "mega column system", since the mega columns are not the only structural elements that resist the external loads.

The 101-story, 508m high *TAIPEI 101* (Taipei, 2004) (Figure 2.37), which has 8 composite mega columns at the ground floor with rectangular cross-sections of 2.4×3m, is one of the most remarkable example of this case.

2.5.2.3 Outriggered frame systems

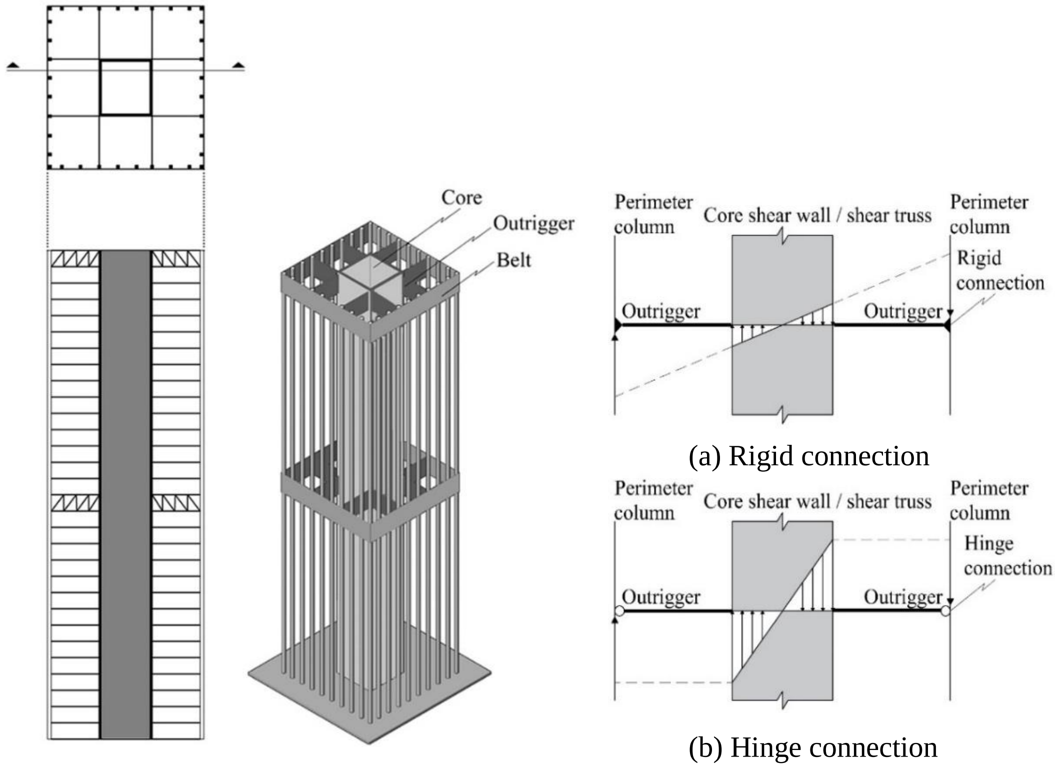
While outriggers have been utilized for about four decades, their existence as a structural member has a much longer history (Venkatesh and Ajitha, 2017). Outriggers have been used in the sailing ship industry for many years in order to resist wind.

As a consequence of the postmodern movement, the structural support systems of tall buildings began to moving from exterior to interior as in the case of outriggered frame systems (Al-Kodmany and Ali, 2016).

Outriggered frame systems have been developed by adding outriggers to shear-frame systems with core (core-frame systems) so as to couple the core with the perimeter (exterior) columns. The outriggers are structural elements connecting the core to the perimeter columns at one or more levels throughout the height of the building so as to stiffen the structure (Figure 2.33).

An outriggered frame system basically functions by tying together two structural systems- typically a rigid frame system on the perimeter and a core system to produce the whole structural behavior that is much better than those of component system. The benefits of the system lie in the fact that the overturning moments causing building deformations get reduced resulting, on the other hand, greater efficiency is achieved in resisting forces (Vijay *et al.,* 2017).

An outrigger consists of a horizontal shear truss or shear wall (or deep beam). This structural element is a horizontal extension of the core shear truss/wall to the perimeter columns in the form of a knee. To make them sufficiently effective, outriggers are at least one story deep, and have a high flexural and shear rigidity. Because the outriggers affect the interior space, they are generally located at the mechanical equipment floors in order to not to hinder the use of normal floors.



(a) Rigid connection

(b) Hinge connection

Figure 2.33 Outriggered frame system (Gunel and Ilgın, 2014)

The outriggers, which are connected rigidly to the core and by hinges to the perimeter columns, increase the effective flexural depth and so the flexural stiffness of the system in the direction of bending under lateral loads by enabling the core to receive support from the perimeter columns (Figure 2.33). The outrigger supports the core shear truss/wall against bending, creating axial tension and compression on the perimeter columns. In this way, the cantilever tube behavior of the system is ensured, and the stiffness of the shear-frame system is increased, while reducing the lateral drift of the building to a significant degree.

At the levels of the outriggers, connecting the perimeter columns to each other with belts, improves the efficiency of the system by equalizing the axial column loads along the perimeter. In this manner, the column which is connected to the core by the outrigger, distributes the axial load effect of the outrigger to other columns by means of the belt. A belt consists of a horizontal shear truss or shear wall (or deep beam) adequately stiff in flexure and shear, and of equal depth to the outrigger (Figure 2.33). In this way, all perimeter columns are connected together to participate in supporting the outriggers.

In cases where an outrigger is used at a single level throughout the height of the building, the most effective, and for this reason the optimum location for the outrigger is approximately 40-60% of the building height (Smith and Coull, 1991; Taranath, 1998). Addition of each new outrigger level increases the stiffness of the building, but by a smaller amount than the increase at the preceding level (Smith and Coull, 1991).

Outriggered frame system minimizes the obstruction created by large exterior structural frames, allowing freely articulation of the façade design. Owing to this functional benefits, the system offers flexibility in perimeter column arrangements and became popular for supertall buildings worldwide. On the other hand, there are some difficulties associated with the use of outriggers that limit the applicability of the concept in the real world:

- The space occupied by the outriggers (especially the diagonals) constraints on the use of the floors at which the outriggers are located. Even in mechanical equipment floors, the presence of outrigger members may be a main problem.
- Architectural and functional constraints might prevent location of large columns for outriggers where they could most appropriately be engaged by outrigger trusses extending out from the core.
- The connections of the outriggers to the core can be very complicated, especially when a concrete shear wall core is used.

Outriggered frame systems efficiently and economically provide sufficient stiffness to resist wind and earthquake induced lateral loads in buildings of more than 75 stories. Some examples of supertall buildings using the outriggered frame system with reinforced concrete structural material include:

- the 163-story, 828m high *Burj Khalifa* (Dubai, 2010) (Figure 2.34),
- the 98-story, 423m high *Trump International Hotel&Tower* (Chicago, 2009) (Figure 2.21e),
- *The* 88-story, 452m high *Petronas Twin Towers* (Kuala Lumpur, 1998) (Figure 2.35),
- the 91-story, 297m high *World Tower* (Sydney, 2004) (Figure 2.36),

with composite structural material include:

- the 101-story, 508m high *TAIPEI 101* (Taipei, 2004) (Figure 2.37),
- the 121-story, 632m high *Shanghai Tower* (Shanghai, 2015) (Figure 2.38),
- the 101-story, 492m high *Shanghai World Financial Center* (Shanghai, 2008)
  (Figure 2.39),
- the 123-story, 554m high *Lotte World Tower* (Seoul, 2017) (Figure 2.20f),
- the 62-story, 335m high *Wilshire Grand Center* (Los Angeles, 2017),
- the 112-story, 518m high *Evergrande IFC 1* (Hefei, under construction) (Figure 2.24b)

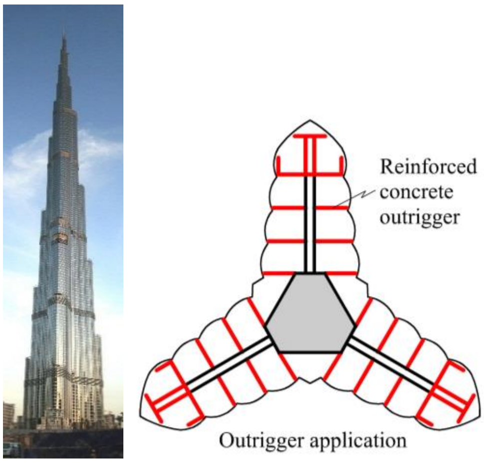


Figure 2.34 Burj Khalifa, Dubai, 2010
(Gunel and Ilgın, 2014)

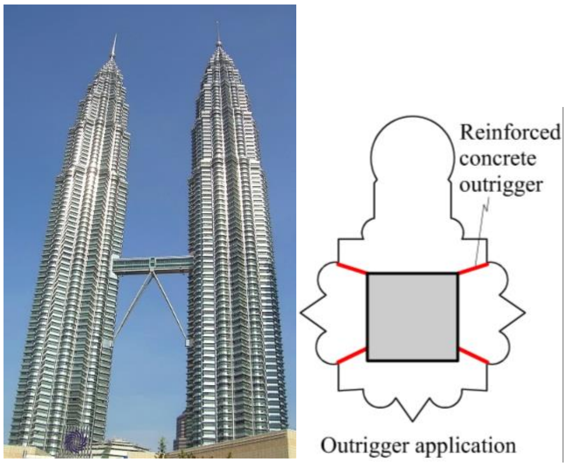


Figure 2.35 Petronas Twin Towers,
Kuala Lumpur, 1998
(Gunel and Ilgın, 2014)

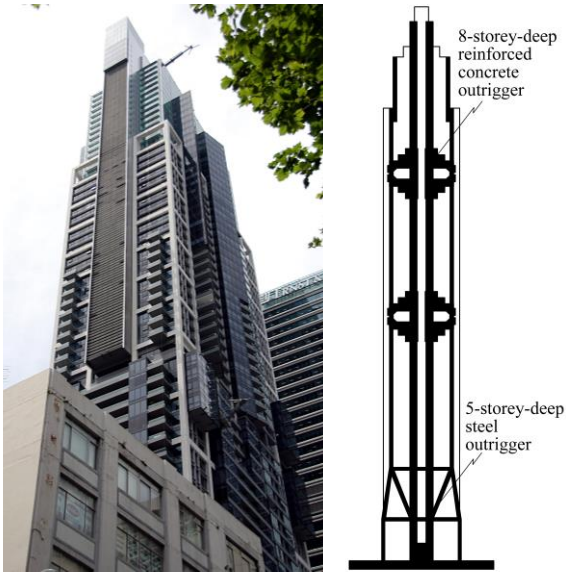


Figure 2.36 World Tower, Sydney, 2004
(Gunel and Ilgın, 2014)

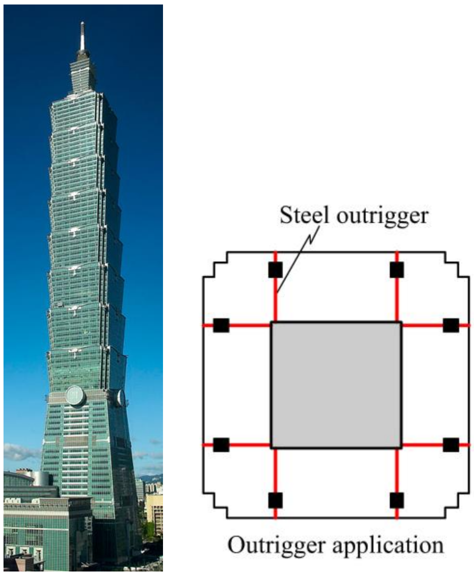


Figure 2.37 TAIPEI 101, Taipei, 2004
(Gunel and Ilgın, 2014)

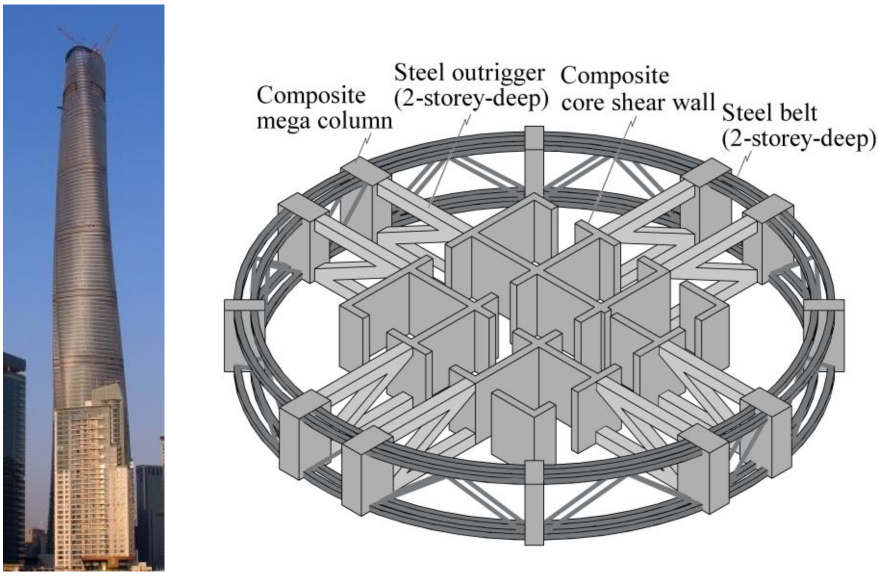


Figure 2.38 Shanghai Tower, Shanghai, 2015 (Gunel and Ilgın, 2014)

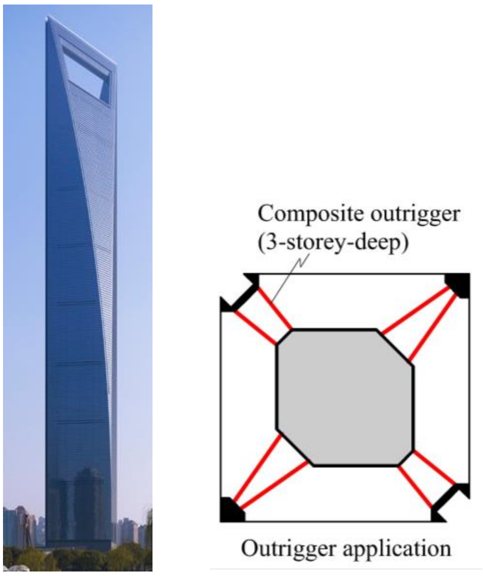


Figure 2.39 SWFC, Shanghai, 2008 (Gunel and Ilgın, 2014)

2.5.2.4 Tube systems

The tube system was innovated in the early 1960s by the famous structural engineer Fazlur R. Khan who is considered as the "father of tubular design" (Weingardt, 2011). Tube system can be likened to a system in which a hollow box column is cantilevering from the ground, and so the building exterior exhibits a tubular behavior against lateral loads. This system is evolved from the rigid frame system and can be defined as a three dimensional rigid frame having the capability of resisting all lateral loads with the facade structure. Tube system was used for the first time as the framed-tube system in the 43-story, 120m high *The Plaza on Dewitt* (Chicago, 1966) (Figure 2.40) by Fazlur R. Khan.

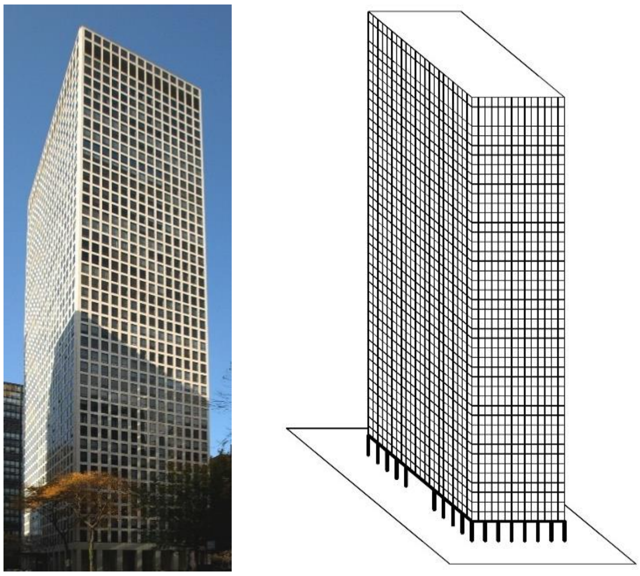


Figure 2.40 The Plaza on Dewitt, Chicago, 1966 (Gunel and Ilgın, 2014)

In tubular design, the rigidity of the structural system against lateral loads can be increased with solutions such as:

- decreasing the spacing of perimeter columns,
- increasing the depth of the spandrel beams connected to the perimeter columns,
- adding shear trusses / braces or shear walls to the core,
- adding an inner tube in place of the core (tube-in-tube),
- adding a truss (multi-story braces) to the building exterior (trussed-tube),
- combining more than one tube (bundled-tube).

In tube systems, the tube formed around the building exterior is designed to resist all lateral and vertical loads. If there is a structural core in the interior of the building, it is assumed to support some part of the vertical loads. Adding a second tube instead of a core can increase the stiffness of the structural system to support some part of the vertical and lateral loads.

As well as its structural efficiency, in a tube system it increases the net usable area of the building while reducing the dimensions of the structural elements in the core, owing to the tubular exterior frame supporting the entire lateral load. Tube systems can be used in several geometrical forms like rectangular, square, triangular, circular and even free-forms in the plan.

Tube systems efficiently and economically provide sufficient stiffness to resist wind and earthquake induced lateral loads in buildings of more than 75 stories.
Tube systems can be divided into three types:

- Framed-tube and diagrid-framed-tube systems
- Trussed-tube systems
- Bundled-tube systems

2.5.2.4.1 Framed-tube systems

The framed-tube systems, which constitute the basis of tube systems, can be described as having evolved from rigid frame systems and are alternative to shear-frame systems. The most significant feature of the system, also known as the "vierendeel tube system" or "perforated tube system", is the closely spaced perimeter/exterior columns, which are usually spaced at 1.5 to 4.5m centres, connected by deep spandrel beams at floor levels. If there is a need to increase the column spacing, in order to secure the behavior of the framed-tube system, it is necessary to increase the dimensions of the perimeter columns and spandrel beams.

The dimensions and spacing of the columns and the flexural rigidity of the spandrel beams directly affect the tubular behavior of the framed-tube system. In the framed-tube system, pure tubular cantilever behavior cannot be fully achieved because of the flexibility of the spandrel beams so that there can be slight bending deformation while transferring the shear forces to the columns. The real behavior of the system is between the behavior of a vertical cantilever and that of a frame.

Limited flexural and shear rigidity (flexibility) of the spandrel beams results in bending deformation, so the axial stresses in the corner perimeter columns increase while they decrease in the inner perimeter columns. In this way, the distribution of axial compressive and tensile stresses formed in the perimeter columns in response to the lateral loads cannot be linear (Figure 2.41). This phenomenon is known as "shear lag", which depends upon the stiffness of the spandrel beam. Making the spandrel beams deeper and the perimeter columns more closely spaced mitigates the "shear lag" phenomenon. Placing the long sides of the rectangular columns' cross-sections along the building facade also contributes positively to the stiffness of the spandrel beams.

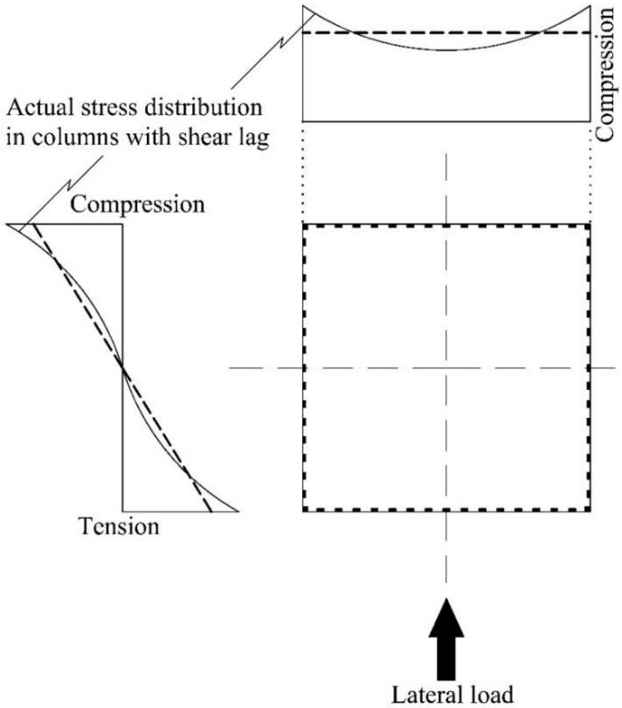


Figure 2.41 Tension and shear lag in perimeter columns in a framed-tube system

The behavior of the framed-tube system is obtained by placing the perimeter columns usually at 1.5 to 4.5m centers. Closely spacing the perimeter columns and increasing the depth of the spandrel beams may test the height limits of the framed-tube system. For example, the 110-story, 415/417m high *World Trade Center Twin Towers* (New York, 1972) (Figure 2.42), the perimeter columns were spaced at 1.02m centers with 0.66m in clear span.

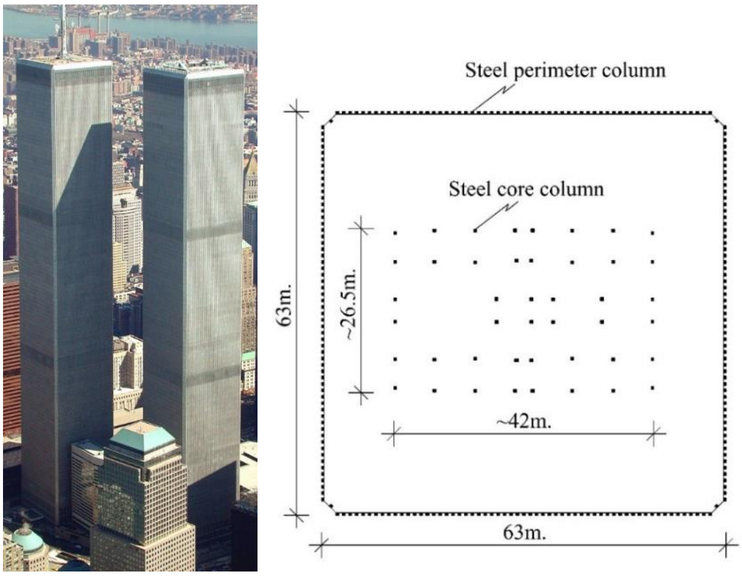


Figure 2.42 World Trade Center Twin Towers, New York, 1972 (Gunel and Ilgın, 2014)

Figure 2.43 Torre Glories Barcelona, 2004 (www.ctbuh.org)

Closely spaced perimeter columns can obstruct the panoramic exterior view from inside the building and, at the ground floor, inhibit the creation of inviting public spaces with wide entrances such as lobbies and shopping centers. As a solution, with the aim of preventing the difficulties of access experienced when passing through these spaces at the building entrance, deep transfer arches or beams can be used, as in the

- 42-story, 183m high *U.S. Bank Center* (Milwaukee, 1973);

or branching columns can be used, as in the

- 110-story, 415/417m high *World Trade Center Twin Towers* (New York, 1972)

(Figure 2.42). Below the transfer levels formed by transfer beams and branching columns, closely spaced columns are replaced with widely spaced columns.

Some examples of tall buildings using the framed-tube system with steel structural material include:

- the 110-story, 415/417m high *World Trade Center Twin Towers* (New York, 1972) (Figure 2.42), and

  with reinforced concrete structural material include:
- the 85-story, 425m high *432 Park Avenue* (New York, 2015) (Figure 2.15a)
- the 35-story, 144m high *Torre Glories* (Barcelona, 2004) (Figure 2.43).

The diagrid-framed-tube system is one of the representative structural systems for supertall buildings, which had been predicted by Khan (1982) as a revival in *Structural Expressionism* in recent years (Moon, 2015a).

The innovations in computational design and construction techniques by 1980s, gave way to the realization of diagrid-framed-tube system, which was once developed in 1970s, but could not be built due to the constructional incapacities until the 2000s (Sev and Tugrul, 2014).

While trussed-tube system has been used in taller buildings more frequently than diagrid-framed-tube system historically, as the height of the tall buildings increases this system become more popular (Korsavi and Maqhareh, 2014).

The first utilization of the diagrid-framed-tube system was the *United Steelworkers Building* (Pittsburg, 1963) (Figure 2.44a). Nevertheless, this advanced structural form could not be improved until the construction of *30 St Mary Axe* (London, 2004) (Figure 2.44b) (Sev and Tugrul, 2014).

This system can be formed by using closely spaced diagonal braces instead of vertical columns (Figure 2.44). The diagrid-framed-tube system is also called as lattice-like system consisting of “light” diagonal elements, which also making a building stiffer and often lighter than a traditional tall buildings.

It is defined also as the structural system which creates triangulated structural geometry at the exterior surface of the building with the help of diagonally supporting beams (Deshpande *et al.*, 2015). The diagrid-framed-tube system is more effective against lateral loads than the conventional framed-tube system. Placing the elements in a closely spaced diagrid pattern provides sufficient resistance against vertical and lateral loads.

The diagrid-framed-tube system is much more effective in terms of minimizing shear deformation since the system can carry shear by axial action of the diagonal members; while framed-tube system carries shear by the bending of the vertical columns and horizontal spandrels, which makes it less efficient than this system (Moon *et al.*, 2007).

While the shear forces caused by lateral loads are met by the bending strength of the columns and beams in the framed-tube system, in the diagrid-framed-tube system they are met by the axial compressive and tensile strength of the diagonal braces. In tall buildings where lateral loads are critical, shear forces are met by axial deformation of the diagonal braces instead of bending deformation of the beams and columns, which significantly increases the efficiency of the structural system. Due to their triangular configuration, the system can effectively carry the shear and moment caused by lateral loads and gravity (Ali and Moon, 2007).

Since an extremely different structural efficiency can be achieved depending on different diagrid configurations, determining geometric configuration is even more important when the diagrid-framed-tube system is utilized for a tall building (Moon, 2012). The optimal uniform angles range from 60º to 70º for tall buildings with the height-to-width aspect ratios ranging from about 4 to 10 (Moon *et al.*, 2007).

The diagrid-framed-tube system can suffer from problems of implementation because of its complex steel joists but recent advances in joint detailing and prefabrication are to address this issue. On the other hand, this system has the potential to eliminate the need for interior columns, facilitating more flexible interior design layout.

Korsavi and Maqhareh (2014) stated that "The steel diagrid, in its ability to create a 'mesh', is capable of conforming to almost any shape that can be created using modern 3-D modelling software." Unconventional forms become buildable owing to its resistance to seismic forces and structural efficiency (Al-Kodmany and Ali, 2016). Moreover, it has the potential of creating unprecedented visual aesthetics in the design as in the case of Dubai's proposed *Cypertecture Sphere* (Figure 2.44j) and Mumbai's proposed *Cypertech Egg* (Figure 2.44k).

Particularly, in the diagrid-framed-tube system with irregular pattern, with changing structural forces, structural pattern for the façade could modify as the building rises, which shows the flow of forces in the structure like a blend of structural functionality and aesthetics. This make the façade's pattern not only ornamental but also structurally meaningful as in the case of Zaha Hadid's *Morpheus* (Macau, 2017) (Figure 2.44h) with its irregular diagrid pattern and Zaha Hadid's *Dorobanti Tower* (Bucharest, vision) (Figure 2.44i) with parametric diagrid pattern.

Unlike other diagrid-framed-tube structures in which diagrid members are usually placed at uniform angles, the diagonals at the *Lotte Super Tower Hotel* (Seoul, 2008, design completion) (Figure 2.49d) are placed at different angles over the tower's height. The diagrid angles become steeper toward the ground in order to resist overturning moments more efficiently there and shallower toward the top, where the impact of lateral shear forces is larger (Moon, 2008).

The diagrid-framed-tube system can be divided into groups: *the large* and *the small*. The flexibility of the diagrid enables building to accommodate the size with ease in a particular context (Al-Kodmany and Ali, 2016).

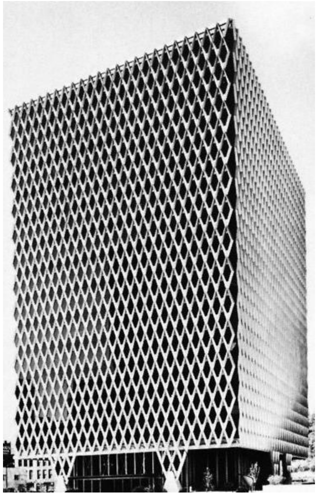
- *The Bow* (Calgary, 2012) (Figure 2.44f) with 6-story-high diagrids and
- *HQ* (Abu Dhabi, 2010) (Figure 2.44g) with also 6-story-high diagrids

are the most spectacular examples of “the large” type.

In contrast,

- *30 St Mary Axe* (London, 2004) (Figure 2.44b) and
- *Capital Gate Tower* (Abu Dhabi, 2011) (Figure 2.19b)

with its finer diagrid arrangement is one of the most remarkable examples of “the small” type (Figure 2.19b).



(a)

(b)

(c)

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(e)

(f)

(g)

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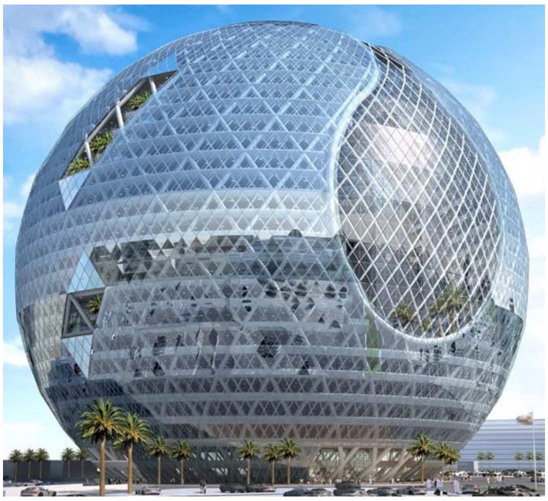
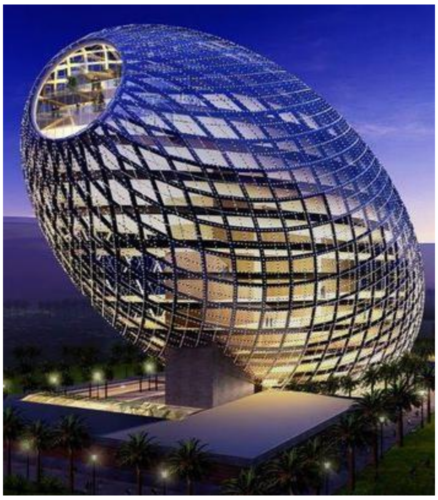


(j)



(k)

Figure 2.44 (a) United Steelworkers Building, Pittsburg, 1963 (www.pinterest.com);
(b) 30 St Mary Axe, London, 2004 (www.ctbuh.org);
(c) O-14, Dubai, 2010 (www.ctbuh.org);
(d) Mode Gakuen Cacoon Tower, Tokyo, 2008 (www.ctbuh.org);
(e) Guangzhou International Finance Center, Guangzhou, 2010 (www.ctbuh.org);
(f) The Bow, Calgary, 2012 (www.ctbuh.org);
(g) HQ, Abu Dhabi, 2010 (www.ctbuh.org);
(h) Morpheus, Macau, 2017 (www.ctbuh.org);
(i) Dorobanti Tower, Bucharest, vision (www.pinterest.com);
(j) Cypertecture Sphere, Dubai, proposed (www.designboom.com);
(k) Cypertech Egg, Mumbai, proposed (www.pinterest.com)

Some examples of tall buildings using the diagrid-framed-tube system with steel structural material include:

- the 40-story, 180m high *30 St Mary Axe* (London, 2004) (Figure 2.44b),
- the 50-story, 204m high *Mode Gakuen Cacoon Tower* (Tokyo, 2008) (Figure 2.44c),

  with reinforced concrete structural material include:

- the 24-story, 106m high *O-14* (Dubai, 2010) (Figure 2.44d),

  and with composite structural material include:

- the 103-story, 439m high *Guangzhou International Finance Center* (Guangzhou, 2010) (Ali and Moon, 2007) (Figure 2.44e).

All the abovementioned buildings are the most spectacular examples of *Structural Expressionism* since they vividly present their structural systems in an aesthetically appealing way and emphasize the ingenuity behind structural logic having the potential of great contribution to the building's overall visual quality. For these and also other similar structures, the structural aspects that mostly resist lateral forces become an important design parameter.

2.5.2.4.2 Trussed-tube (braced-tube) systems

In the framed-tube system, closely spaced perimeter columns can obstruct the panoramic exterior view from inside the building. In order to increase the spacing between the columns without inhibiting the tubular behavior, connecting the perimeter columns with exterior multi-story braces, led to the development of the trussed-tube system (Figure 2.45a-b).

Adding braces to the exterior of the framed-tube system makes it approach very closely pure tubular cantilever behavior by increasing the structural stiffness, effectiveness, and reduces the negative effect of the "shear lag" caused by the flexibility of the spandrel beams. An angle of about 35° produces the maximum shear rigidity for trussed-tube system (Moon, 2010).

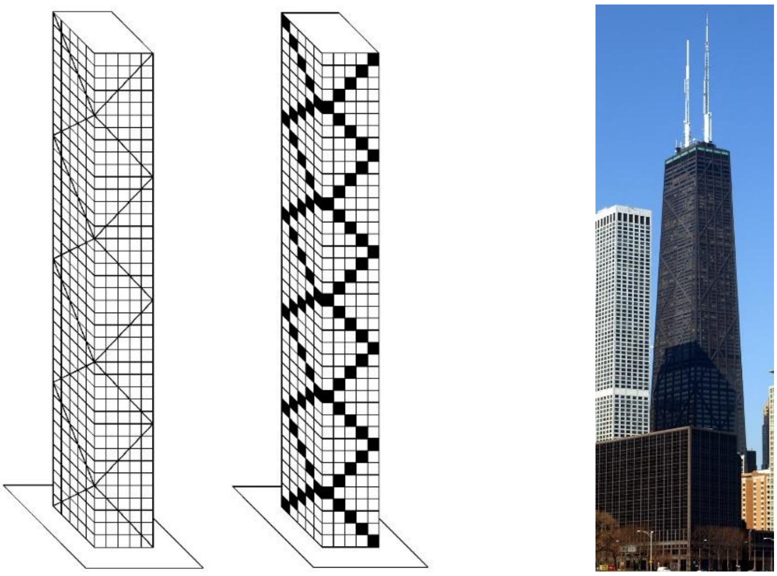
In buildings with steel or composite trussed-tube systems, multi-story braces are used on the facade of the building (Figure 2.45a). These mega braces allow their respective supertalls to be distinguishable from a far distance, qualifying them as urban landmarks.

In the case of buildings with reinforced concrete trussed-tube systems, spaces between the columns are filled with reinforced concrete shear walls to form multi-story diagonal or X-brace pattern on the exterior of the building (Figure 2.45b).

Compared with the framed-tube system, the trussed-tube system gives scope for increasing the height of the structure with wider spacing between columns, as in the case of

- the 100-story, 344m high *John Hancock Center* (Chicago, 1969) (Figure 2.45c),
- and the 63-story, 279m high *601 Lexington* (New York, 1977)

with maximum column spacing of 13.3m and 11.5m centers, respectively.



(a) (b) (c)

Figure 2.45 (a) Steel or composite trussed-tube system;
(b) Reinforced concrete trussed-tube system;
(c) John Hancock Center, Chicago, 1969 (www.ctbuh.org)

Fazlur R. Khan used the trussed-tube system for the first time in the 100-story, 344m high *John Hancock Center* (Chicago, 1969), with a steel structural system (Figure 2.45c). The 50-story, 174m high *780 3rd Avenue* (New York, 1983) (Figure 2.46d) was the first reinforced concrete building in which a trussed-tube system was used.

Fazlur R. Khan emphasized that the exterior braces, which made it possible to have wide spaces between the columns, would behave like inclined columns, and moreover they transferred load to or from the columns by allowing redistribution of the stresses resulting with almost evenly load distribution in the columns. According to Khan, this system would increase the structural system's efficiency and that this would allow the construction of supertall buildings.

The external nature of trussed-tube system, as in the case of framed-tube-diagrid system, can visually communicate the inherent structural logic of a supertall building while serving as a medium of the effect with aesthetically pleasing, geometrically coherent and also respecting the laws of physics and mechanics. *John Hancock Center* (Chicago, 1969) (Figure 2.45c) is one of the best example of this approach.

While trussed-tube systems and diagrid-framed-tube system have the similar logic in terms of lateral load transfer mechanism, trussed-tube system tends to more efficient than the other for mega tall buildings owing to large height-to-width aspect ratio. On the other hand, as alluded before, compared to brace elements in trussed-tube system diagrid elements are lighter and less obstructive (Al-Kodmany and Ali, 2016).

Some examples of tall buildings using the trussed-tube system with composite structural material include:

- the 72-story, 367m high *Bank of China Tower* (Hong Kong, 1990) (Figure 2.8),
- the 108-story, 528m high *Citic Tower* (Beijing, under construction) (Figure 2.46a)
- the 54-story, 234m high *CCTV Headquarters* (Beijing, 2012) (Figure 2.46b), and
- the 128-story, 596m high *Goldin Finance 117* (Tianjin, under construction) (Figure 2.46c),

with reinforced concrete structural material include:

- 50-story, 174m high *780 3rd Avenue* (New York, 1983) (Figure 2.46d),
- 58-story, 174m high *Onterie Center* (Chicago, 1986),

and with steel structural material include:

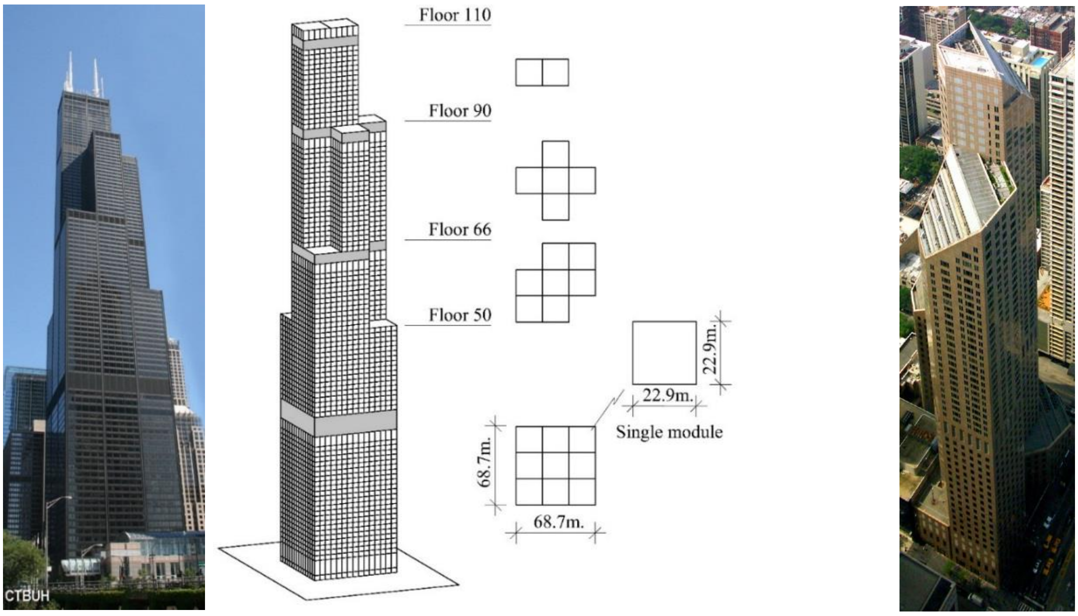
- 52-story, 224m high *The Leadenhall Building* (London, 2014) (Figure 2.46e).

(a) (b) (c) (d) (e)

Figure 2.46 (a) Citic Tower, Beijing, under construction (www.ctbuh.org);
(b) CCTV Headquarters, Beijing, 2012 (www.ctbuh.org);
(c) Goldin Finance 117, Tianjin, under construction (www.ctbuh.org);
(d) 780 3rd Avenue, New York, 1983 (www.ctbuh.org);
(e) The Leadenhall Building, London, 2014 (www.ctbuh.org)

2.5.2.4.3 Bundled-tube systems

Bundled-tube systems are a combination of more than one tube (framed-tube and/or trussed-tube) acting together as a single tube (Figure 2.47). Like the framed-tube and trussed-tube systems, the bundled-tube system was also innovated by the structural engineer Fazlur R. Khan. Among the advantages of the bundled-tube system are: the securing of architectural freedom owing to the ability to create tubes of different heights in the system; the attainment of higher building heights and wider column spaces than in framed-tube systems; and the ability to control the aspect ratio.



(a) (b)

Figure 2.47 (a) Willis Tower, Chicago, 1974 (Gunel and Ilgın, 2014);
(b) One Magnificent Mile, Chicago, 1983 (www.ctbuh.org)

In the bundled-tube system, setbacks with floor plans of different shapes and dimensions are obtained by ending tubes at the desired levels. Single tubes in the system can be arranged together in different shapes such as rectangles and triangles, and thus different forms can be created.

As the heights of buildings increase, in general their aspect ratios also increase. The increase in the aspect ratio increases the slenderness and flexibility of the building, and thus its lateral drift. In order to keep control of the aspect ratio, it is necessary to increase the cross-sectional dimensions of the base, which affects the denominator in this ratio.

Bundled-tube systems consist of two or more tubes, where the tubes can rise to different levels of the building height (Figure 2.47). Thus, in bundled-tube systems, the increase in the cross-sectional dimensions at the ground floor in order to control the slenderness of the building makes it possible to reduce the cross-sectional dimensions by different amounts throughout the height of the building.

In bundled-tube systems formed from framed-tubes and/or trussed-tubes, greater building heights and wider column spaces are obtained than in framed-tube systems. For example, in the *Willis Tower* (Chicago, 1974) (Figure 2.47a), which has 9 framed-tubes, the spaces between the columns are much greater than the column spaces in a framed-tube building of the same height.

While the 110-story, 415/417m high *World Trade Center Twin Towers* had perimeter columns spaced at 1.02m centers, the 108-story, 442m high *Willis Tower* has perimeter columns spaced at 4.6m centers.

Some examples of tall buildings using the bundled-tube system with steel structural material include:

- the 108-story, 442m high *Willis Tower* (Chicago, 1974) (Figure 2.47a),
  with reinforced concrete structural material include:
- the 57-story, 205m high *One Magnificent Mile* (Chicago, 1983) (Figure 2.47b).

2.6 Aerodynamic Design Considerations

As the height of today supertall buildings rises with developments in the field of structural system design and the use of high-strength materials, their weight and rigidity decrease, and their slenderness and flexibility - and thus their sensitivity to wind loads - increase.

Wind loads, which cause large lateral drift, play a critical role in the design of supertall buildings, and can be even more critical than earthquake loads. As a result, the wind loads and lateral drift to which supertall buildings are subject have become an important problem.

Form determines the aerodynamic behavior of the building consequential to the natural forces acting on it. In this context, aerodynamic design considerations have to be considered in the early/schematic design and planning stages of supertall buildings. These considerations can be divided into two main categories as follows (Gunel and Ilgın, 2014; Kareem *et al.*, 1999; Schueller, 1977; Irwin, 2009):

- Aerodynamic architectural design (major modifications)
    - building orientation (position)
    - aerodynamic form
    - plan variation
    - aerodynamic top
- Aerodynamic architectural modifications (minor modifications)
    - corner modifications
    - air passes

2.6.1 Aerodynamic architectural design

Aerodynamic architectural design is realized by taking into consideration matters such as “building orientation (position)”, “aerodynamic form”, “plan variation”, and “aerodynamic top”. Aerodynamic architectural design plays an important role in reducing the effect of wind on tall buildings (Gunel and Ilgın, 2014; Ali and Armstrong, 1995; Holmes, 2001; Irwin, 2009; Irwin *et al.*, 2006; Irwin *et al.*, 2008a; Irwin *et al.*, 2008b; Kareem *et al.*, 1999; Schueller, 1977; Scott *et al.*, 2005; Al-Kodmany and Ali, 2016). This reduction is generally in the region of 20-30%, but can even exceed 50% (Kim *et al.*, 2008; Scott *et al.*, 2005). These approaches are described below.

2.6.1.1 Building orientation

Orienting the building according to the prevailing wind direction is an effective design approach for reducing wind loads. A reduction of between 10-20% of the across-wind building response can be obtained by rotating the building to within 10º of the wind direction (Scott *et al.,* 2005). The effectiveness of this approach is dependent on both the wind climate at the project site and the shape of the building. In wind climates with very directional extreme winds and building shapes that are directionally sensitive this is more effective than, say, for a more regularly shaped building in a wind climate without strong directional characteristics.

2.6.1.2 Aerodynamic form

Gradually, architects and engineers are interested in creating aerodynamic forms that streamline the wind flow to improve a supertall building’s performance in regards to wind resistance, in particular higher altitudes where wind forces become amplified. The utilization of aerodynamic forms is an effective method of reducing the wind loads on buildings. In this context, cylindrical, elliptical, conical, and twisted forms can be accepted among the efficient building forms.

Because cylindrical buildings have a smaller surface perpendicular to the wind direction, the wind pressure is less than in prismatic buildings. For buildings having circular plan form, the wind load is about 20% less, compared with buildings having a rectangular plan form (Taranath, 2005).

Buildings with elliptical plans also exhibit similar behavior to buildings with circular plans as in the case of *Le France Building* in Paris. Owing to its elliptical form, the wind load could be reduced by 27% (Schueller, 1977). Twisted forms are effective in reducing vortex-shedding induced dynamic response of tall buildings by disturbing vortex shedding (Amin and Ahuja, 2010).

From aerodynamic point of view, in particular the across-wind direction, it should be noted that twisted forms and irregular free forms generally performs better than a comparable prismatic one, as it can mitigate wind-induced vibrations by disturbing the development of organized alternating vortexes (Moon, 2011; Moon, 2015a). Since the twisted form is rotated as it rises, the building form itself helps to reduce the lateral force by confusing the wind loading (Park, 2005).

Examples of buildings with aerodynamic forms include:

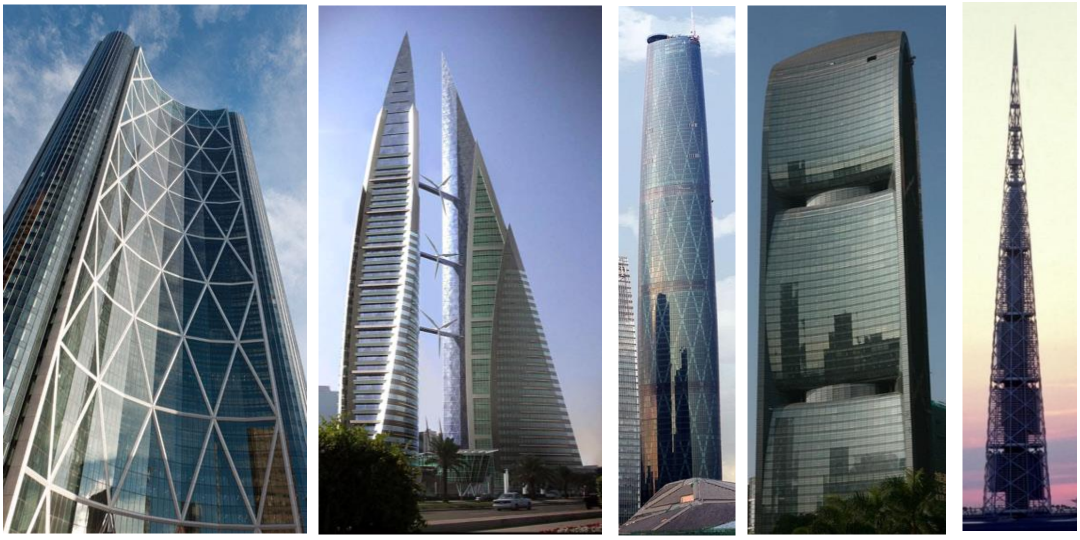
- *30 St Mary Axe* (London, 2004) (Figure 2.44b) with a cylindrical form (Al-Kodmany and Ali, 2016),
- *The Bow* (Calgary, 2012) (Figure 2.48a) with crescent-shaped plan (Al-Kodmany and Ali, 2016),
- *The Bahrain World Trade Center* (Manama, 2008) (Figure 2.48b) with a sail-shaped form (Gunel and Ilgın, 2014),
- *Guangzhou International Finance Center* (Guangzhou, 2010) (Figure 2.48c) with curved triangular form with corner tapering (Kwok and Lee, 2016; Wilkinson, 2016; Wilkinson, 2012),
- The *Chicago Spire* (Chicago, never completed) (Figure 2.22d), *Shanghai Tower* (Shanghai, 2015) (Figure 2.38), and *Cayan Tower* (Dubai, 2013) (Figure 2.22b) (Amin and Ahuja, 2010), all of which have twisted forms,
- *Al Hamra Tower* (Kuwait, 2011) (Figure 2.23a) with its sculpted form (Ahci and Sarkisian, 2011),
- *Pearl River Tower* (Guangzhou, 2013) (Figure 2.48d) with its aerodynamic sculpted curvilinear form funneling air through the wind turbines (Daraphet, 2013; Tomlinson II *et al.*, 2014),
- Norman Foster's proposal of a conical form for *The Millennium Tower* (Tokyo, 1989, proposed) (Figure 2.48e) (Kareem *et al.*, 1999; Gunel and Ilgın, 2014),
- *Absolute World Complex* (Mississauga, 2012) (Figure 2.48f) with its naturally aerodynamic fluid form (torsional form) adeptly handling wind loads (Lagendijk *et al.*, 2012),

- *Mode Gakuen Cacoon Tower* (Tokyo, 2008) (Figure 2.48g) with elliptical shape aerodynamically scattering tough wind streams (Tange and Minami, 2009),
- *Haeundae I'Park* (Busan, 2011) (Figure 2.48h) with theirs sculpted curvilinear shapes (Swickerath and Tillson, 2011),
- *Greenland Suzhou Center* (Wujiang, under construction) (Figure 2.48i) with its elliptical shape (Wimer *et al.*, 2012),
- *Shreepati Skies Tower* (Mumbai, proposed) (Figure 2.48j) with its cylindrical shape (Amin and Ahuja, 2010).

Owing to the façade channels made possible by the twisted form of the design of the *Chicago Spire* (Chicago, never completed) (Figure 2.48e), the effect of wind on the building is blocked by breaking up the wind flow and so wind-induced lateral loads are reduced (Amin and Ahuja, 2010; Tomasetti, 2007).

In *Al Hamra Tower* (Kuwait, 2011) (Figure 2.23a), owing to uneven cuts, organized vortex shedding is disrupted, which result in confusion of applied wind loads (Ahci and Sarkisian, 2011).
Capital Gate Tower (Abu Dhabi, 2011) (Figure 2.19b) with its rounded aerodynamic organic form, presents less resistance to wind than a rectangular building, thereby requiring less structure for lateral loads (Schofield, 2012).

In *Cayan Tower* (Dubai, 2013) (Figure 2.22b), the variation in the building silhouette over its height creates a constantly changing frontal wind sail dimension as the building ascends, acting to disorganize the wind forces. When compared to a similar building taken as a straight extrusion without twist, it is estimated that the twisted form of the *Cayan Tower* (Dubai, 2013) reduced the structure's across-wind excitation by some 25% or more (Baker *et al.*, 2010).



(a) (b) (c) (d) (e)

(f) (g) (h) (i) (j)

Figure 2.48 (a) The Bow, Calgary, 2012 (www.ctbuh.org);
(b) Bahrain Word Trade Center, Manama, 2008 (Gunel and Ilgın, 2014);
(c) Guangzhou International Finance Center, Guangzhou, 2010 (www.ctbuh.org);
(d) Pearl River Tower, Guangzhou, 2013 (www.ctbuh.org);
(e) The Millennium Tower, Tokyo, 1989, proposed (www.ctbuh.org);
(f) Absolute World Complex, Mississauga, 2012 (www.ctbuh.org);
(g) Mode Gakuen Cacoon Tower, Tokyo, 2008 (www.ctbuh.org);
(h) Haeundae I’Park, Busan, 2011 (www.ctbuh.org);
(i) Greenland Suzhou Center, Wujiang, under construction (www.ctbuh.org);
(j) Shreepati Skies Tower, Mumbai, proposed (www.pinterest.com)

2.6.1.3 Plan variation

Varying the building plan results from the variation in plan dimensions or shape throughout the height of the building, and can be achieved by:

- reducing the plan area
- changing the plan shape

a- Plan variation by reducing the plan area toward the top of the building results in a reduction in the surface area affected by the wind at the upper levels of the building, which lessens the wind intensity and thus the excess pressure. The reduction in the plan area of the building as it rises can be in the form of:

- tapering
- setbacks

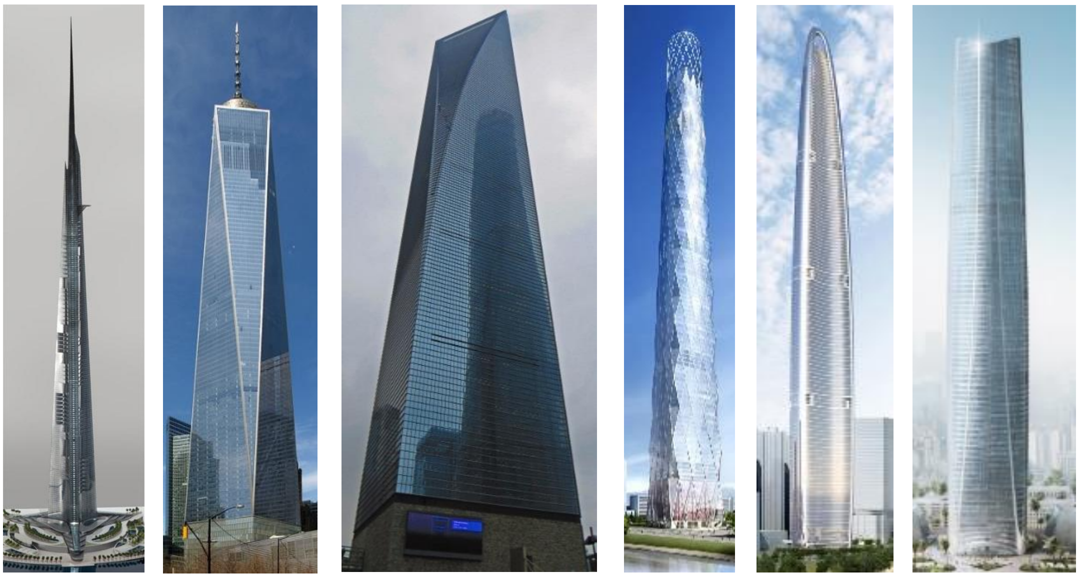
Creating an inward-tapered façade or providing setbacks are effective methods for reducing the across-wind building response (Schueller, 1977; Ali and Armstrong, 1995; Cooper *et al.*, 1997; Scott *et al.*, 2005; Irwin, 2008; Irwin *et al.*, 2008a; Irwin *et al.*, 2008b; Kim *et al.*, 2008; Irwin, 2009; Amin and Ahuja, 2010; Tanaka *et al.*, 2013; Gunel and Ilgın, 2014; Alaghmandan *et al.*, 2014; Hansora *et al.*, 2015; Moon, 2015a; Moon, 2015b).

Owing to the utilization of tapering effect in tall buildings, lateral drift can be reduced by 10 to 50% (Schueller, 1977). An analytical study by Khan (1972) has shown that, by creating a slope of 8% in the façade of a 40-story building, a 50% reduction of the lateral drift in the upper stories can be obtained. Tapered forms also reduce the downward wash of turbulent wind gusts that often exists around tall buildings (Nordenson and Riley, 2003; Park, 2005).

Similar to *Burj Khalifa* (Dubai, 2010) (Figure 2.21d), *Jeddah Tower* (Jeddah, under construction) (Figure 2.49a) with continuous tapered “Y” shaped plan “confuses the wind” by reducing the cross-sectional size of the building as it rises, namely tapering affect (Weismantle and Stochetti, 2013).

Examples of buildings with tapering include:

- the *John Hancock Center* (Chicago, 1969) (Figure 2.20a),
- the *Chase Tower* (Chicago, 1969) (Figure 2.20d),
- the *One World Trade Center* (New York, 2014) (Figure 2.49b) (Lewis and Holt, 2011),
- the *Shanghai World Financial Center* (Shanghai, 2008) (Figure 2.49c),
- the *Lotte Super Tower Hotel* (Seoul, 2008, design completion) (Figure 2.49d) (Moon, 2015b),
- the *Wuhan Greenland Center* (Wuhan, under construction) (Figure 2.49e) (Viise et al., 2012),
- the *Haikou Tower 1* (Haikou, under construction) (Henn, 2016) (Figure 2.49f).



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

Figure 2.49 (a) Jeddah Tower, Jeddah, under construction (www.ctbuh.org);
(b) One World Trade Center, New York, 2014 (www.ctbuh.org);
(c) Shanghai World Financial Center, Shanghai, 2008 (www.ctbuh.org);
(d) Lotte Super Tower Hotel, Seoul, 2008, design completion (Moon, 2015b);
(e) Wuhan Greenland Center, Wuhan, under construction (www.ctbuh.org);
(f) Haikou Tower 1, Haikou, under construction (www.ctbuh.org)

Buildings in which setbacks have been used to reduce the plan area:

- the *Petronas Twin Towers* (Kuala Lumpur, 1998) (Figure 2.21a),
- the *Bank of China Tower* (Hong Kong, 1990) (Figure 2.21b),
- the *Willis Tower* (Chicago, 1974) (Figure 2.21c), and
- the *Trump International Hotel&Tower* (Chicago, 2009) (Figure 2.21e) (Baker *et al.*, 2009),
- the *Burj Khalifa* (Dubai, 2010) (Figure 2.21d)

Among these examples, aerodynamic form played an important role in the architectural design of the *Burj Khalifa* (Dubai, 2010) (Figure 2.21d) from the earliest stages of the design (Irwin and Baker, 2006; Weismantle *et al.*, 2007; Moon, 2015b).

In *Trump International Hotel&Tower* (Chicago, 2009) (Figure 2.21e), the stiffness and weight of the building combined with asymmetrical setbacks, laterally support and stabilize the building and minimize perceptible motion (Baker *et al.*, 2009).

The *TAIPEI 101* (Taipei, 2004) (Figure 2.24a), is an example of the use of both setbacks and tapering. However, since the façades are tapered outward, in the form of repetitive modules, setback formation does not cause a reduction in the plan area toward the top of the building (Gunel and Ilgın, 2014).

b- Varying the plan by changing the plan shape at various levels throughout the height of the building causes a corresponding change in the vortex shedding effect, which disorients the across-wind vortices and breaks up their organization (Irwin, 2009).

2.6.1.4 Aerodynamic top

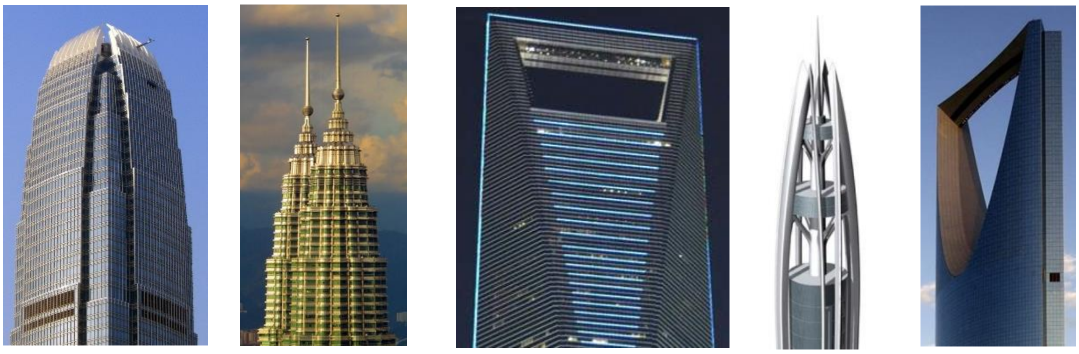
The basis of the *aerodynamic top* approach is the creation of an aerodynamic form near the top of the building that is part of the aerodynamic design of the building overall. These elements include approaches such as tapering the upper part of the building by progressively reducing the plan area and/or providing wind openings.

Paying attention to the aerodynamics of the building top secures improvements not only in the along-wind, but also in the across-wind building response, by reducing the effect of wind-induced turbulence (Dutton and Isyumov, 1990; Isyumov *et al.*, 1992; Kareem *et al.*, 1999; Ho, 2007; Irwin *et al.*, 2008a; Irwin *et al.*, 2008b; Irwin, 2009; Gunel and Ilgın, 2014). To reduce the across-wind response of the building, the optimum location for the along-wind openings is positioned between 80% and 90% of the building height (Kikitsu and Okada, 2003).

Examples of tall buildings with an aerodynamic top include:

- the *TAIPEI 101* (Taipei, 2004) (Figure 2.24a),
- the *Jin Mao Tower* (Shanghai, 1999) (Figure 2.24c),
- the *Two International Finance Centre* (Hong Kong, 2003) (Figure 2.50a),
- the *Petronas Twin Towers* (Kuala Lumpur, 1998) (Figure 2.50b),
- the *Shanghai World Financial Center* (Shanghai, 2008) (Figure 2.50c) (Kareem *et al.*, 1999; Ho, 2007),
- the *Nakheel Tower* (Dubai, never completed) (Figure 2.50d) (Mitchson-Low *et al.*, 2009),
- the *Kingdom Centre* (Riyadh, 2002) (Figure 2.50e) (Amin and Ahuja, 2010).

Among these examples, an aerodynamic top consisting of trapezoidal wind openings played an important role in the architectural design of the *Shanghai World Financial Center* (Kareem *et al.*, 1999; Moon, 2015b). The effectiveness of this modification diminishes if the openings are provided at lower levels of the building. Provision of opening and other such type of changes adversely affect the habitability if they reduce the resonant vortex frequency (Tamura, 1997).



(a) (b) (c) (d) (e)

Figure 2.50 (a) Two International Finance Centre, Hong Kong, 2003 (www.ctbuh.org);
(b) The Petronas Twin Towers, Kuala Lumpur, 1998 (www.ctbuh.org);
(c) Shanghai World Financial Center, Shanghai, 2008 (www.ctbuh.org);
(d) Nakheel Tower, Dubai, never completed (www.ctbuh.org);
(e) Kingdom Centre, Riyadh, 2002 (www.ctbuh.org)

2.6.2 Aerodynamic architectural modifications

Aerodynamic architectural modifications consist of corner modifications and air passes that do not significantly alter the existing architectural design.

2.6.2.1 Corner modifications

Modifications to corner geometry by means of recessed/notched, cut, slotted, and rounded corners reduce the across-wind building response, as compared with an original building shape with sharp corners.

When buildings have sharp - 90° corners - vortex shedding phenomenon can develop, which causing unpleasant acceleration (Macklowe, 2015). In a prismatic building, recessed (notched), cut, slotted, and rounded corners can reduce the along-wind and across-wind building response to an important degree (Figure 2.51) (Kwok *et al.*, 1988; Melbourne and Cheung, 1988; Melbourne, 1989; Kwok, 1995; Kawai, 1998; Gu and Quan, 2004; Scott *et al.*, 2005; Irwin *et al.*, 2008a; Irwin *et al.*, 2008b; Irwin, 2009; Tse *et al.*, 2009; Kim *et al.*, 2008; Malott, 2010; Amin and Ahuja, 2010; Lewis and Holt, 2011; Malott and KPF Ass., 2014; Gunel and Ilgın, 2014; Tang, 2016).

Building modifications such as horizontal slots, slotted corners and cut corners causes major disruption of the vortex-shedding process and result in a 30% or more reduction in the crosswind response (Amin and Ahuja, 2010).

A recessed/notched or cut corner, which reduces the width of the building by 10% compared with a sharp corner, reduces the along-wind building response by 40% and the across-wind building response by 30% (Holmes, 2001). Irwin (2009) terms "modified corners" as "softened corners" and states that "*The corner softening should extend about 10% of the building width in from the corner.*" However, corner modifications may cause adverse effects in serviceability and safety of the building (Kareem et al., 1999).

Rounded corners are the most effective type of corner modification (Gu and Quan, 2004). Approximating a circular plan form by increasing the corner roundness also reduces the wind loads affecting the building to an important degree (Miyashita *et al.*, 1995; Kareem *et al.*, 1999; Gu and Quan, 2004).

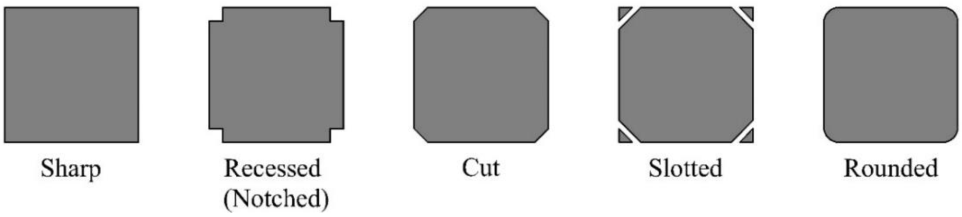


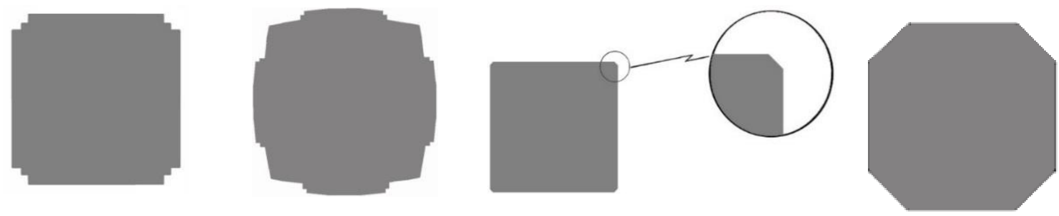
Figure 2.51 Modifications to corner geometry

When comparing saw-tooth corners that are a development of recessed corners, with sharp corners, in the view of Poon *et al.* (2004) they reduce the wind load affecting the building to an important degree. According to Irwin (2008, 2009) they cause nearly a 25% reduction in the wind-induced base moment in *TAIPEI 101* (Taipei, 2004) (Figure 2.52a).

Examples include the use of;

- saw-tooth (double-notch) corners in the *Two International Finance Centre* (Hong Kong, 2003) (Figure 2.52b),
- of cut corners in the *World Trade Center Twin Towers* (New York, 1972) (Figure 2.52c), and
- of cut corners of *One World Trade Center* (New York, 2014) (Figure 2.52d) (Lewis and Holt, 2011).

In *Cayan Tower* (Dubai, 2013), corners are also designated as notched to contribute buildings performance against the wind forces (Baker *et al.*, 2010).



(a) (b) (c) (d)

Figure 2.52 Examples of corner modifications
(a) TAIPEI 101, saw-tooth corners;
(b) Two International Finance Centre, saw-tooth corners;
(c) World Trade Center Twin Towers, cut corners;
(d) One World Trade Center, cut corners

The results of preliminary wind tunnel testing for *International Commerce Center (ICC)* (Hong Kong, 2010) (Figure 2.53) indicated that a square with notches had similar beneficial properties as circular tower (Malott, 2010; Malott and KPF Ass., 2014; Tang, 2016).

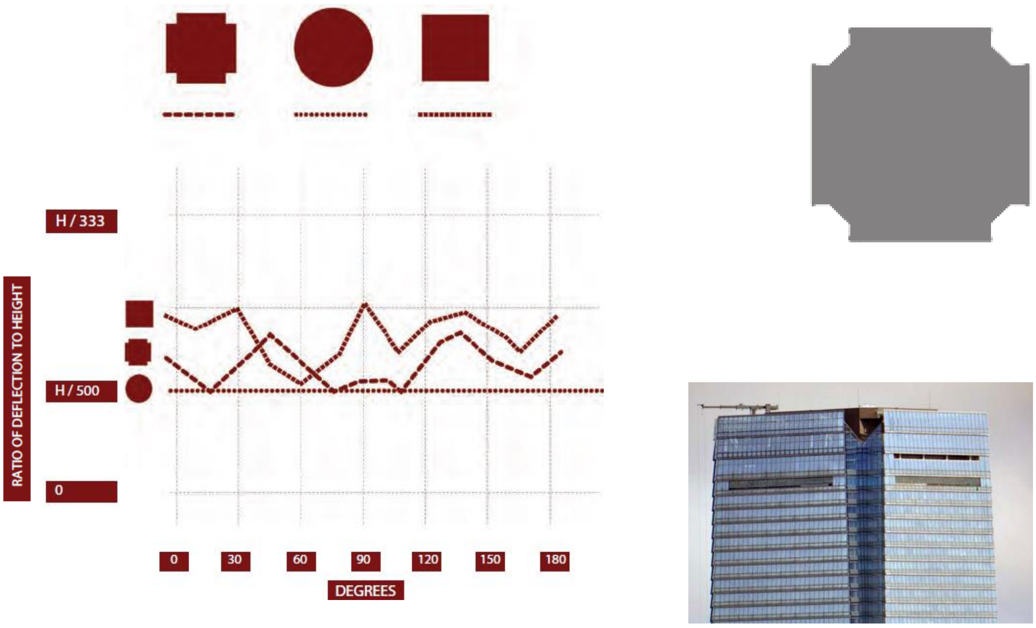


Figure 2.53 Corner modification of ICC (Malott and KPF Ass., 2014)

Ping An Finance Center (PAFC) (Shenzhen, 2017) features tapering corners, which is extremely effective in reduction of wind loading (Figure 2.54). Owing to its form, PAFC achieves a 32% reduction in overturning moment and 35% reduction in wind load according to Chinese code (Malott and KPF Ass., 2014).

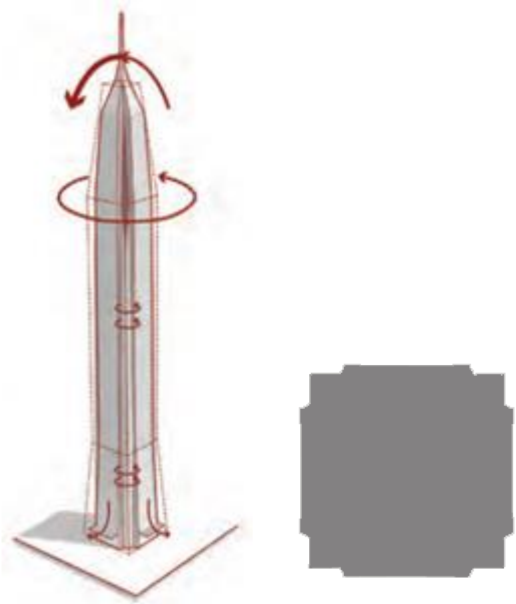


Figure 2.54 (a-b) Corner modification of PAFC (Malott and KPF Ass., 2014)

2.6.2.2 Air passes

Air passes in the building would allow the air to bleed into the wake and separated regions so increase the base pressure and therefore decrease aerodynamic forces (Amin and Ahuja, 2010).

In *432 Park Avenue* (New York, 2015) (Figure 2.55a) owing to two-story open floors, achieved porosity causes not only breaking up the monotony but also reduction in wind loads on the building by minimization of vortex forces (Durst *et al.*, 2015; Macklowe, 2015; Marcus, 2015).

Owing to the slots through height of the building, *Nakheel Tower* (Dubai, never completed) (Figure 2.55b) deals with the issues of wind by allowing the wind pass through the tower (Mitchson-Low *et al.*, 2009).

Greenland Group Suzhou Center (Wujiang, under construction) (Figure 2.55c), called as “breathing tower”, has aerodynamically favorable air passes (Wimer *et al.*, 2012).

In *Aspire Tower* (Doha, 2006) (Figure 2.30), some part of the surface of the facade on the building is in the form of permeable mesh and some part being in the form of solid cladding. By means of the wind permeable part of the facade, the across-wind effect on the building is reduced and as a result, the response of the building in the along-wind direction, rather than its response in the across-wind direction becomes critical and governs the design (Chikaher and Hirst, 2007).

(a) (b) (c)

Figure 2.55 (a) 432 Park Avenue, New York, 2015 (www.ctbuh.org);
(b) Nakheel Tower, Dubai, never completed (www.ctbuh.org) (Mitchson-Low *et al.*, 2009);
(c) Greenland Group Suzhou Center, Wujiang, under construction (www.ctbuh.org)

Overall, the issue of "***aerodynamically adaptive building form***" comes to forefront. In this concept, during the generation of architectural form especially at early/schematic stages, "aerodynamic form" and "plan variation", which are the major modifications to affect the overall building form, are taken into consideration as a significant design input. At the end of the iterative processes through the design stages supported by wind tunnel tests in most cases, an ideal form is figured out in terms of integration between architectural and aerodynamic form as in the case of:

- *Burj Khalifa* (Dubai, 2010)
  (Irwin and Baker, 2006; Weismantle *et al.*, 2007; Moon, 2015b),
- *Shanghai Tower* (Shanghai, 2015) (Amin and Ahuja, 2010),
- *Ping An Finance Center* (Shanghai, 2015) (Malott and KPF Ass., 2014), and
- *One World Trade Center* (New York, 2014) (Lewis and Holt, 2011).

In conclusion, it is obvious that major aerodynamic modifications like utilization of tapered, setback or other aerodynamic forms predominantly shape today's supertalls as a key design parameter, and the collaboration between the architect and the wind engineer has been gaining importance inevitably.

CHAPTER 3

PARAMETRIC STUDY ON PLANNING CONSIDERATIONS OF SUPERTALL BUILDINGS

Planning considerations of supertall buildings; namely

- *architectural design considerations* including:
  - *function,*
  - *core planning (core type),*
  - *aspect ratio,*
  - *building form,*
- *structural design considerations* including:
  - *structural materials,*
  - *structural systems,* and

with their interrelations, namely

- *completion date and building height,*
- *structural system and structural material,*
- *structural system and building form,*
- *structural system and building height,*
- *structural system and core planning (core type),*
- *timeline and structural material,*
- *building function and building form,*
- *building location and building form,*
- *building location and structural system,*
- *building height and building form,*
- *building height and building function,*
- *building form and aspect ratio,*

- *structural system and aspect ratio, and*
- *aspect ratio and building height,*

will be scrutinized in this chapter.

In order to analyze architectural, structural, and aerodynamic design considerations, 91 supertall buildings (300 meters' height or greater) with completed and under construction status have been selected.

The main determinant factor for the selection of 91 supertall buildings is availability of the data demonstrated in the supertall building list (Appendix-A). The difficulty in data collection process has been experienced because of security issues of supertall buildings particularly in the United States after the tragedy of *WTC Twin Towers* at September 11th 2001.

On the other hand, for the sake of comparison of all structural systems together, the supertall buildings completed after 1980 are included in the sample group for this study because *"outrigger"* and resulting structural system called as *"outriggered frame system"* were introduced in late 1970s as the latest invented structural system of supertall buildings.

According to CTBUH database;

- *under construction* refers to that site clearing has been completed and foundation/piling work has begun,
- a*rchitecturally topped out refers to* that the building is under construction and has reached its full height both structurally and architecturally (e.g., including its spires, parapets, *etc*.), and
- *structurally topped out* refers to that the building is under construction and the highest primary structural element is in place.

In this study, it is assumed that *"under construction status"* covers:

- architecturally topped out,
- structurally topped out, and also
- under construction in which foundation/piling work has begun.

In the supertall building list (Appendix-A), the information columns about;

- *building name (official name),*
- *location,*
- *height,*
- *number of floors,*
- *completion date,*
- *architect,*
- *energy label,*
- *photo/image,*
- *tower gross floor area,*
- *average floor area and ground floor area,* and
- *function,*

is totally based on the Global Tall Building Database of the CTBUH (May, 2018).

At this point, according to CTBUH database;
Tower Gross Floor Area (Tower GFA) refers to the total gross floor area within the tower footprint above ground, not including adjoining podiums, connected buildings or other towers within the development. By using this definition above, *average floor area* is calculated as *(Tower GFA) / (Number of floors)*. In this calculation, "*number of floors"* is taken as the number of floors above ground.

In addition to the information columns above, in the supertall building list, *building form,* namely morphological form classification explained in the part of 2.4.6, is completely proposed by the author. Furthermore, the information columns about;

- *ground floor area,*
- *typical floor plan,*

- *core dimensions,*
- *lease span,*
- *core planning (core type),*
- *aspect ratio,*
- *structural systems*,
- *structural material*, and
- *aerodynamic design considerations*

are mainly collected from the book of "*Tall Buildings: Structural Systems and Aerodynamic Forms"* (Gunel and Ilgın, 2014) and "*METU graduate course of BS 536: Studies of Tall Buildings: Design Considerations"*.

Other auxiliary resources consist of fact sheets, construction documents, journals, magazines, internet sources, and mailing correspondences to related architectural and structural design offices.

Consequently, this chapter has been developed to build a comprehensive database for this research. The results of these analyses will address the findings that will aid in the planning and development of supertall building projects and address the quest for the design guideline directing architects to develop structurally and aerodynamically viable supertall building forms.

3.1 Analysis of Architectural Design Considerations

This section presents an analysis of architectural design considerations for 91 supertall buildings with completed and under construction status in the Appendix-A. These considerations, which mainly affect structural systems of supertall buildings, include:

- *function,*
- *core planning (core type),*
- *aspect ratio*, and
- *building form*.

In addition to the architectural design considerations mentioned above, as a supplementary part, the analysis of geographical location of *286 supertall buildings with completed and under construction status* after 1980 according to the statistical data from Global Tall Building Database of the CTBUH (May, 2018), is illustrated below:

SUPERTALL BUILDINGS WITH COMPLETED & UNDER CONSTRUCTION STATUS (286 buildings) (CTBUH, May, 2018)		
Location	***#***	***app. %***
China	153	53%
United Arab Emirates	41	14%
United States	27	10%
Others	65	23%
TOTAL	**286**	**100%**

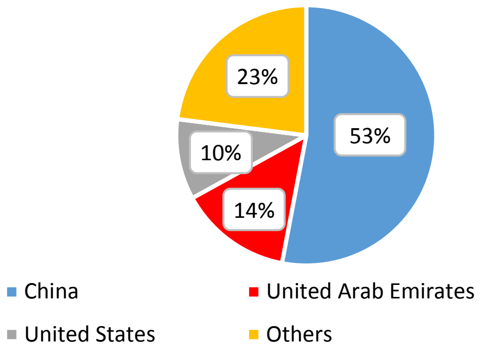


Figure 3.1 The rate of "the supertall buildings with completed and under construction status" regarding location (286 buildings) (Appendix-B)

By geographical location, *286 supertall buildings with completed and under construction status* after 1980 from CTBUH database (May, 2018) are distributed as follows (Figure 3.1):

- *China: 53%,*
- *United Arab Emirates: 14%,*
- *United States: 10%,* and
- *Other countries (Malaysia, Russia, Saudi Arabia, South Korea and so forth): 23%.*

Supertall buildings, which were previously thought to be exclusively a North American urban phenomenon, have today entered the skylines of almost all major cities, especially in Asia. Among Asian countries, *China* with ratio of 53% is demanding and challenging in construction of supertall buildings.

Among the countries where tallest buildings are constructed, three countries become prominent. *China, United Arab Emirates,* and *United States* have approximately 77% of the total number of the *supertall buildings with completed and under construction status* after 1980 all over the world.

At the beginning of the 20th century, in the history of American urban architecture, tall buildings emerged as a response to the rapidly growing urban population, with the aim of meeting the demand for office units to be positioned as closely as possible to one another.

Today, owing to the effort to generate a skyline concept, a cultural identity, a prestige or a national pride, skyscrapers become an inevitable feature of urban development especially in Far East. Thus, the number of supertall buildings has been increasing over the decades in that regions with the effort of creation in notions of "uniqueness", "being a symbol" or "building the tallest".

3.1.1 Analysis of function

Function is one of the significant architectural parameters of supertall buildings. Generally, supertall buildings are divided into *single-use* and *multi-function* according to their function. In supertall building design, *hotel, residential* and *office* are considered as the primary functions.

Analysis of function is based on the following configurations (Figure 3.2a-b):

- *hotel,*
- *residential,*
- *office,* and
- *multi-function.*

SUPERTALL BUILDINGS WITH COMPLETED & UNDER CONSTRUCTION STATUS (91 buildings) (CTBUH, May, 2018)		
Function	***#***	***app. %***
Hotel	2	2%
Residential	18	20%
Office	32	35%
Multi-function	39	43%
TOTAL	**91**	**100%**

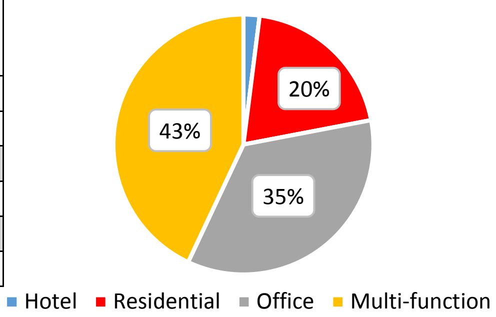


Figure 3.2a The rate of "the supertall buildings with completed and under construction status" regarding function (91 buildings) (Appendix-A)

As seen in (Figure 3.2a), *multi-function* with ratio of 43% and *office use* with ratio of 35% are the most preferred functions among 91 supertall buildings.

When single-use and multi-function are compared with each other, it is observed that the ratio of *multi-function* is close to the total ratio of *single-use* functions (hotel, residential, and office) (Figure 3.2a-b).

If multi-function is analyzed in terms of internal functional distribution, it is seen that *hotel* is the essential component. Hotel use reaches up to 45% with the addition of multi-function. This function in mostly in collaboration with other functions either commercial or residential purposes.

According to the statistical data from Global Tall Building Database of the CTBUH (May, 2018), after 1980, the total number of supertall buildings with completed and under construction status will reach up to 286 as projected. On the other hand, in *The Skyscraper Centre of CTBUH*, since there is no dedicated function for 23 supertall buildings to be constructed, the figure below illustrates the functions for 263 supertall buildings.

SUPERTALL BUILDINGS WITH COMPLETED & UNDER CONSTRUCTION STATUS (263 buildings) (CTBUH, May, 2018)		
Function	***#***	***app. %***
Hotel	13	5%
Residential	36	14%
Office	91	35%
Multi-function	123	46%
TOTAL	**263**	**100%**

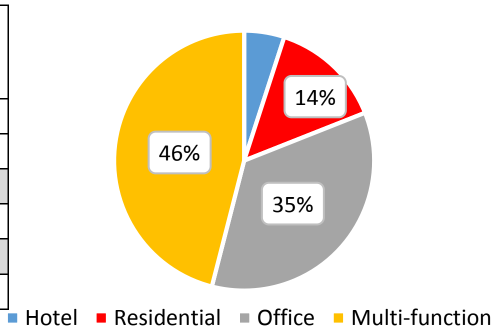


Figure 3.2b The rate of "the supertall buildings with completed and under construction status" regarding function (263 buildings) (Appendix-B)

As seen the Figure 3.2a-b, the findings from the sample group of 91 supertall buildings reflect the similar results with that of 263 supertall buildings from CTBUH database. Thus, it can be claimed that the sample group used in the dissertation is representative from functional point of view.

As a consequence, in supertall building design, *multi-function* and *office use* are the most preferred functions. On the other hand, with the addition of multi-function, *hotel use* reaches up to almost half of number of supertalls.

3.1.2 Analysis of core planning (core type)

Core planning (core type) is also one of the significant architectural parameters of supertall buildings.

Analysis of core planning is based on the following configurations (Figure 3.3):

- *central core,*
- *peripheral core,*
- *external core,* and
- *atrium core.*

SUPERTALL BUILDINGS WITH COMPLETED & UNDER CONSTRUCTION STATUS (91 buildings) (CTBUH, May, 2018)		
Core planning	*#*	***app.%***
Central core	86	95%
Peripheral core	2	2%
External core	1	1%
Atrium core	2	2%
TOTAL	**91**	**100%**

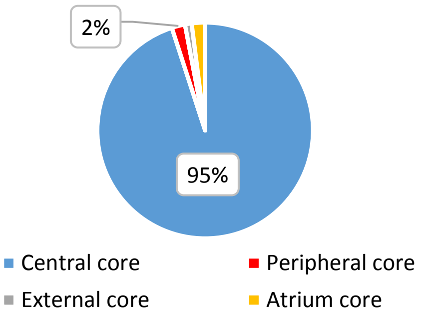


Figure 3.3 The rate of "the supertall buildings with completed and under construction status" regarding core planning (91 buildings) (Appendix-A)

As seen in (Figure 3.3), *central core* arrangement with ratio of approximately 95% is the most employed type of core arrangement; while *external core* is the least common preference. *Atrium core* and *peripheral core* with ratio of 2% are also relatively less utilized core arrangements.

The reason behind the central core dominance could be explained with its potentials of structural contribution, compactness, enabling of openness in the exterior façade for light and views and safety concerns allowing easy access for fire escape.

In conclusion, it is obvious that *central core* is the most preferred arrangement by a wide margin; whereas *peripheral, external and atrium core types* are rarely utilized in the design of today's supertalls.

3.1.3 Analysis of aspect (slenderness) ratio

In the design of tall buildings, for buildings *below 40 stories* and buildings with an *aspect ratio below 6*, the values predicted in the design codes can be used to determine wind loads. On the other hand, in order to estimate the wind load in buildings of *more than 40 stories*, or that have an *aspect ratio of 6 or higher*, or that have *unusual forms*, dynamic effect of the wind and dynamic building response must be taken into account. In this context, wind tunnel tests are recommended for estimating the wind loads on such buildings (Gunel and Ilgın, 2014).

As mentioned in the previous chapter, under wind load, the overturning moment at the base of a building varies in proportion to the square of the height of the building, and lateral deflection varies as the fourth of the height of the building (Almusharaf, 2011). For supertall buildings with high aspect ratios, lateral loads typically become dominant, and stiffness rather than strength begins to govern the design.

As seen in the available data of *aspect ratio* from the supertall buildings list (Appendix-A), for supertall buildings having an *aspect* ratio of 6 and higher, even some of them with *10* and higher such as:

- *Jeddah Tower* (Jeddah, under construction) with *10*,
- *Burj Khalifa* (Dubai, 2010) with *10.5*,
- *Pearl River Tower* (Guangzhou, 2013) with *11.7*,
- *Burj Mohammed Bin Rashid* (Abu Dhabi, 2014) with *13*,
- *MahaNakhon* (Bangkok, 2016) with *13.6*,

wind tunnel tests are mostly used in order to estimate wind loads exposed to them.

Besides these buildings, as super-slender supertalls,

- *432 Park Avenue* (New York, 2015) (Figure 2.15a),
- *Collins House* (Melbourne, under construction) (Figure 2.15b),
- *Highcliff* (Hong Kong, 2003) (Figure 2.15c), and
- *111 West 57th Street* (New York, under construction) (Figure 2.15d)

with their extraordinary aspect ratio of approximately 1/15, 1/16.5, 1/20, and 1/24 respectively, are the slenderest supertall buildings in the world.

At this point, selection of structural system and architectural form, in particular aerodynamically favorable ones, come into prominence in order to mitigate overturning base moments, to control lateral deflection, and to ensure occupancy comfort.

As a result, in light of the data about aspect ratio in the supertall building list (Appendix-A), today, the architects' of skyscrapers show a general tendency towards designing the supertalls with the slenderness ratio of 7 and higher.

3.1.4 Analysis of building form

Building form is one of the significant architectural parameters of supertall buildings. Analysis of building form is based on the following configurations (Figure 3.4a-b):

- *simple forms,*
- *tapered forms,*
- *setback forms,*
- *twisted forms,* and
- *free forms.*

SUPERTALL BUILDINGS WITH COMPLETED & UNDER CONSTRUCTION STATUS (91 buildings) (CTBUH, May, 2018)		
Building form	***#***	***app.%***
Simple forms	19	21%
Tapered forms	33	36%
Setback forms	9	10%
Twisted forms	3	3%
Free forms	27	30%
TOTAL	**91**	**100%**

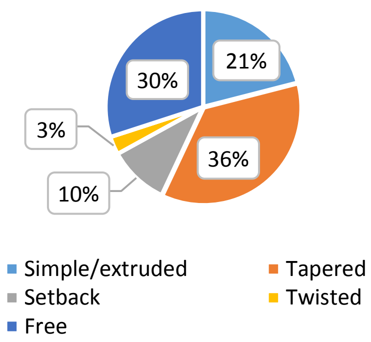


Figure 3.4a The rate of "the supertall buildings with completed and under construction status" regarding building form (91 buildings) (Appendix-A)

According to the morphological building form classification, *tapered forms* with ratio of almost 36% are mostly employed in the supertall building list (Figure 3.4a). The reason behind the highest ratio could be structural and aerodynamic efficiency of tapered forms for the supertall buildings of today, such as:

- *TAIPEI 101* (Taipei, 2004) (Figure 2.24a),
- *One World Trade Center* (New York, 2014) (Figure 2.20c),
- *Ping An Finance Center* (Shenzhen, 2017) (Figure 2.20e), and
- *Lotte World Tower* (Seoul, 2017) (Figure 2.20f).

In addition to the facts above, facilitation of multi-function by housing different function with various lease span opportunities could make tapered forms architecturally more desirable.

Free forms with ratio of nearly 30% are the second preferred form in the supertall building list. The reason behind this relatively high ratio can be architects' enthusiasm to search for original and unique building forms.

Simple forms with ratio of around 21% are relatively favorite form in the supertall building list (Figure 3.4a). They are rarely designed as just pure simple. Simple forms are mostly either articulated and/or with architectural top. These type of considerations in many cases result in building top or corner modifications aerodynamically as well. On the other hand, *setback forms* with ratio of about 10% are one of the least preferred forms in the supertall building list (Figure 3.4a).

Twisted forms for supertall buildings are recent architectural phenomenon as a reaction to rectangular box forms of modern architecture. *Twisted forms* with ratio of almost 3% in the supertall building list are the least utilized forms as well (Figure 3.4a). The reason behind this ratio can be that from structural point of view, these forms are not advantageous since the lateral stiffness of a twisted building is smaller than that of the straight one (Ali and Moon, 2007).

Leaning/tilted forms are not employed in the list. The reason behind the lowest ratio can be that from structural point of view, these forms are not advantageous since gravity-induced lateral displacements increase as the angle of tilt increases.

According to the statistical data from Global Tall Building Database of the CTBUH (May, 2018), after 1980, the total number of supertall buildings with completed and under construction status will reach up to 286 as projected. On the other hand, in *The Skyscraper Centre of CTBUH*, since there is no image for 31 supertall buildings to be constructed, the figure below demonstrates the building forms for 255 supertalls.

SUPERTALL BUILDINGS WITH COMPLETED & UNDER CONSTRUCTION STATUS (255 buildings) (CTBUH, May, 2018)		
Building form	***#***	***app.%***
Simple forms	53	20%
Tapered forms	86	34%
Setback forms	38	15%
Twisted forms	5	2%
Free forms	73	29%
TOTAL	**255**	**100%**

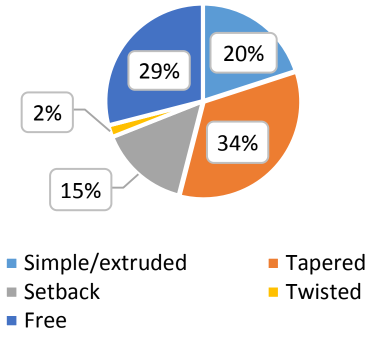


Figure 3.4b The rate of "the supertall buildings with completed and under construction status" regarding building form (255 buildings) (Appendix-B)

As seen the Figure 3.4a-b, the findings from the sample group of 91 supertall buildings reflect the similar results with that of 255 supertall buildings from CTBUH database. Thus, it can be claimed that the sample group used in the dissertation is representative in terms of building form.

Overall, in supertall building design of today, it is no doubt that *tapered and free forms* are the most commonly used forms; while *twisted forms* are rarely employed. On the other hand, *lining/tilted forms* have never been encountered in the supertalls.

3.2 Analysis of Structural Design Considerations

This section presents an analysis of structural design considerations for 91 supertall buildings with completed and under construction status in the Appendix-A.

These considerations include:

- *structural materials* and
- *structural systems*.

3.2.1 Analysis of structural materials

Analysis of structural materials is based on the following configurations (Figure 3.5a-b):

- *steel*,
- *reinforced concrete (RC)*, and
- *composite*.

SUPERTALL BUILDINGS WITH COMPLETED & UNDER CONSTRUCTION STATUS (91 buildings) (CTBUH, May, 2018)		
Structural material	***#***	***app.%***
Steel	4	4%
Reinforced concrete (RC)	28	31%
Composite	59	65%
TOTAL	**91**	**100%**

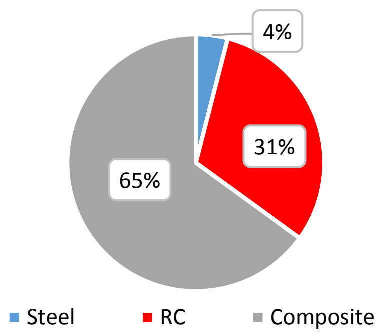


Figure 3.5a The rate of "the supertall buildings with completed and under construction status" regarding structural material (91 buildings) (Appendix-A)

The significant use of *composite construction* can be mostly attributed to combination the advantages of both materials, such as the high-strength of steel, and the fire resistance and rigidity of reinforced concrete. Therefore, it may not be surprising to find out that nearly 65% of the supertall buildings utilize *composite materials* (Figure 3.5a-b). Among composite construction, concrete filled and/or encased structural elements with ratio almost 75% are mostly employed.

Utilization of *RC* as structural material is around 31% in the supertall building list (Figure 3.5a).

- Its relative ubiquity and lower cost in many regions,
- its comparative simplicity in construction,
- its potential to produce unusual building forms,
- its ability to be cast in any form,
- its much greater natural resistance to fire, and
- its better performance at dampening wind induced building sway - compared with steel,

could make reinforced concrete the second most preferred structural material for the structural systems of supertall buildings.

Owing to the advances in technology, the increase in strength and developments in concrete pumping technology - the ability to pump it to higher levels - reinforced concrete can now be used in all structural systems for supertall buildings. Owing to this fact, it is not surprising that the tallest building, over 800m tall *Burj Khalifa,* and the strongest candidate for getting the tallest building title as expected, over 1000m tall *Jeddah Tower,* are made of reinforced concrete.

Utilization of *steel* as structural material is about 4% in the supertall building list (Figure 3.5).

According to the statistical data from Global Tall Building Database of the CTBUH (May, 2018), after 1980, the total number of supertall buildings with completed and under construction status will reach up to 286 as projected. On the other hand, in *The Skyscraper Centre of CTBUH*, since there is no dedicated structural material for 51 supertall buildings to be constructed, the figure below presents the functions for 235 supertall buildings.

SUPERTALL BUILDINGS WITH COMPLETED & UNDER CONSTRUCTION STATUS (235 buildings) (CTBUH, May, 2018)		
Structural material	***#***	***app.%***
Steel	8	3%
Reinforced concrete (RC)	77	32%
Composite	150	65%
TOTAL	**235**	**100%**

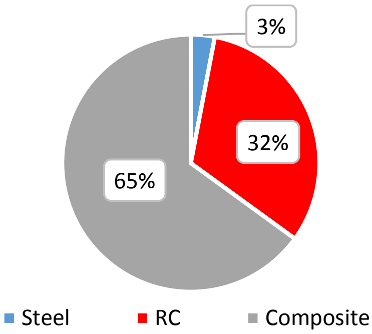


Figure 3.5b The rate of "the supertall buildings with completed and under construction status" regarding structural material (235 buildings) (Appendix-B)

As seen the Figure 3.5a-b, the findings from the sample group of 91 supertall buildings reflect the similar results with that of 235 supertall buildings from CTBUH database. Thus, it can be claimed that the sample group used in the dissertation is representative in terms of structural material.

Consequently, in supertall building design of today, it is clear that *composite utilization* with concrete filled and/or encased structural elements shows a great dominance; while *steel* is the least preferred structural material.

3.2.2 Analysis of structural systems

Many planning considerations are dependent upon the structural system for their proper performance. The structural system affects not only building's exterior aesthetics but also its interior space planning.

Analysis of structural systems is based on the following configurations (Figure 3.6):

- *shear-frame systems,*
- *mega column/frame,*
- *mega core,*
- *outriggered frame,*
- *framed-tube & diagrid-framed-tube,*
- *trussed-tube.*

SUPERTALL BUILDINGS WITH COMPLETED & UNDER CONSTRUCTION STATUS (91 buildings) (CTBUH, May , 2018)		
Structural system	***#***	***app.%***
Shear-frame	9	10%
Mega column/frame	3	3%
Mega core	1	1%
Outriggered frame	62	69%
(Diagrid)-framed-tube	13	14%
Trussed-tube	3	3%
TOTAL	**91**	**100%**

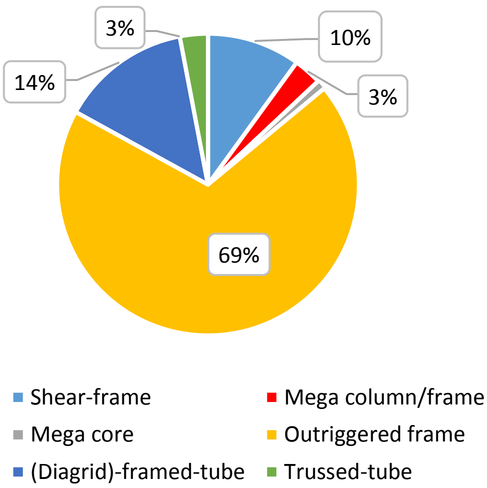


Figure 3.6 The rate of "the supertall buildings with completed and under construction status" regarding structural system (91 buildings) (Appendix-A)

As seen in (Figure 3.6), *outriggered frame system* with ratio of almost 69% is utilized predominantly for the supertall building list. The reasons behind this dominance could be the merits of this structural system. Namely, outriggered frame system minimizes the obstruction created by large exterior structural frames, allowing freely articulation of the façade design. Owing to this functional benefits, the system offers flexibility in perimeter column arrangements and became popular for supertall buildings worldwide. This system has a great height potential up to 150 stories and possibly more. It can be formed in any combination of steel, reinforced concrete, and composite material as well. In addition to this, by means of articulating the building elements like façade or cantilevering slab, up to a certain point, desired architectural form could be generated in structurally inadaptive manner as in the case of *Shanghai Tower* (Shanghai, 2015) (Figure 2.38).

Tube systems including *framed-tube, diagrid-framed-tube, and trussed-tube* have the ratio of around 17% in the supertall building list (Figure 3.6).

In this section, the issue of "***structurally adaptive building form***" comes to forefront. As mentioned in the structural system section, some special structural system could be fully integrated to the architectural form. That is, structure follows form or vice versa. For example, diagrid-framed-tube system is given wide coverage in the related chapter owing to its great potential to be developed as one of the most appropriate structural solutions for irregular free form buildings as in the case of:

- *Guangzhou International Finance Center* (Guangzhou, 2010) (Figure 2.44e) and
- *53 West 53rd* (New York, under construction).

As a consequence, in supertall building design of today, it is clear that owing to its merits, outriggered frame system is the most preferred structural system; whereas mega core and mega column systems are rarely utilized.

3.3 Interrelations among Design Considerations

This section presents the interrelations between;

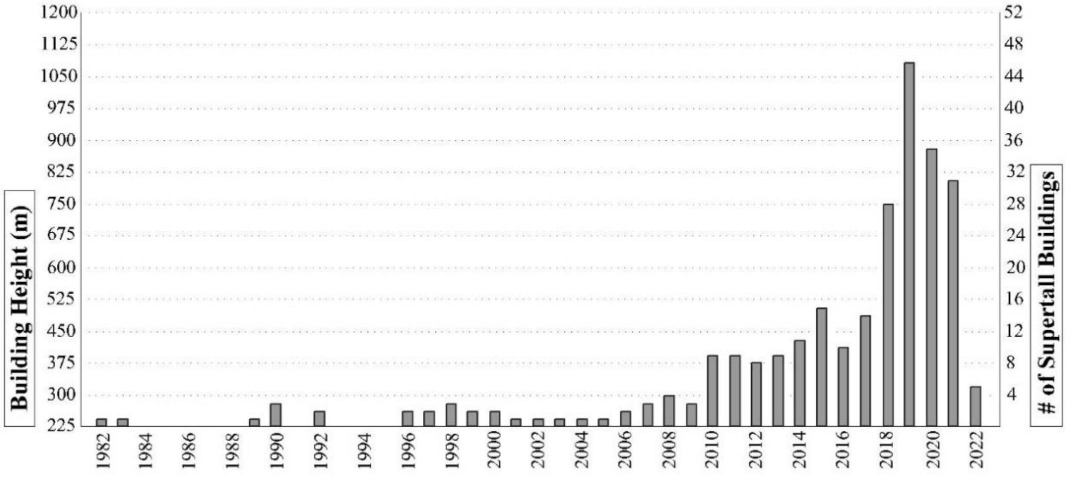
- *completion date and building height,*
- *structural system and structural material,*
- *structural system and building form,*
- *structural system and building height,*
- *structural system and core planning (core type),*
- *timeline and structural material,*
- *building function and building form,*
- *building location and building form,*
- *building location and structural system,*
- *building height and building form,*
- *building height and building function,*
- *building form and aspect ratio,*
- *structural system and aspect ratio, and*
- *building height and aspect ratio,*

for supertall buildings with completed and under construction status in the Appendix-A.

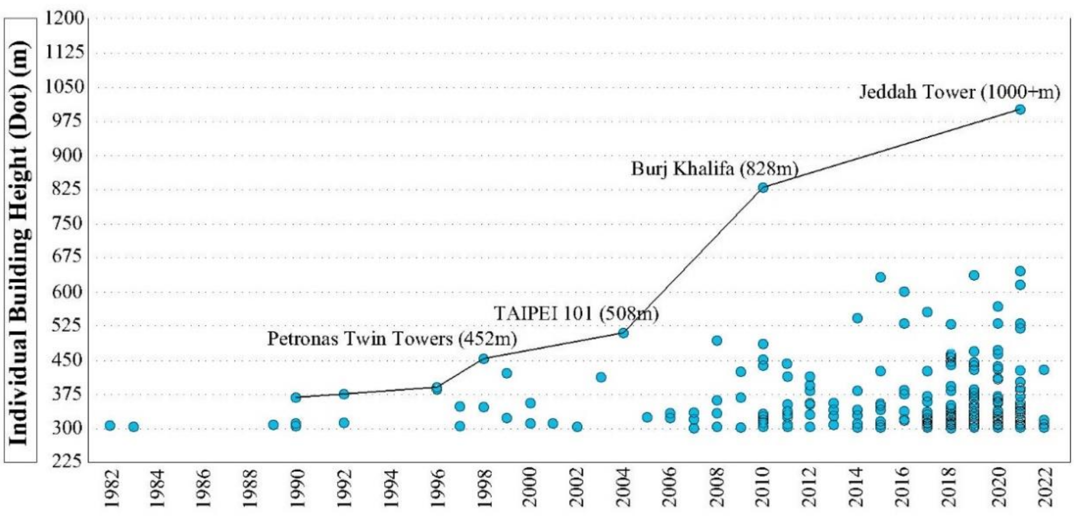
As mentioned before, in this research, it is assumed that "under construction status" covers *architecturally topped out*, *structurally topped out*, and also *under construction* in which foundation/piling work has begun.

3.3.1 Interrelation of completion date and building height

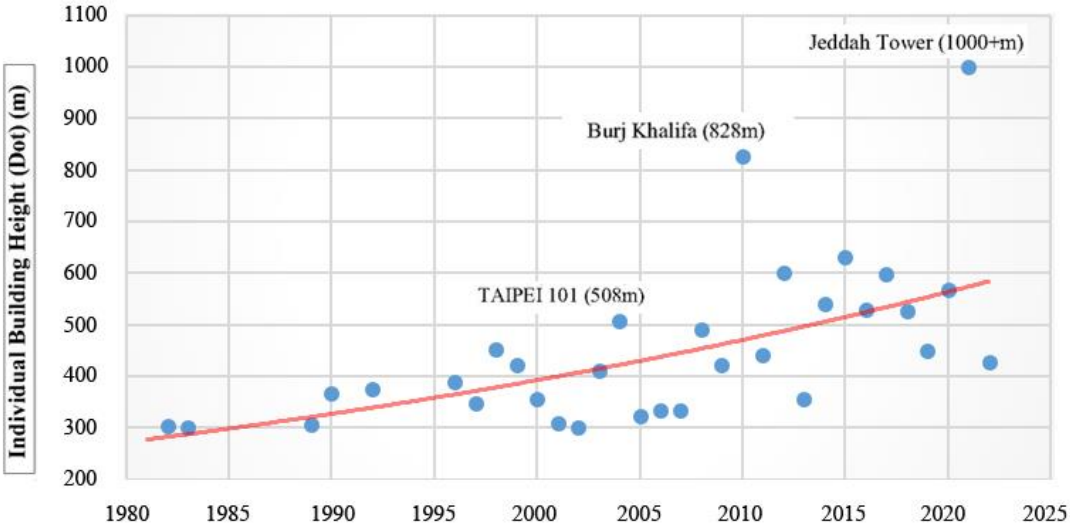
Figure 3.7a-c presents the total number of supertall building (namely 300 meters' height or greater) completions by year and the heights of supertall buildings completed or to be completed in that year. Individual supertall buildings are highlighted with dots in blue and the number of supertall buildings is represented by bars in grey.


Building Height (m)
# of Supertall Buildings

(a)


Individual Building Height (Dot) (m)
Jeddah Tower (1000+m)
Burj Khalifa (828m)
TAIPEI 101 (508m)
Petronas Twin Towers (452m)

(b)



(c)

Figure 3.7 Interrelation of completion date and building height (CTBUH, May 2018) (265 buildings) (Appendix-B)

According to the statistical data from Global Tall Building Database of the CTBUH (May, 2018), after 1980, the total number of supertall buildings with completed and under construction status will reach up to 286 as projected. However, in *The Skyscraper Centre of CTBUH*, since there is no estimated completion date for 21 supertall buildings to be constructed, the chart above presents 265 supertall buildings for which estimated completion date is shown in that database.

The 46 supertall building completions in 2019 seem to beat every year on record in the chart as projected. This brings the total number of supertall buildings in the world 196 by the year of 2019 as expected, increasing about 23% from 2018, marking an over 930% increase from 2000, when only 19 existed (Figure 3.7a).

As seen in the chart, as a record-braking year of 2019 in terms of total number, most of the supertall buildings are from height range of between 300-375m as in the case of other top 4 record-braking years. These are the years, namely top records in 2020, 2021, 2018, and 2015, respectively, when the number of supertall building' completions are/will be much more than the rest of years in the chart.

The chart shows that after 2010, the number of supertall buildings has a tendency to increase. Until 2010, only 36 supertall buildings completions were executed. However, by the end of that year, 9 supertalls were built, which means a great increase (25%), in the total number. In the following years, the number has turned into 8 or 9 in average, and this sustainable trend is going on for a while. Finally, the number of completion of supertall buildings annually will reach a peak in 2019.

When the chart is analyzed regarding megatall building (namely 600 meters' height or greater) completions, only 8 megatalls have been existed since 2010. That year has also symbolized such a great milestone, when the construction of over 800m tall *Burj Khalifa* began to push the limits in the height of megatall construction. Such an extreme jump in the building height has also resulted in a record for getting the title of "World's tallest". It seems that until the completion of over 1000m tall *Jeddah Tower* in 2021, the world will never be a witness to such a great height in the area of megatall structures.

If the increases in height of the tallest buildings in terms of the completion dates, namely 452m high *Petronas Twin Towers* (1998), 508m high *TAIPEI 101* (2004), 828m high *Burj Khalifa* (2010), and over 1000m high *Jeddah Tower*, are taken into consideration; there has been rise of 56m in 6 years, 320m in the following 6 years, more than 170m in the next 6 years, respectively (Figure 3.7b-c).

Overall, as seen in the chart, between the periods of 1980 and 2022, there are mostly completions of supertall buildings with the height range between *300-650m*. After 2010, a dramatic rise has been observed in density of construction, and by 2019, the number of supertall buildings to be built will reach a peak, 46 as projected.

3.3.2 Interrelation of structural system and structural material

Figure 3.8 shows the total number of supertall building (namely 300 meters' height or greater) completions by structural system and by structural material.

For each category in the structural system of supertall buildings, namely

- *outriggered frame,*
- *tube,*
- *mega column/core, and*
- *shear-frame systems,*

utilized structural materials for that type of structural system, namely

- *steel,*
- *reinforced concrete, and*
- *composite,*

are indicated both totally and separately as bars and pie charts in different colors.

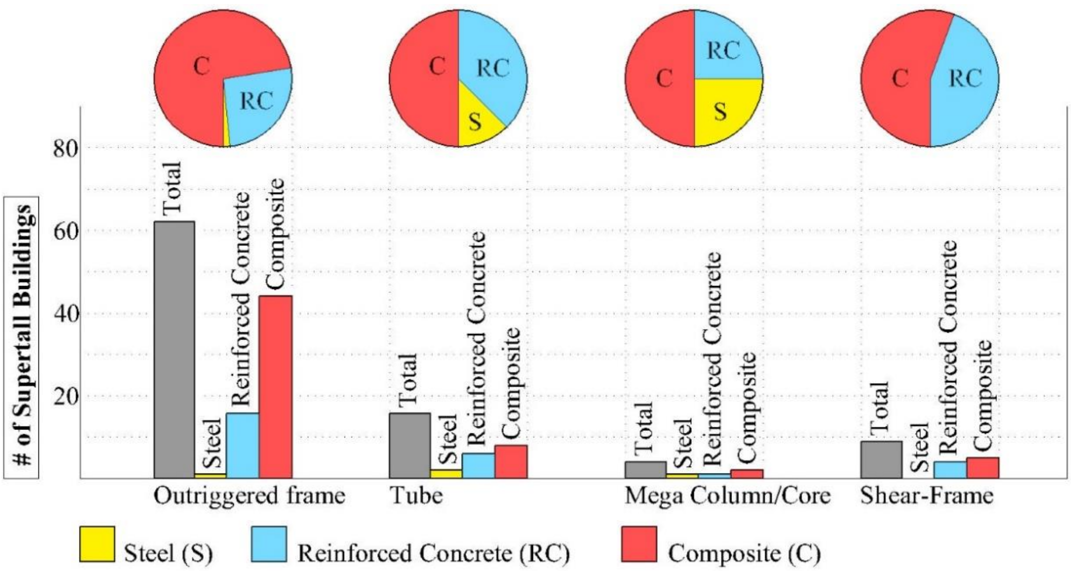


Figure 3.8 Interrelation of structural system and structural material (91 buildings) (Appendix-A)

As seen in the chart, for all the structural systems, particularly for outriggered fame system by a wide margin, *composite* is preferred over *reinforced concrete* and *steel*.

Of the 62 supertall buildings with *outriggered frame system*, 45, or 73%, are utilizing *composite* as the main structural material; while almost 17, or 27% are employing *reinforced concrete* and only 1 is using *steel*.

The chart shows that of the 16 supertall buildings with *tube system*, as the second most favored structural system, 8, or almost 50%, are using *composite* as the main structural material; whereas only 2 are utilizing *steel* as structural material.

Since the number of supertall buildings with *mega column/mega core systems* in the sample group is very low, only 4 existed, it does not seem possible to scientifically claim that *composite* dominates over *reinforced concrete or steel* for this type of structural system. As an inference from the chart, it can be only said that in the supertall buildings with *mega column/mega core systems*, all types of structural material are employed at similar range.

In the chart, *shear-frame systems* only consist of shear walled frame systems, that is, none of supertall buildings utilize shear trussed frame system. At this point, even though it is generally thought that shear walled frame systems are mostly matched with reinforced concrete construction in terms of both shear walls and columns, surprisingly, the results in the chart indicate an uncommon tendency. Of the 9 supertall buildings with shear-frame system, namely shear walled frame system, 5, or about 55%, are utilizing composite - reinforced concrete core shear walls and steel perimeter columns - as the main structural material; while the rest are employing reinforced concrete.

Consequently, it can be claimed that for all the structural systems of supertall buildings except mega column/core category, *composite* shows a great dominance; whereas *steel* is the least preferred structural material. On the other hand, steel is mostly used in tube systems among the structural systems of the supertalls. 3 out of every 4 of the supertalls with outriggered frame system benefit from the merits of composite.

3.3.3 Interrelation of structural system and building form

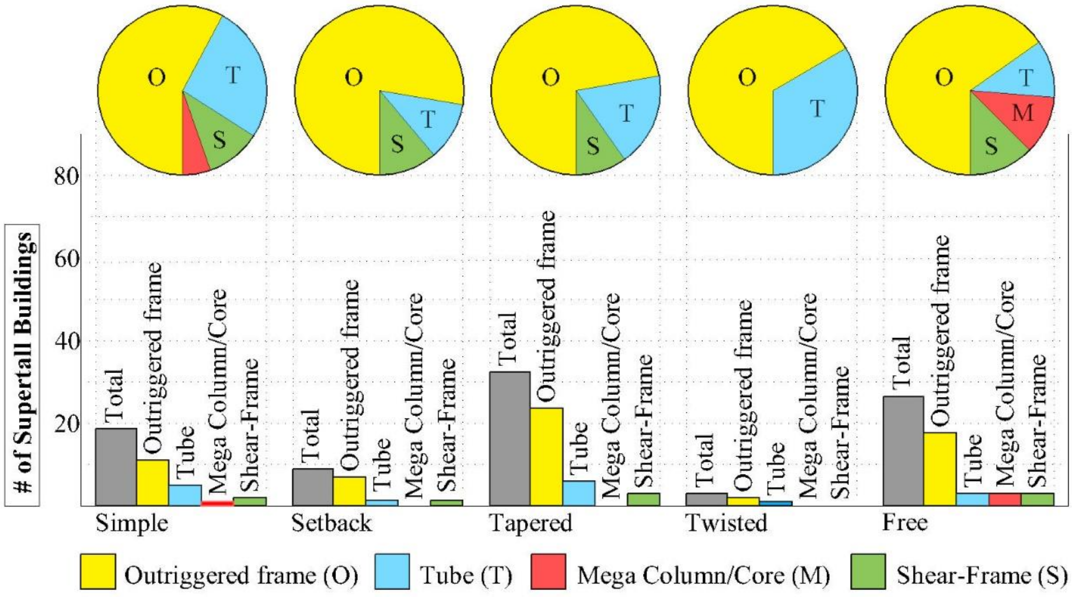
Figure 3.9 illustrates the total number of supertall building (namely 300 meters' height or greater) completions by structural system and by building form.
For each category in the structural system of supertall buildings, namely

- *outriggered frame,*
- *tube,*
- *mega column/core, and*
- *shear-frame systems*

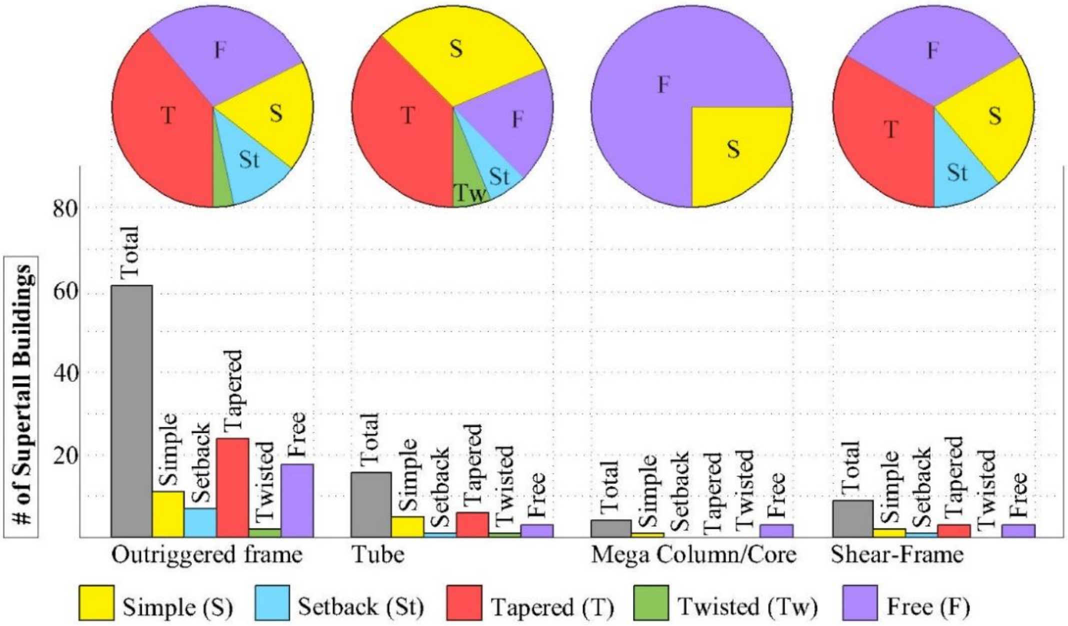
employed building forms for that type of structural system, namely

- *simple,*
- *setback,*
- *tapered,*
- *twisted, and*
- *free*

are indicated both totally and separately as bars and pie charts in different colors.



(a)



(b)

Figure 3.9 Interrelation of structural system and building form (91 buildings) (Appendix-A)

In the 62 supertall buildings with *outriggered frame system*, *tapered forms* with ratio of about 39% and *free forms* with ratio of nearly 29% are utilized as the main building forms; while only 2 are using twisted form. *Simple form* with ratio of almost 18% and *setback form* with ratio of approximately 11% are employed.

As seen in the chart, of the 16 supertall buildings with *tube system*, as the second most favorite structural system, 6, or about 38%, are utilizing tapered form as the main building form; whereas *twisted and setback forms* with ratio of nearly 8% are the least preferred form.

Since the number of supertall buildings with *mega column/mega core systems* in the sample group is very low, just 4 existed, it is hard to establish an interrelation between structural system and building form in a scientific manner. However, as an inference from the charts, it can be only said that the supertall buildings with *mega column/mega core systems*, of the 4 supertall buildings, 3 are employing *free form* as the main building form; while only 1 is utilizing *simple form*.

In the 9 supertall buildings with *shear-frame system*, *tapered forms* and free *forms* with ratio of about 33% are utilized as the main building forms; while *twisted forms* are never used.

As a result, *tapered and free forms* are mostly used for *outriggered frame and shear-frame systems;* while utilization of *tapered and simple forms* comes to forefront for *tube systems.* In addition to this, *outriggered frame systems* are dominantly preferred for all types of building forms.

3.3.4 Interrelation of structural system and building height

Figure 3.10 demonstrates the total number of supertall building (namely 300 meters' height or greater) completions by structural system and the heights of supertall buildings completed or to be completed in that year for that type of structural system, namely

- *outriggered frame,*
- *tube,*
- *mega column/core, and*
- *shear-frame systems.*

Individual supertall buildings are highlighted with dots in blue and the number of supertall buildings is represented by bars in grey.

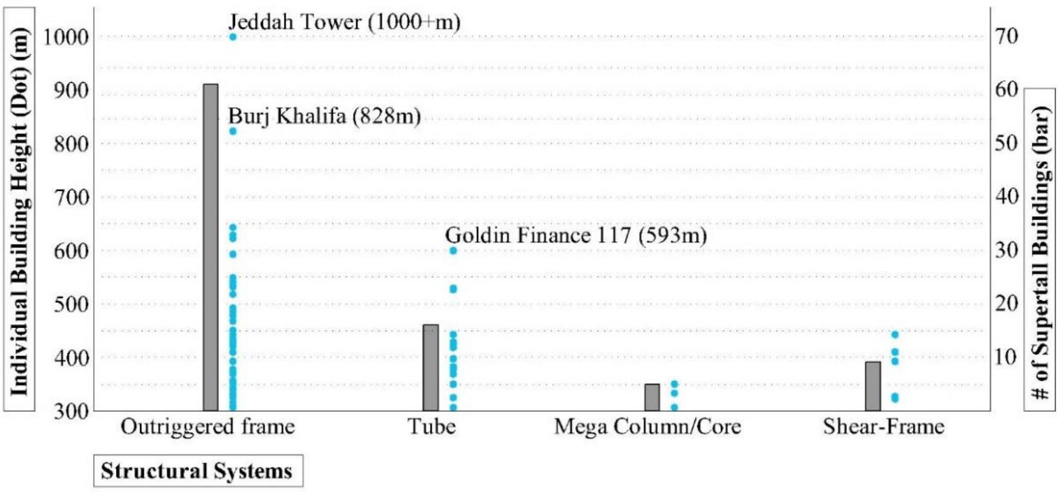


Figure 3.10 Interrelation of structural system and building height (91 buildings) (Appendix-A)

Of the 62 supertall buildings with *outriggered frame system*, 57, or about 92%, are built at the height range *between 300-600m*; while only a few of them, 5 existed, could be called as megatalls. Only 1 completed supertall building, which is titled as "World tallest", *Burj Khalifa* surpassed 800m in height. Besides this, just 1 supertall building to be completed.

10 completed tallest buildings from CTBUH database utilized *outriggered frame system* as in the case of:

- 828m high *Burj Khalifa* (Dubai, 2010),
- 632m high *Shanghai Tower* (Shanghai, 2015),
- 599m high *Ping An Finance Center* (Shenzhen, 2016),
- 554m high *Lotte World Tower* (Seoul, 2017), and
- 541m high One World Trade Center (New York, 2014).

As seen in the chart, of the 16 supertall buildings with *tube system*, as the second most favored structural system, 9, or almost 56%, are located at height range between *300-400m*; while only 1 could be included in the megatall category.

The supertall buildings with *mega column/core system*, only 4 existed, were built up to the height limit of *350m*, which means that the system is rarely preferred for supertall building construction.

Of the 11 supertall buildings with *shear-frame system*, 9, almost 81%, were constructed at the height range between *300-400m*., whereas only 2 could surpass *400m* in height.

In conclusion, *outriggered frame systems* are mostly used for the supertall buildings with height range between *300-600m*; while *tube systems* are dominantly utilized for the supertall buildings with height range between *300-400m*. On the other hand, mega *column/core and shear-frame systems* are generally employed for the supertall buildings *up to 350m high*. In *megatall* construction, *outriggered frame system* is the most favorite structural system.

3.3.5 Interrelation of structural system and core planning (core type)

Figure 3.11 presents the total number of supertall building (namely 300 meters' height or greater) completions by structural system and by core type.

For each category in the structural system of supertall buildings, namely

- *outriggered frame,*
- *tube,*
- *mega column/core, and*
- *shear-frame systems*

employed core types for that type of structural system, namely

- *central,*
- *peripheral,*
- *external, and*
- *atrium*

are indicated both totally and separately as bars and pie charts in different colors.

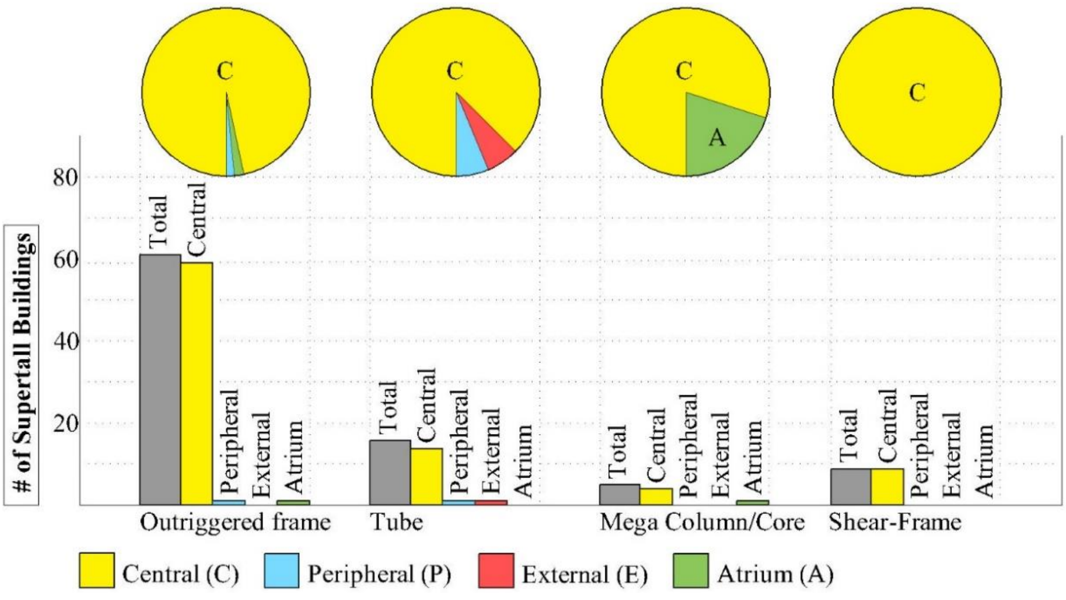


Figure 3.11 Interrelation of structural system and core type (91 buildings) (Appendix-A)

In the 62 supertall buildings with *outriggered frame system*, by a wide margin, *central core* with ratio of nearly 97% is the most preferred core type; while there is only 1 supertall building for each configuration of *peripheral and atrium cores*.

As shown in the chart, of the 16 supertall buildings with *tube system*, 13 or almost 81%, are utilizing *central core* as the main core type; whereas there is only 1 supertall building for each configuration of *peripheral and external cores*.

As abovementioned cases, *central core dominance* is also obviously seen for both *mega column/core and shear-frame systems*, where *peripheral and atrium cores* are never used.

As a conclusion, for all the structural systems of today's supertall buildings, it is obvious that *central core* is the most favored arrangement by a wide margin; whereas *peripheral, external and atrium core types* are used either once or never for each category in structural system.

3.3.6 Interrelation of timeline and structural material

Figure 3.12 shows the total number of supertall building (namely 300 meters' height or greater) completions by year and by structural material, namely

- *steel,*
- *reinforced concrete (RC), and*
- *composite*.

The number of supertall buildings completed or to be completed are indicated with bars in different colors representing related structural material for each year.

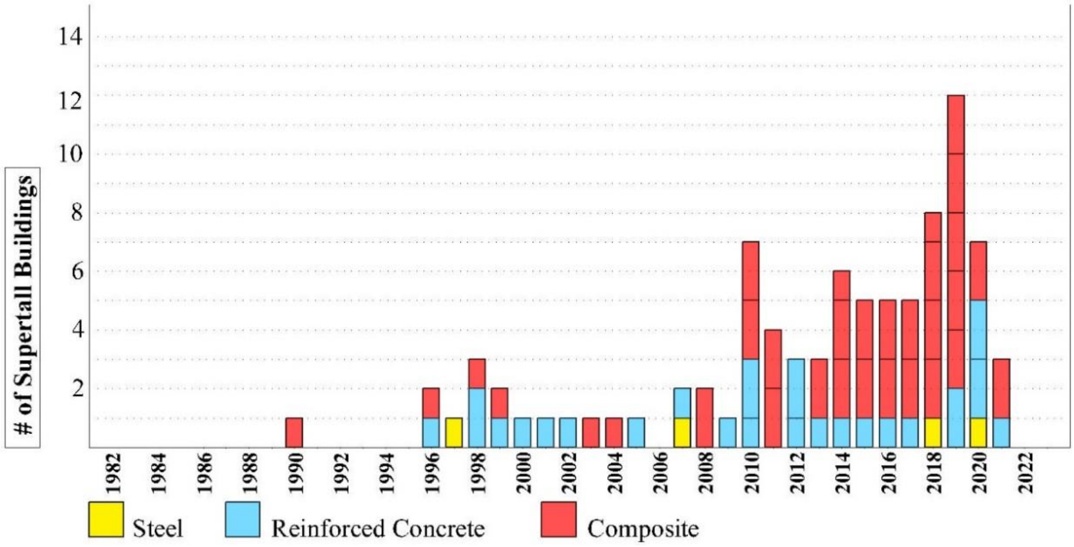


Figure 3.12 Interrelation of timeline and structural material (91 buildings) (Appendix-A)

If the chart above is overviewed in general, the red color, namely composite construction, dominance is immediately drawing the attention. Especially 2010 and later, composite as structural material has gained momentum and become the most preferred structural material today. The 10 out of 12 supertall buildings to be completed in 2019 beat every year on record in the chart as projected, including the second record expected to break with 7 completions in 2018.

As seen in the chart, reinforced concrete is the second most favored structural material. Most probably the reason behind this ratio could be explained with the booming in high-strength RC use after the construction of *Petronas Twin Towers* in 1998. After this year, reinforced concrete has begun to have an important place in the supertall building construction industry. As the strongest candidate for getting the tallest building title, *Jeddah Tower* with 1000m height also utilizes reinforced concrete as structural material.

Of the 91 supertall buildings, only 4, or about 5%, are employing steel as structural material.

- 1997 with *T&C Tower*,
- 2007 with *New York Times Tower*,
- 2018 with *Hanking Center Tower*, and
- 2020 with *Akhmat Tower*

are the years of steel construction for supertall buildings.

Overall, in the skyscraper industry, by 2010, a dramatic increase has been observed in density of *composite construction*. Through the end of 2019, it is expected to reach a peak. On the other hand, *reinforced concrete* followed a more stable trendline particularly between 1996 and 2016; while it seems to gain acceleration in the coming years.

3.3.7 Interrelation of building function and building form

Figure 3.13 illustrates the total number of supertall building (namely 300 meters' height or greater) completions by building function and by building form.
For each category in the function of supertall buildings, namely

- *multi-function,*
- *hotel,*
- *residential,*
- *office,*

employed building forms, namely

- *simple,*
- *setback,*
- *tapered,*
- *twisted, and*
- *free*

for that type of building function are indicated both totally and separately as bars and pie charts in different colors.

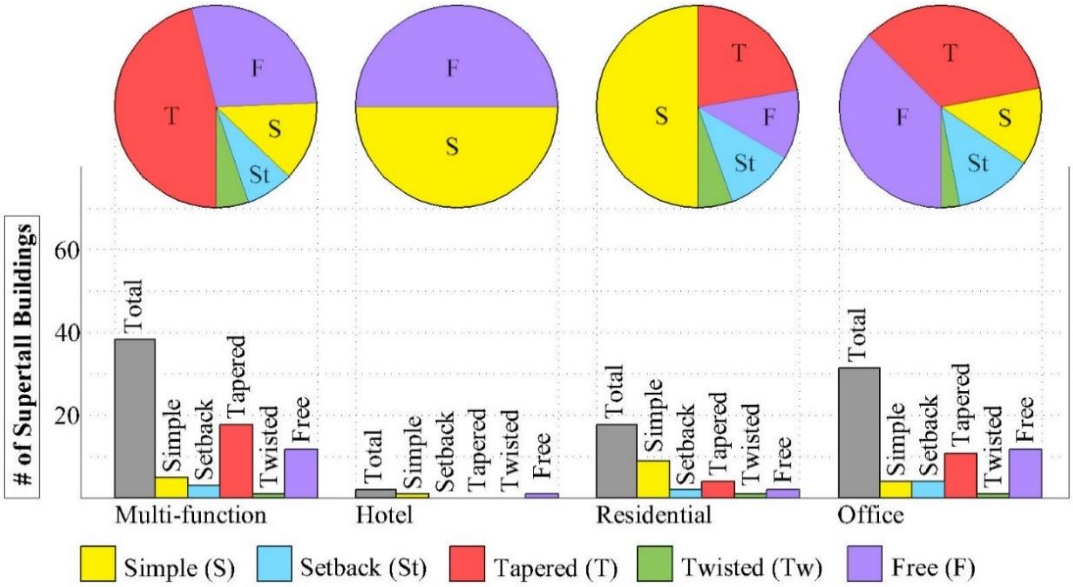


Figure 3.13 Interrelation of building function and building form (91 buildings) (Appendix-A)

In the 39 supertall buildings with *multi-function*, *tapered forms* with ratio of about 46% and *free forms* with ratio of nearly 31% are the most employed buildings forms; while only 1 is using *twisted form*. *Simple* and *setback forms* have the ratios of almost 13% and 8% respectively.

Since the number of supertall buildings with *hotel use* in the sample group is very low, only 4 existed, it does not seem possible to develop scientific interrelation among the forms employed. As an inference from the chart, it can be only said that *simple and free forms* have been utilized for *hotel use*, but there is only 1 for each group. On the other hand; *setback, tapered, and twisted forms* are not preferred for this type of use.

Of the 18 supertall buildings with *residential use*, 10, or about 55%, are utilizing *simple forms* as the main building form; while only 3 in total are using *twisted and setback forms*. In contrast to especially multi-function; *tapered form*, only 3 existed, does not show a dominance for residential use.

As seen in the chart, in the 32 supertall buildings with *office use*, *tapered and free forms* with ratio of almost 34% are the most commonly used forms as in the case of multi-function above; whereas only 1 is using *twisted form*.

Consequently, in the supertall buildings of today, *tapered and free forms* are seen to be preferable for *multi-function and office use*; while *residential use* has a tendency towards *simple forms*. On the other hand, *twisted forms* are the least common forms for all the building functions.

3.3.8 Interrelation of location and building form

Figure 3.14 shows the total number of supertall building (namely 300 meters' height or greater) completions by location and by building form.

The locations of supertall buildings, namely

- *China,*
- *United Arab Emirates (UAE),*
- *Unites States (US), and*
- *other countries* (Malaysia, Russia, Saudi Arabia, South Korea and so forth)

and employed building forms for these locations, namely

- *simple,*
- *setback,*
- *tapered,*
- *twisted, and*
- *free*

are indicated both totally and separately as bars and pie charts in different colors.

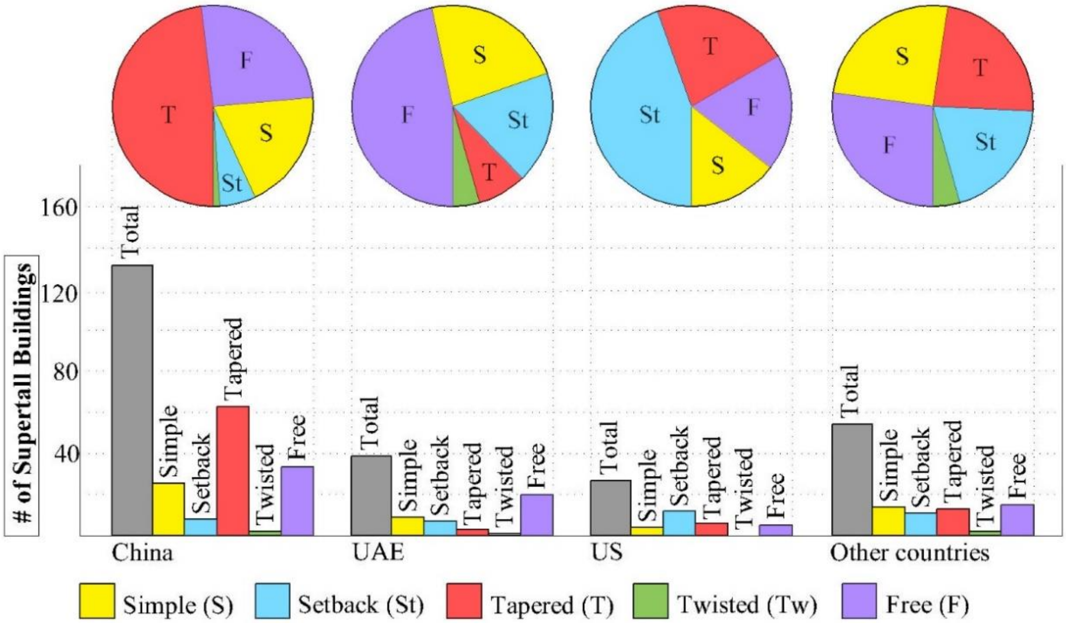


Figure 3.14 Interrelation of location and building form
(255 buildings) (Appendix-B)

Of the 134 supertall buildings in *China*, 64, or almost 48%, are using *tapered forms* as the main building form; while *setback forms* with ratio of nearly 6% and *twisted forms* with ratio of about 2% are uncommon building forms.

United Arab Emirates has 39 supertall buildings. Almost 50% of the supertalls are using *free form*; whereas *tapered forms* with ratio of nearly 7% and *twisted forms* with ratio of about 2% are rarely used building forms.

As illustrated in the chart, of the 27 supertall buildings in *United States*, 12, or almost 44%, are employing *setback forms*; whereas *twisted form* is never used. On the other hand; *simple, free, and tapered forms* are utilized in similar rates.

In other countries (Malaysia, Russia, Saudi Arabia, South Korea and so forth), *all building forms except twisted forms* are commonly used in similar rates.

As a result, it is obvious that *tapered forms* are dominantly utilized forms in *China*; while *free forms* are the most commonly used forms in *United Arab Emirates*. On the other hand, for *United States, setback forms* are the most popular forms; whereas *all the building forms except twisted forms* are employed for the supertall buildings in *other countries*.

3.3.9 Interrelation of location and structural system

Figure 3.15 shows the total number of supertall building (namely 300 meters' height or greater) completions by location and by structural system.

The locations of supertall buildings, namely

- *China,*
- *United Arab Emirates (UAE),*
- *Unites States (US), and*
- *other countries* (Malaysia, Russia, Saudi Arabia, South Korea and so forth)

and utilized structural systems for these locations, namely

- *outriggered frame,*
- *tube,*
- *mega column/core, and*
- *shear-frame systems*

are indicated both totally and separately as bars and pie charts in different colors.

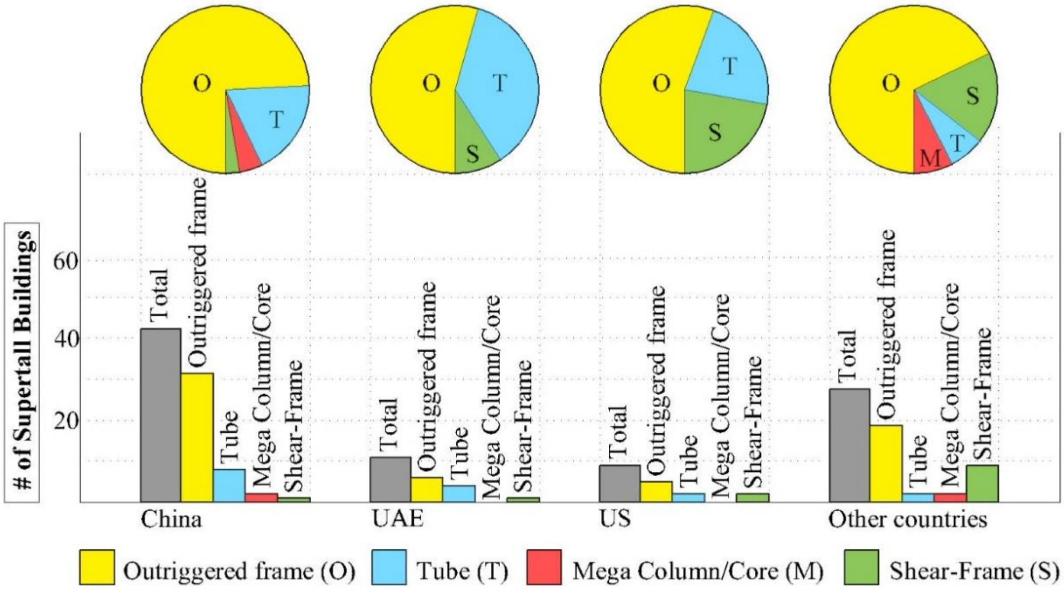


Figure 3.15 Interrelation of location and structural system (91 buildings) (Appendix-A)

Of the 43 supertall buildings in *China*, 32, or almost 74%, are employing *outriggered frame system* as the main structural system; while only 2 are using *mega column/core system* and just 1 is utilizing *shear-frame system.*

As illustrated in the chart, of the 11 supertall buildings in *United Arab Emirates*, 6, or almost 55%, are employing *outriggered frame system*; whereas only 1 is using *shear-frame system.*

United States has 9 supertall buildings, where *outriggered frame system* with ratio of nearly 55% shows a dominancy; while *mega column/core system* is never used as in the case of *United Arab Emirates.*

In the 28 supertalls of *other countries*, 19, or almost 68%, are employing *outriggered frame system* as the main structural system; whereas *tube* and *mega column/core systems* with ratio of about 14% in total are uncommon structural systems.

Overall, *outriggered frame system* is the most popular structural system all over the world. Besides utilization of this system, *tube systems* are commonly used in *United Arab Emirates;* whereas *other countries* show a tendency to employ shear-frame system in high ratios.

3.3.10 Interrelation of building height and building form

Figure 3.16 demonstrates the total number of supertall building (namely 300 meters' height or greater) completions by building form and by building height.
Different intervals for the height, namely

- *300-349m,*
- *350-399m,*
- *400-449m,*
- *450-499m,*
- *500-599m,* and
- *600m or higher*

and employed building forms for each category, namely

- *simple,*
- *setback,*
- *tapered,*
- *twisted, and*
- *free*

are indicated both totally and separately as bars and pie charts in different colors.

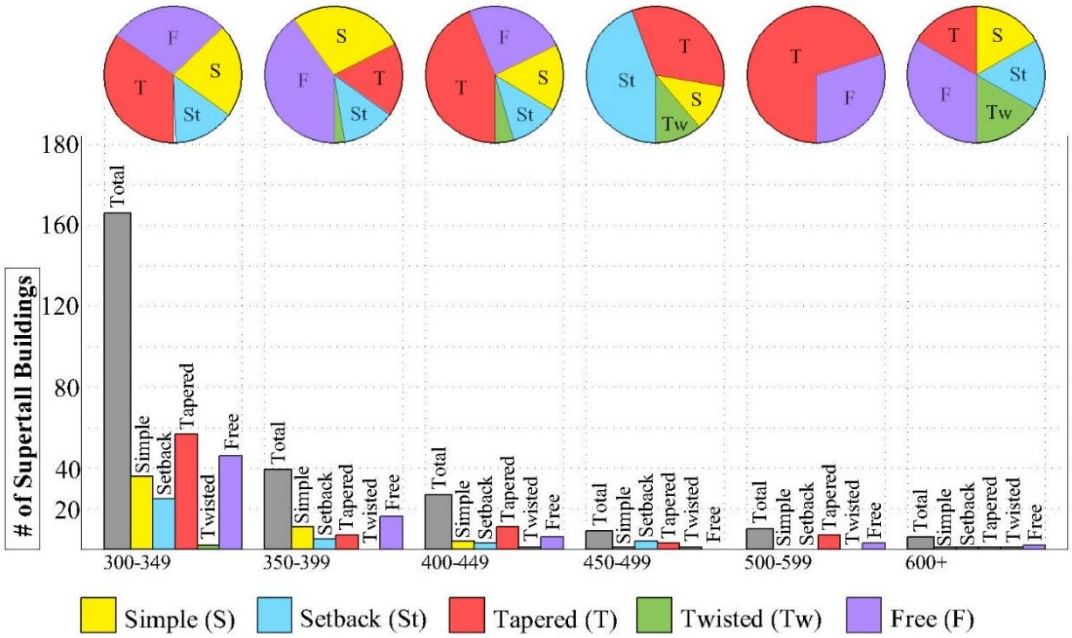


Figure 3.16 Interrelation of building height and building form (255 buildings) (Appendix-B)

In the 166 supertall buildings with height range between *300-349m*, *tapered forms* with ratio of almost 34% and *free forms* with ratio of nearly 28% are the most commonly used forms; whereas only 2 are built with *twisted forms.*

The chart also shows that of the 39 supertall buildings with height range between *350-399m*, 16, or almost 41% are employing free *forms*, and nearly 28% are utilizing *simple forms* as common forms; while *twisted form* is never used.

In the 25 supertall buildings with height range between *400-449m*, *tapered forms* with ratio of 44% are the most dominant forms; whereas only 1 is designed as *twisted form*.

As seen in the chart, *tapered and setback forms* are the most preferred forms in the 9 supertall buildings with height range between *450-499m*. There is only 1 supertall building for each group of *simple and twisted forms*; while *free forms* are never employed.

Of the 10 supertall buildings with height range between *500-599m*, 70% are employing *tapered forms*, and 30% are utilizing *free forms*. *Simple, setback, and twisted forms* are never used.

In the 6 supertall buildings of *600m or higher*, there is only 1 supertall building for each group of *simple, tapered, setback, and twisted forms*; while *free forms* are utilized for 2 supertalls.

In conclusion, *tapered and free forms* are the most commonly used forms for the height ranges between *300-349m, 400-449m and 500-599m*. The supertall buildings with height range between *350-399m* are generally built with *free and simple forms*; while *tapered and setback forms* are the most popular for the supertalls constructed in height range between *450-499m*. On the other hand, all the building forms are employed for *megatall* category.

3.3.11 Interrelation of building height and building function

Figure 3.17 indicates the total number of supertall building (namely 300 meters' height or greater) completions by building function and by building height.
Different intervals for the building height, namely

- *300-349m,*
- *350-399m,*
- *400-449m,*
- *450-499m,*
- *500-599m,* and
- *600m or higher*

and dedicated building functions for each category, namely

- *multi-function,*
- *hotel,*
- *residential, and*
- *office*

are indicated both totally and separately as bars and pie charts in different colors.

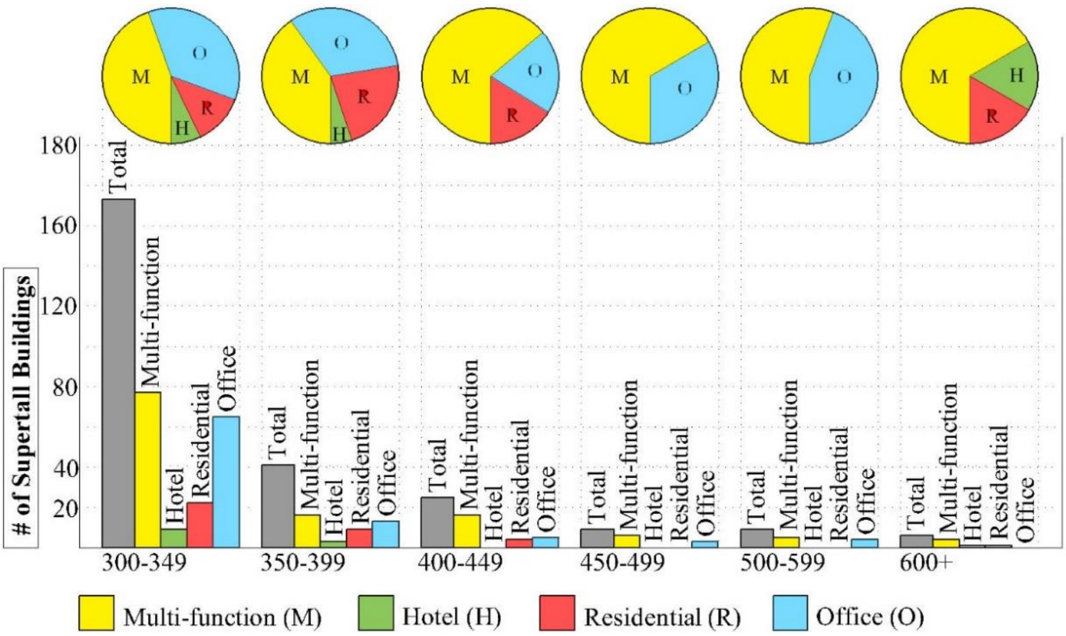


Figure 3.17 Interrelation of building height and building function (255 buildings) (Appendix-B)

As shown in the chart, in the 173 supertall buildings with height range between *300-349m*, *multi-function* with ratio of almost 45% and *office* with ratio of nearly 38% are the most commonly preferred functions; whereas *residential use* with ratio of about 13% is dedicated. Just 9 supertall buildings are designed as *hotel use* only.

As in the case of abovementioned group, of the 41 supertall buildings with height range between *350-399m*, *multi-function* with ratio of almost 39% and *office* with ratio of nearly 32% are the most dedicated functions; while just 3 supertall buildings are designed as *hotel use* only.

In the 25 supertall buildings with height range between *400-449m*, *multi-function* shows a great dominance with ratio of about 64%; whereas *hotel* is never employed.

The chart illustrates that *multi-function* is the most preferred use in the 9 supertall buildings with height range between *450-499m*; while *hotel and residential* use are never dedicated.
The 9 supertall buildings with height range between *500-599m* are mostly built with *multi-function and office use*; whereas *hotel and residential use* are never preferred.

In the 6 supertall buildings of *600m or higher*, there is only 1 supertall building for each group of *hotel and residential use*; while *multi-function* is the most common use.

Overall, supertall buildings are mostly designed as *multi-function*. *Office* is also highly dedicated function among all the function in supertall construction. As single use, *hotel and residential* have never been encountered for the height ranges between *450-499m and 500-599m*.

3.3.12 Interrelation of aspect ratio and structural system

Figure 3.18 demonstrates the total number of supertall building (namely 300 meters' height or greater) completions by aspect ratio and by structural system.
Different intervals for the aspect ratio, namely

- *6-6.9,*
- *7-7.9,*
- *8-8.9,*
- *9-9.9,*
- *10-14.9,* and
- *15 or higher*

and employed structural systems for each category, namely

- *outriggered frame,*
- *tube,*
- *mega column/core, and*
- *shear-frame systems*

are indicated both totally and separately as bars and pie charts in different colors.

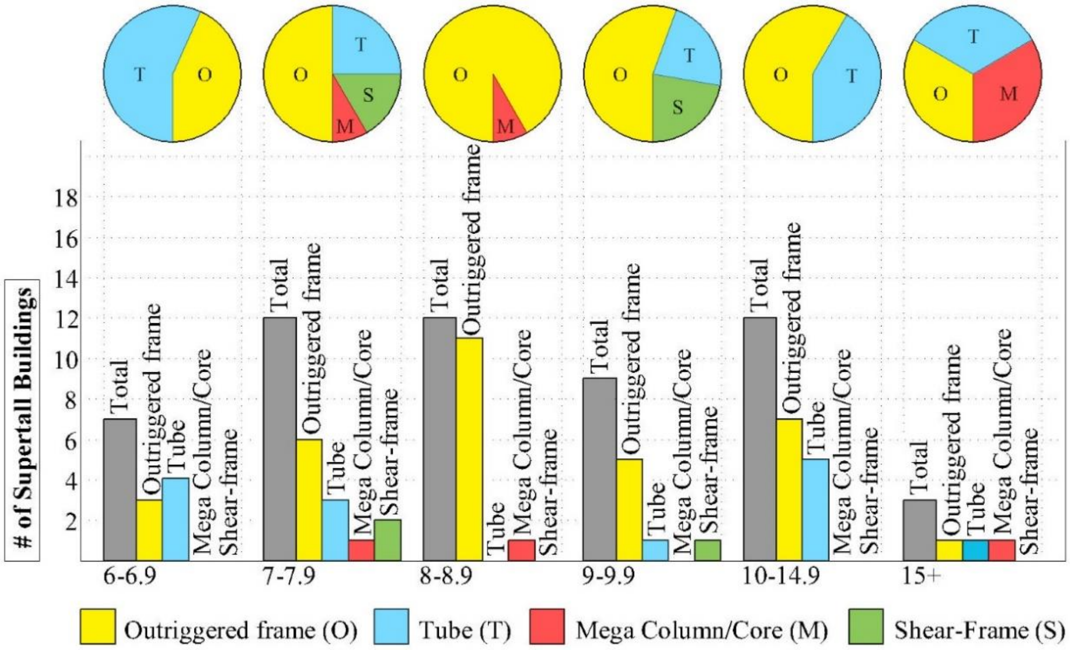


Figure 3.18 Interrelation of aspect ratio and structural system (55 buildings) (Appendix-A)

In the 7 supertall buildings with aspect ratio between *6-6.9*, *outriggered frame and tube systems* are the most commonly used structural systems; whereas *mega column/core and shear frame systems* are never used.

The chart illustrates that of the 12 supertall buildings with aspect ratio between *7-7.9*, 50% are employing *outriggered frame system*; while *only 1* is using *mega column/core system*.

In the 12 supertall buildings with aspect ratio between *8-8.9*, 11 are utilizing *outriggered frame system*; whereas *only 1* is built with *mega column/core system*.

As shown in the chart, for the supertall buildings with aspect ratios between *9-9.9* and *10-14.9, outriggered frame systems* with ratios of about 78% and 58% respectively, are the most dominantly used systems; while *mega column/core systems* are never employed.

The supertall buildings with aspect ratio of 15 or higher are constructed with all the structural systems except shear-frame system.

Consequently, the supertall buildings with aspect ratios between *7-9.9 and 10-15* are dominantly built with *outriggered frame system; whereas* for the supertall buildings with aspect ratio between 6-6.9, namely relatively less slender supertalls, commonly prefer *tube systems*. On the other hand, all types of structural systems except shear-frame are employed for the slenderest supertalls in equal rates.

3.3.13 Interrelation of aspect ratio and building form

Figure 3.19 shows the total number of supertall building (namely 300 meters' height or greater) completions by aspect ratio and by building form.
Different intervals for the aspect ratio, namely

- *6-6.9,*
- *7-7.9,*
- *8-8.9,*
- *9-9.9,*
- *10-14.9,* and
- *15 or higher*

and employed building forms for each category, namely

- *simple,*
- *setback,*
- *tapered,*
- *twisted, and*
- *free*

are indicated both totally and separately as bars and pie charts in different colors.

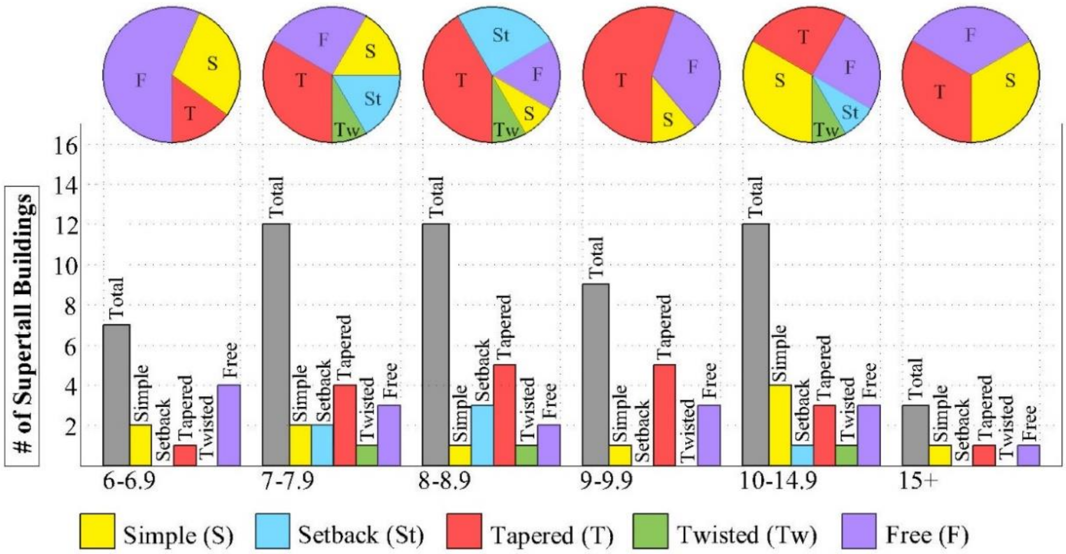


Figure 3.19 Interrelation of aspect ratio and building form (55 buildings) (Appendix-A)

In the 7 supertall buildings with aspect ratio between *6-6.9*, *free forms* are the most commonly used forms; whereas *setback and twisted forms* are never used.

The chart demonstrates that *tapered forms* with 33% *and free forms* with 25% are mostly employed forms for the 12 supertall buildings with aspect ratio between *7-7.9*; while *only 1* is using *twisted form*.

In the 12 supertall buildings with aspect ratio between *8-8.9*, 42% are utilizing *tapered forms*; whereas *twisted and simple forms* are the least employed forms.

As presented in the chart, for the supertall buildings with aspect ratio between *9-9.9*, *tapered forms* with ratio of about 42% and *free forms* with ratio of almost 33% are the most dominantly used forms; while *setback and twisted forms* are never used.

The chart shows that *simple form* with ratio of nearly 33% is the most dominant form for the 12 supertall buildings with aspect ratio between *10-14.9*; while *setback and twisted forms* are employed for only 2 in total.

The supertall buildings with aspect ratio of *15 or higher* are built with all the building forms *except setback and twisted forms*.

As a conclusion, the supertall buildings with aspect ratios between *7-9.9*, are dominantly built with *tapered forms;* whereas the supertall buildings with aspect ratio between *6-6.9*, namely relatively less slender supertalls, commonly prefer *free forms*. On the other hand, *simple form* dominancy is observed for the supertall buildings with aspect ratio between *10-14.9*.

3.3.14 Interrelation of aspect ratio and building height

Figure 3.20 illustrates the total number of supertall building (namely 300 meters' height or greater) completions by aspect ratio and by building height.
Different intervals for the aspect ratio, namely

- *6-6.9,*
- *7-7.9,*
- *8-8.9,*
- *9-9.9,*
- *10-14.9,* and
- *15 or higher*

and different height intervals for each category namely

- *300-349m,*
- *350-399m,*
- *400-449m,*
- *450-499m,*
- *500-599m*, and
- *600m or higher*

are indicated both totally and separately as bars and pie charts in different colors.

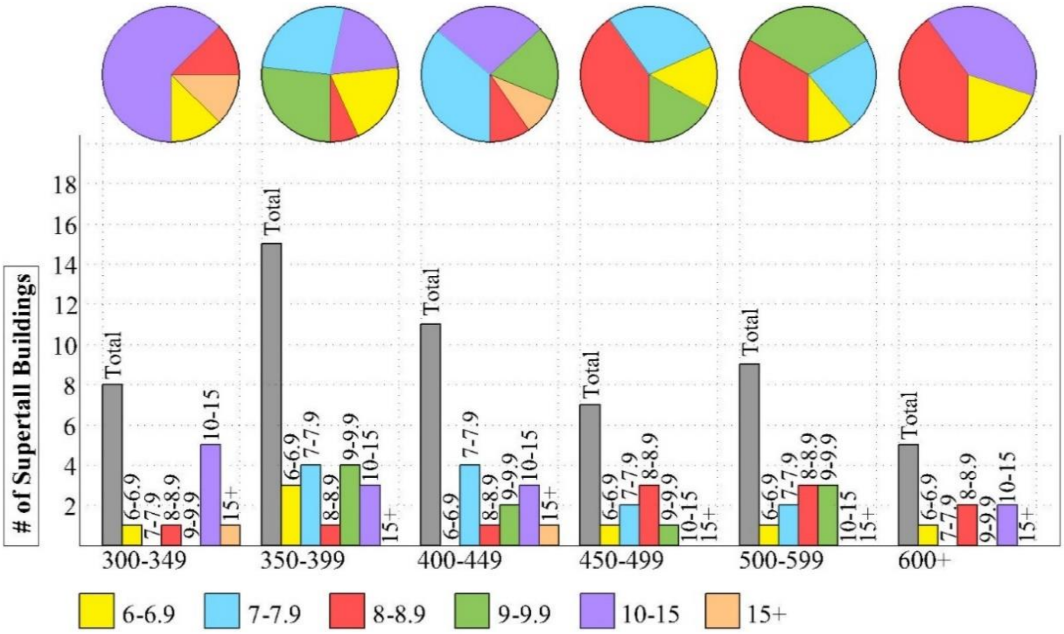


Figure 3.20 Interrelation of aspect ratio and building height (55 buildings) (Appendix-A)

As shown in the chart, in the 8 supertall buildings with height range between *300-349m*, the supertalls having aspect ratio between *10-15* with ratio of almost 63% show a great dominancy; whereas the supertalls with aspect ratios between *7-7.9 and 9-9.9* have not been encountered.

Of the 15 supertall buildings with height range between *350-399m*, totally 8, or more than 50%, are built in aspect ratios between *7-7.9 and 9-9.9*; while there is no supertall building with aspect ratio of *15 or higher*.

In the 11 supertall buildings with height range between *400-449m*, the aspect ratios between *7-7.9 and 10-15* are mostly employed. On the other hand, only 2 supertalls are designed with aspect ratios between *8-8.9 and 15 or higher*.

The chart demonstrates that aspect ratio between *8-8.9* is the most preferred for the design of supertall buildings with height range between *450-499m; whereas* the supertalls with aspect ratios between *10-15 and 15 or higher* have not been encountered as in the case of the height range between *500-599m.*
The 9 supertall buildings with height range between *500-599m* are mostly built in aspect ratios between *8-8.9* and *9-9.9*; while *megatall buildings (600m or higher)* have generally aspect ratios between *8-8.9* and *10-15.*

As a result, the supertall buildings with height range between *350-399m* and *400-449m* are generally designed in aspect ratio between *7-7.9*; whereas the height ranges between *450-499m* and *500-549m* are commonly built in aspect ratio between *8-8.9.* On the other hand, aspect ratio between *6-6.9* is mostly employed for the height range between *300-349m.*

CHAPTER 4

POTENTIALS AND LIMITATIONS OF SUPERTALL BUILDING STRUCTURAL SYSTEMS IN RELATION TO ARCHITECTURAL AND AERODYNAMIC FORM

4.1 Simple/extruded Forms

Simple/extruded form refers to building form with two ends are similar, equal, and parallel figures, whose sides are identical, and whose axle are fully vertical, could be designed by means of all the structural systems discussed in this research:

- *shear walled,*
- *mega column,*
- *mega core,*
- *outriggered frame and*
- *tube systems*

as in the case of:

- *CITIC Plaza (Guangzhou, 1996)* (Figure 4.1a)
  with shear walled system,
- *The Center* (Hong Kong, 1998) (Figure 4.1b)
  with mega column system,
- *New York Times Tower* (New York, 2007) (Figure 4.1c)
  with outriggered frame system,
- *432 Park Avenue* (New York, 2015) (Figure 4.1d)
  with framed-tube system in structurally adaptive manner or not.

(a) (b) (c) (d)

Figure 4.1 Simple/extruded forms
(a) CITIC Plaza, Guangzhou, 1996 (www.ctbuh.org);
(b) The Center, Hong Kong, 1998 (www.ctbuh.org);
(c) New York Times Tower, New York, 2007 (www.ctbuh.org);
(d) 432 Park Avenue, New York, 2015 (www.ctbuh.org)

By its nature, in particular box-shaped like simple forms free from major aerodynamic considerations could employ all the supertall buildings' structural systems efficiently from structural point of view. On the other hand, if cage like façade is desired to create in structurally adaptive manner, because of closely spaced columns and deep spandrel beams, framed-tube system could be an ideal selection as in the case of *432 Park Avenue* (New York, 2015) (Figure 4.1d).

In addition to this, "*articulated simple/extruded forms"* (Figure 4.1a), which having some minor façade articulations like recessed, cut corner through the building height, or "*articulated simple/extruded form with architectural top*", which have some minor architectural modification/articulation particularly on the building top, could show a tendency for mitigation of wind loading aerodynamically.

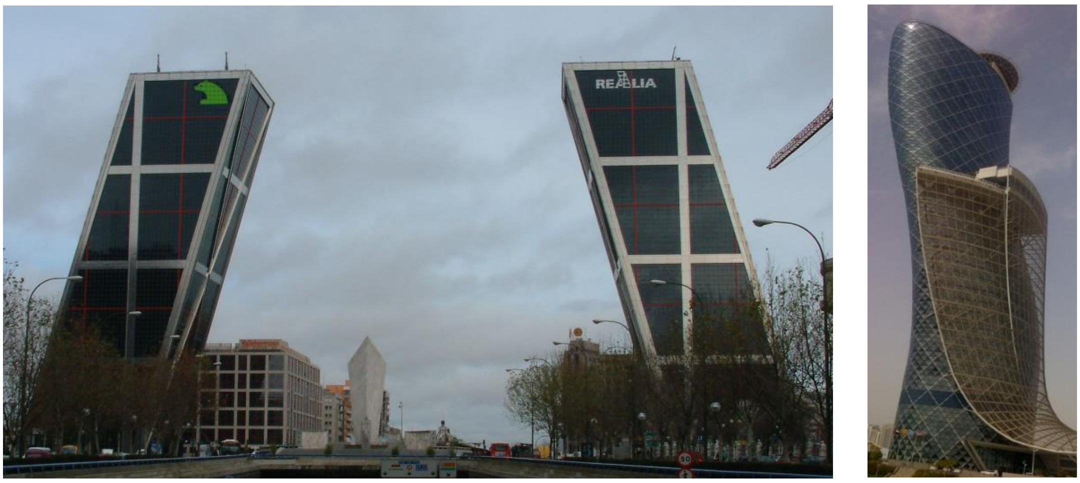
From aerodynamic point of view, utilization of simple/extruded forms with cylindrical or elliptical plan is advantageous. They are exposed to less wind pressure than simple forms with rectangular plan. For buildings having circular plan, the wind load is about 20% less, compared with buildings having a rectangular plan (Taranath, 2005).

As a result, in supertall building design, all types of structural systems can be utilized efficiently for *simple/extruded forms*. On the other hand, simple forms *except box-like* shape could be preferred to create *aerodynamically adaptive forms*.

4.2 Leaning/tilted Forms

Leaning/tilted form refers to buildings with inclined form as in the case of:

- *Puerta de Europa Complex* (Madrid, 1996) (Figure 4.2a), and
- *Capital Gate Tower* (Abu Dhabi, 2011) (Figure 4.2b).



(a) (b)

Figure 4.2 Leaning/tilted forms
(a) Puerta de Europa Complex, Madrid, 1996 (www.ctbuh.org);
(b) Capital Gate Tower, Abu Dhabi, 2011 (www.ctbuh.org)

From structural point of view, utilization of tilted forms is not advantageous in terms of gravity loads. The structural performance of these forms is dependent upon its structural system and the angle of tilt. Supertall buildings with tilted form are subjected to significant initial lateral deformations due to eccentric gravity loads (Moon, 2014; Moon, 2015a). Gravity-induced lateral displacements increase as the angle of tilt increases. Compared to the tube systems, the outriggered frame system provides fairly greater lateral stiffness for tilted forms owing to the triangulation of the major structural components (Moon, 2014; Moon, 2015a; Choi *et al.*, 2017) (Figure 4.3).

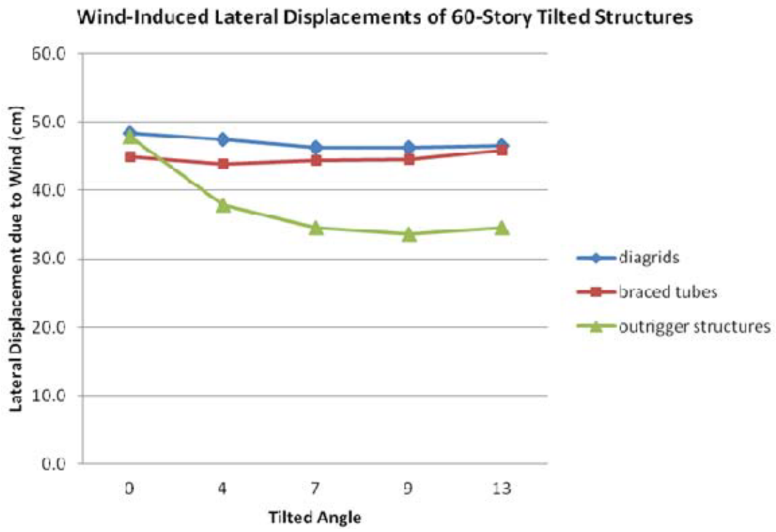


Figure 4.3 Maximum lateral displacement of 60-story tilted structures (Moon, 2015a)

During design of a leaning/tilted form, one of the structural challenges is to overwhelm the effects of gravity-induced overturning moments. Such overturning characteristically causes deflection in the direction of the lean, which adds to the overall wind-induced deflections (Figure 4.4a) (Almusharaf, 2011).

The gravity-induced overturning moment could sometimes surpass that of wind, which is an uncommon condition in supertall buildings whose design is usually governed by lateral loads. In order to minimize excessive overturning forces, one basic method is to modify architectural form in such a way that its overall mass is concentrated near the base where it meets the ground (Figure 4.4b) (Almusharaf, 2011).

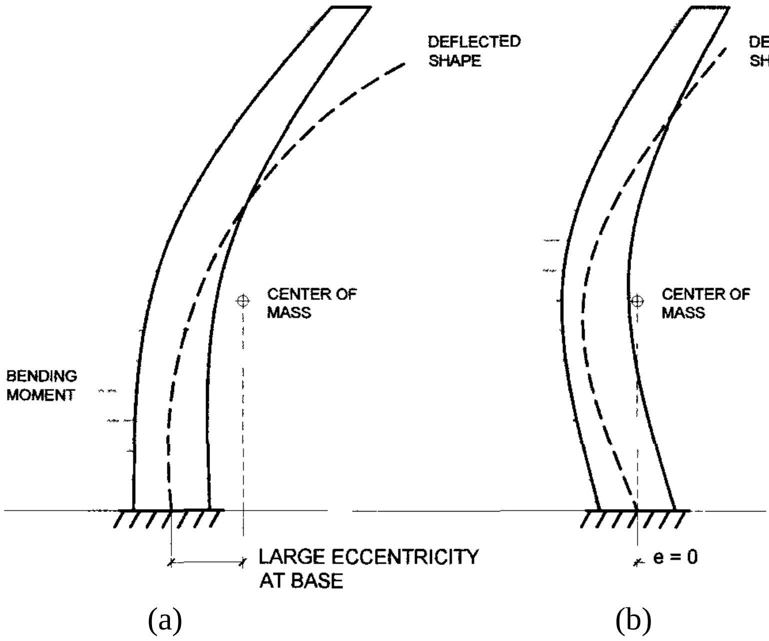


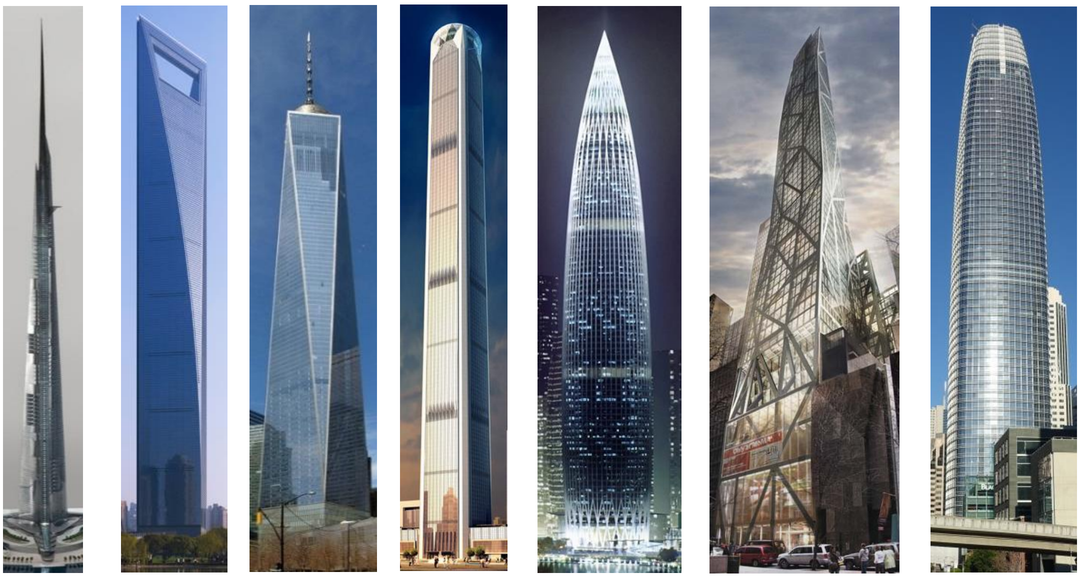
Figure 4.4 Minimizing the bending moments by centering the mass of the building near the base support in leaning form (Almusharaf, 2011)

In conclusion, from structural point of view, even though the use of *tilted forms* is not favorable regarding gravity loads, outriggered frame systems are preferred over tube systems in terms of lateral loads. On the other hand, any researches have been encountered to examine aerodynamic performance of supertall buildings with tilted/leaning forms in the literature.

4.3 Tapered Forms

Tapered form refers to buildings with tapering effect by reduced floor plans and surface areas through the height into either linear or non-linear profiles as in the case of:

- *Jeddah Tower* (Jeddah, under construction) (Figure 4.5a)
- *Shanghai World Financial Center* (Shanghai, 2008) (Figure 4.5b),
- *One Word Trade Center* (New York, 2014) (Figure 4.5c),
- Goldin Finance 117 (Tianjin, under construction) (Figure 4.5d),
- China Resources Headquarters (Shenzhen, under construction) (Figure 4.5e),
- 53 West 53rd (New York, under construction) (Figure 4.5f),
- *Salesforce Tower* (San Francisco, under construction) (Figure 4.5g).



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

Figure 4.5 Tapered forms
(a) Jeddah Tower, Jeddah, under construction (www.ctbuh.org);
(b) SWFC, Shanghai, 2008 (www.ctbuh.org);
(c) One World Trade Center, New York, 2014 (www.ctbuh.org);
(d) Goldin Finance 117, Tianjin, under construction (www.ctbuh.org);
(e) China Resources Headquarters, Shenzhen, under construction (www.ctbuh.org);
(f) 53 West 53rd, New York, under construction (www.ctbuh.org);
(g) Salesforce Tower, San Francisco, under construction (www.ctbuh.org)

From architectural point of view, tapered forms can be often more desirable for multi-function supertall buildings to house different function by offering various lease span opportunities.

From structural point of view, utilization of tapered forms is advantageous. Owing to greater building width, tapered forms show more resistance to shear and overturning moments resulting from lateral loads than prismatic forms. As the angle of taper increases, the lateral stiffness of the structural system (diagrid-framed-tube and trussed-tube system) increases (Moon, 2015a) (Figure 4.6) and the wind loads applied to the structure decreases as in the case of:

- *John Hancock Center* (Chicago, 1969) (Figure 2.20a),
- *Jeddah Tower* (Jeddah, under construction) (Figure 4.5a), and
- *One World Trade Center* (New York, 2014) (Figure 4.5c).

Performance of tapered outriggered frame systems are somewhat different from those of tapered diagrid-framed-tube and trussed-tube system, since the stiffness of lower level outriggers is reduced as the building is tapered because of their increased length. However, the lateral stiffness of outriggered frame system still significantly increases as the angle of taper increases (Moon, 2015a).

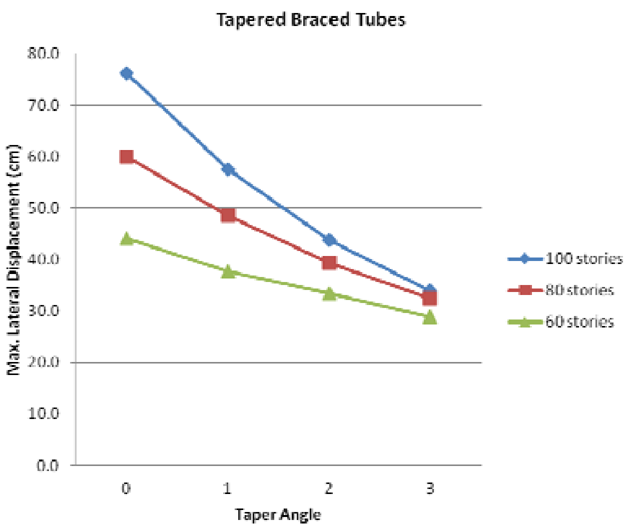


Figure 4.6 Maximum lateral displacement of 60-story tapered braced-tube system (Moon, 2015a)

In order to generate structurally adaptive tapered form, *trussed-tube* and *diagrid-framed-tube systems* could be favorable choices as in the case of *John Hancock Center* (Chicago, 1969) (Figure 2.20a) and *Goldin Finance 117* (Tianjin, under construction) (Figure 4.5d) with trussed-tube system, and *China Resources Headquarters* (Shenzhen, under construction) (Figure 4.5e) and *53 West 53rd* (New York, under construction) (Figure 4.5f) with diagrid-framed-tube system.

If the architect desires loosely spaced columns on the façade, *trussed-tube system* could be employed; while if triangulated façade is expected to create with relatively smaller elements due to the elimination of columns, *diagrid-framed-tube system* could be used.

Outriggered frame system as in the case of *Jeddah Tower* (Jeddah, under construction) (Figure 4.5a) and *shear walled frame system* as in the case of *Salesforce Tower* (San Francisco, under construction) (Figure 4.5g) also can be utilized to produce tapered form due to inclined perimeter columns.

From aerodynamic point of view, utilization of tapered forms is advantageous. Owing to the utilization of tapering effect in supertall buildings, lateral drift can be reduced by 10 to 50% (Schueller, 1977). An analytical study by Khan (1972) has shown that, by creating a slope of 8% in the façade of a 40-story building, a 50% reduction of the lateral drift in the upper stories can be obtained. Tapered forms also reduce the downward wash of turbulent wind gusts that often exists around tall buildings (Nordenson and Riley, 2003; Park, 2005).

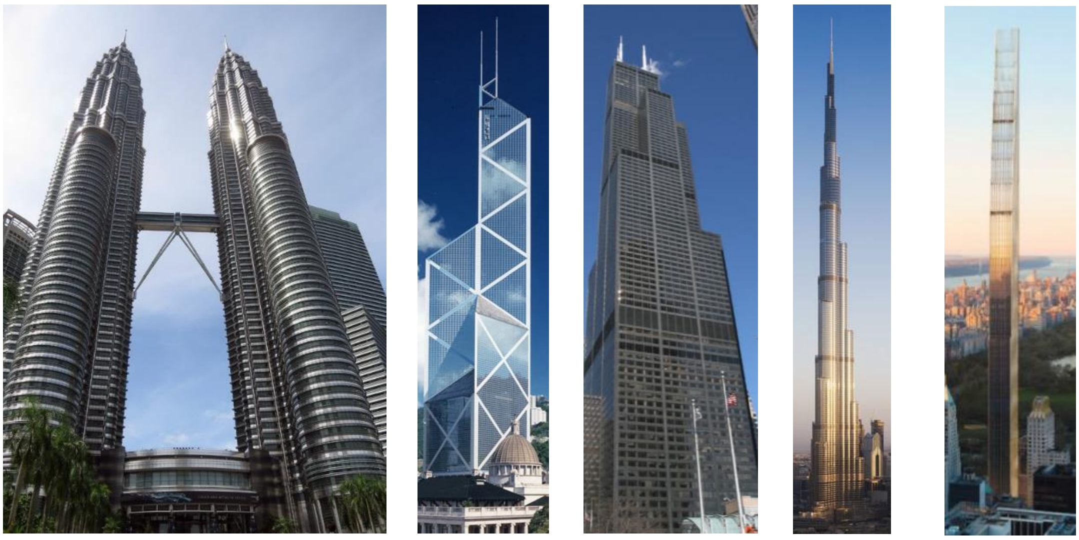
As a consequence, in the design of supertall building, utilization of *tapered forms* offers numerous advantages architecturally, structurally and also aerodynamically. The use of shear walled frame, outriggered frame, framed-tube, especially diagrid, and also trussed-tube systems could enable to create structurally and aerodynamically adaptive tapered forms.

4.4 Setback Forms

Setback forms refer to buildings with recessed horizontal sections through the height of the building as in the case of:

- *Petronas Twin Towers* (Kuala Lumpur, 1998) (Figure 4.7a),
- *Bank of China Tower* (Hong Kong, 1990) (Figure 4.7b),

- *Willis Tower* (Chicago, 1974) (Figure 4.7c),
- *Burj Khalifa* (Dubai, 2010) (Figure 4.7d),
- *111 West 57th Street* (New York, under construction) (Figure 4.7e).



(a) (b) (c) (d) (e)

Figure 4.7 Setback forms
(a) Petronas Twin Towers, Kuala Lumpur, 1998 (www.ctbuh.org);
(b) Bank of China Tower, Hong Kong, 1990 (www.ctbuh.org);
(c) Willis Tower, Chicago, 1974 (www.ctbuh.org);
(d) Burj Khalifa, Dubai, 2010 (www.ctbuh.org);
(e) 111 West 57th Street, New York, under construction (www.ctbuh.org)

From architectural point of view, setback forms can be more desirable for multi-function supertall buildings to accommodate different function by offering various lease span opportunities as in the case of tapered forms.

From structural point of view, utilization of setback forms could not be advantageous, since they present several problems at the setback location. Structurally, the number of setbacks and their rates should be carefully considered with transferring beam, transferred column, column setback distance, and locations. In this context, utilization of *outriggered frame system* can be an ideal solution to overcome the structural problems resulting from the irregularities of columns at setback locations through the building height as in the case of *111 West 57th Street* (New York, under construction) (Figure 4.7e).

By its nature, *bundled-tube system* also can be considered as an ideal system for setbacks arrangement. In this system, different shapes, such as rectangles and triangles, and dimensions are obtained by ending tubes at the desired levels as in the case of *Willis Tower* (Chicago, 1974) (Figure 4.7c). In addition to this, trussed-tube system could be utilized to generate setback form in structurally adaptive manner as in the case of *Bank of China Tower* (Hong Kong, 1990) (Figure 4.7b).

From aerodynamic point of view, utilization of setback forms is advantageous as in the case of *Burj Khalifa* (Dubai, 2010) (Figure 4.7d). In the tower, the wind vortexes never become organized, which creates “confusing” effect for the wind since at each new tier the wind encounters a different building shape, allowing for a very economical structure (Weismantle *et al.*, 2007).

As a consequence, employment of *setback forms* presents several advantages architecturally and aerodynamically; while these forms could cause drawbacks from structural point of view, but these problems could be eliminated owing to utilization of outriggered frame, trussed-tube and bundled systems, which enables to create structurally and aerodynamically adaptive forms in the design of supertall building.

4.5 Twisted Forms

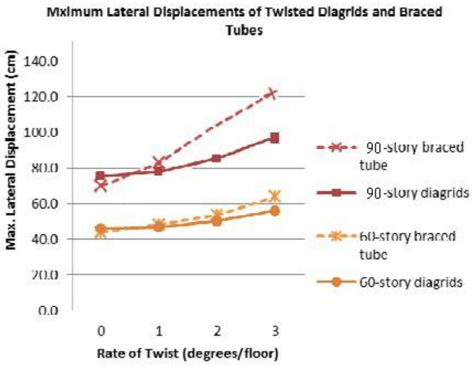
Twisted form refers to buildings with rotating floors as they multiply upward along an axis by inputting a twist angle as in the case of:

- *Cayan Tower* (Dubai, 2013) (Figure 4.8a),
- *Evolution Tower* (Moscow, 2015) (Figure 4.8b),
- *Lakhta Center* (St. Petersburg, under construction) (Figure 4.8c), and
- *Shanghai Tower* (Shanghai, 2015) (Figure 4.8d).

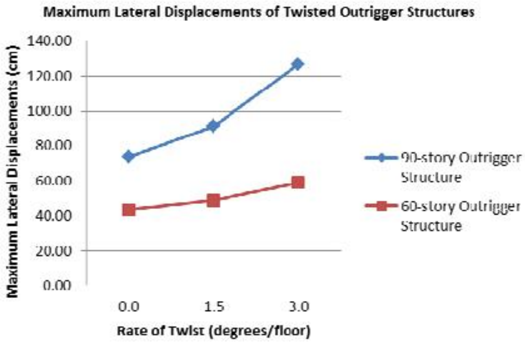
(a) (b) (c) (d)

Figure 4.8 Twisted forms
(a) Cayan Tower, Dubai, 2013 (www.ctbuh.org);
(b) Evolution Tower, Moscow, 2015 (www.ctbuh.org);
(c) Lakhta Center, St. Petersburg, under construction (www.ctbuh.org);
(d) Shanghai Tower, Shanghai, 2015 (www.ctbuh.org)

From structural point of view, utilization of twisted forms is not advantageous. The lateral stiffness of a twisted building is smaller than that of the straight building (Ali and Moon, 2007). If diagrid-framed-tube and trussed-tube systems are employed for twisted supertall buildings, lateral stiffness of these systems decreases as the rate of twist increases (Moon, 2010; Moon, 2015a). The stiffness reduction of trussed-tube system is more sensitive to the rate of twist, compared to that of diagrid-framed-tube system and this sensitivity is accelerated as the building height increases (Figure 4.9a) (Moon, 2015a). Similarly, lateral stiffness of outriggered framed system significantly reduces as the rate of twist increases (Figure 4.9b) (Moon, 2015a).



(a)



(b)

Figure 4.9 (a) Maximum lateral displacement of twisted diagrid-framed-tube system and trussed-tube system;
(b) Maximum lateral displacement of twisted outriggered frame system (Moon, 2015a)

Outriggered frame system as in the case of *Lakhta Center* (St. Petersburg, under construction) (Figure 4.8c) and *framed-tube system* as in the case of *Cayan Tower* (Dubai, 2013) (Figure 4.8a) can be employed to create twisted forms in structurally adaptive manner owing to perimeter twisted columns.

If a supertall building with twisted form is intended to design in structurally efficient manner, *mega core system* could be one of the favorite structural system since the structure does not twist. At this point, obtaining panoramic view could be a significant parameter for residential facilities owing to the location of main lateral and vertical load resisting structural elements at the center instead of perimeter. By means of a mega core and rotating cantilever slabs positioned with desired angles and shapes, twisted forms could be generated but in structurally inadaptive manner as in the case of *Turning Torso* (Malmö, 2005) (Figure 2.29).

From aerodynamic point of view, utilization of twisted forms could be advantageous. In particular the across-wind direction, it should be noted that twisted form generally performs better than a similar prismatic one, as it can mitigate wind-induced vibrations by disturbing the development of organized alternating vortexes (Amin and Ahuja, 2010; Moon, 2011; Moon, 2015a) as in the case of:

- *Cayan Tower* (Dubai, 2013) (Figure 4.8a), and
- *Shanghai Tower* (Shanghai, 2015) (Figure 4.8d).

As a consequence, in the design of supertall building, utilization of *twisted forms* is advantageous aerodynamically; whereas they create problems structurally. For twisted forms, (diagrid)-framed-tube, trussed-tube and outriggered frame systems could be utilized in structurally adaptive manner; whereas mega core system could be employed in structurally unadaptive manner.

4.6 Free Forms

Free form refers to buildings which is out of the abovementioned forms as in the case of:

- *Al Hamra Tower* (Kuwait, 2011) (Figure 4.10a),
- *CCTV Headquarters* (Beijing, 2012) (Figure 4.10b),
- *Capital Market Authority Tower* (Riyadh, under construction) (Figure 4.10c), and
- *Guangzhou International Finance Center* (Guangzhou, 2010) (Figure 4.10d).

(a) (b) (c) (d)

Figure 4.10 Free forms
(a) Al Hamra Tower, Kuwait city, 2011 (www.ctbuh.org);
(b) CCTV Headquarters, Beijing, 2012 (www.ctbuh.org);
(c) Capital Market Authority Tower, Riyadh, under construction (www.ctbuh.org);
(d) Guangzhou International Finance Center, Guangzhou, 2010 (www.ctbuh.org)

If a supertall building with free form is intended to design in structurally and aerodynamically adaptive manner, as in the case of:

- *Bank of China Tower* (Hong Kong, 1990) (Figure 4.7b),
- *Capital Market Authority Tower* (Riyadh, under construction) (Figure 4.10c),
- *Guangzhou International Finance Center* (Guangzhou, 2010) (Figure 4.10d),

the architect should operate the structure within a pure unity in a single body that refers to the "*tubular concept"* even just "*trussed-tube system*", and "*diagrid-framed-tube system*."

Korsavi and Maqhareh (2014) stated that "The steel diagrid, in its ability to create a 'mesh', is capable of conforming to almost any shape that can be created using modern 3-D modelling software". Unconventional forms become buildable owing to its resistance to seismic forces and structural efficiency (Al-Kodmany and Ali, 2016). Moreover, it has the potential of creating unprecedented visual aesthetics in the design.

Shear walled frame system could be utilized to generate free form in structurally adaptive manner as in the case of *Al Hamra Tower* (Kuwait City, 2011) (Figure 4.7b).

From aerodynamic point of view, utilization of free forms could be advantageous. In particular, the across-wind direction, it should be noted that irregular free form generally performs better than a similar prismatic one, as it can mitigate wind-induced vibrations by disturbing the development of organized alternating vortexes (Moon, 2011; Moon, 2015a).

Overall, utilization of *free forms* can present numerous advantages aerodynamically. The use of shear walled frame, diagrid-framed-tube and trussed-tube systems could enable to create structurally and aerodynamically adaptive free forms.

CHAPTER 5

CONCLUSION

5.1 Summary and Conclusion

Today, the role of the architect results in greater challenging task to put the conceptual ideas into practice as not only visually satisfying, but also as feasible from the structural, aerodynamic, and construction points of view.

In order to propose a design guideline for architects, parametric studies based on data about contemporary supertall buildings regarding architectural, structural and aerodynamic design considerations with their interrelations, and analyses of the buildings forms from architectural, structural and aerodynamic points of views, were conducted.

At this point, the awareness about potentials and limitations of supertall building structural systems leads in developing their original supertall building forms that are "adaptive" to the structural and aerodynamic designs. Structural and aerodynamic issues must also be addressed in concert with other design considerations at a very early stage of the design process.

In supertall building design, early architectural form development is critical and can have substantial implications for the latter stages of the design. Placing less emphasis on structural and aerodynamic concerns in the design process frequently yields ineffective design solutions that naturally lead to costly construction.

Toward achieving the design guideline for the architect of supertall buildings (over 300m high or 75 stories), this research presents the following results:

- Today, owing to the effort to generate a skyline concept, a cultural identity, a prestige or a national pride, skyscrapers become an inevitable feature of urban development especially in Far East. Thus, the number of supertall buildings has been increasing over the decades in that regions with the effort of creation in notions of “uniqueness”, “being a symbol” or “building the tallest”.
- *Tapered forms* are dominantly utilized forms in *China*; while *free forms* are the most commonly used forms in *United Arab Emirates*. On the other hand, for *United States, setback forms* are the most popular forms; whereas *all the building forms except twisted forms* are employed for the supertall buildings in other than abovementioned countries.
- *Outriggered frame system* is the most popular structural system all over the world. Besides utilization of this system, *tube systems* are commonly used in *United Arab Emirates;* whereas *other countries (except China, USA and UAE)* show a tendency to employ shear-frame system in high ratios.
- In supertall building design, *multi-function* (46%) and *office use* (35%) are the most preferred functions. On the other hand, with the addition of multi-function, *hotel use* reaches up to almost half of number of supertalls. The reason behind multi-function dominance can be economic considerations in order to meet the needs of all types of users.
- *Tapered* and *free forms* are seen to be preferable for *multi-function* and *office use*; while *residential use* has a tendency towards *simple forms*. On the other hand, *twisted forms* are the least common forms for all the building functions.
- Supertall buildings are mostly designed as *multi-function*. *Office* is also highly dedicated function among all the function in supertall construction. As single use, *hotel* and *residential* have never been encountered for the height range between *450-599m*.

- *Central core* (95%) is the most preferred arrangement by a wide margin; whereas *peripheral* (2%), *atrium* (2%), and *external* (1%) *core types* are rarely utilized in the design of today's supertalls. The reasons behind central core dominancy can be its advantageous of structural contribution, compactness, enabling of openness in the exterior façade for light and views and safety concerns allowing easy access for fire escape.
- For all the structural systems of today's supertall buildings, it is obvious that *central core* is the most favored arrangement by a wide margin; whereas *peripheral, external and atrium core types* are used either once or never for each category in structural system.
- Today, the architects of skyscrapers show a general tendency towards designing the supertalls with the slenderness ratio of 7 and higher.
- The supertall buildings with aspect ratio between *7-10* are dominantly built with *tapered forms;* whereas the supertall buildings with aspect ratio between *6-7*, namely relatively less slender supertalls, commonly prefer *free forms*. On the other hand, *simple form* dominancy is observed for the supertall buildings with aspect ratio between *10-15*.
- The supertall buildings with aspect ratio between *7-15* are dominantly built with *outriggered frame system;* whereas for the supertall buildings with aspect ratio between *6-7*, namely relatively less slender supertalls, *tube systems* are commonly preferred. On the other hand, all types of structural systems except shear-frame are employed for the slenderest supertalls in equal rates.
- The supertall buildings with height range between *350-449m* are generally designed in aspect ratio between *7-8*; whereas the height range between *450-549m* are commonly built in aspect ratio between *8-9.* On the other hand, aspect ratio between *6-7* is mostly employed for the height range between *300-349m.*

- In supertall building design of today, *tapered* (34%) and *free forms* (29%) are by far the most commonly used forms; while *twisted forms* are rarely employed. On the other hand, *lining/tilted forms* have never been encountered in the supertalls. The reason behind tapered form dominancy can be its architectural, structural, and also aerodynamic advantages.
- In supertall building design, all types of structural systems can be utilized efficiently for *simple/extruded forms*. On the other hand, simple forms *except box-like* shape could be preferred to create *aerodynamically adaptive forms*. From structural point of view, even though the use of *tilted forms* is not favorable regarding gravity loads, outriggered frame systems are preferred over tube systems in terms of lateral loads.
- In the design of supertall building, utilization of *tapered forms* offers numerous advantages architecturally, structurally and also aerodynamically. From architectural point of view, tapered forms can be often more desirable for multi-function supertall buildings to house different function by offering various lease span opportunities. From structural point of view, owing to greater building width, these forms show more resistance to shear and overturning moments resulting from lateral loads than prismatic forms. From aerodynamic point of view, owing to the utilization of tapering effect in supertall buildings, lateral drift can be reduced. The use of shear walled frame, outriggered frame, framed-tube, especially diagrid, and also trussed-tube systems could enable to create structurally and aerodynamically adaptive tapered forms.

- Employment of *setback forms* presents several advantages architecturally and aerodynamically. From architectural point of view, setback forms can be more desirable for multi-function supertall buildings to accommodate different function by offering various lease span opportunities. From aerodynamic point of view, owing to these forms, the wind vortexes never become organized, which creates "confusing" effect for the wind as in the case of Burj Khalifa (Dubai, 2010). On the other hand, these forms could cause drawbacks from structural point of view, but these problems could be eliminated owing to utilization of outriggered frame, trussed-tube and bundled systems, which enables to create structurally and aerodynamically adaptive forms in the design of supertall building.
- In the design of supertall building, utilization of *twisted forms* is advantageous aerodynamically; whereas they create problems structurally. With the utilization of (diagrid)-framed-tube, trussed-tube, outriggered frame, and mega core systems, twisted forms could be generated.
- Utilization of *free forms* can present numerous advantages aerodynamically. The use of shear walled frame, diagrid-framed-tube and trussed-tube systems could enable to create structurally and aerodynamically adaptive free forms.
- *Tapered* and *free forms* are mostly used for *outriggered frame* and *shear-frame systems;* while utilization of *tapered and simple forms* comes to forefront for *tube systems.* In addition to this, *outriggered frame systems* are dominantly preferred for all types of building forms.
- *Tapered* and *free forms* are the most commonly used forms for the height ranges between *300-349m, 400-449m* and *500-599m*. The supertall buildings with height range between *350-399m* are generally built with *free* and *simple forms*; while *tapered* and *setback forms* are the most popular for the supertalls constructed in height range between *450-499m*. On the other hand, all the building forms are employed for *megatall* category.

- *Composite utilization* with concrete filled and/or encased structural elements shows a great dominance; while *steel* is the least preferred structural material in supertall building design of today. However, in 1990, 90% of the supertalls were having steel as structural material. The reason behind this dominancy can be the technical innovations in concrete such as pumping to higher levels and utilization of high strength concrete.
- In the skyscraper industry, by 2010, a dramatic increase has been observed in density of composite construction, which reached up to 60%. Through the end of 2019, it is expected to reach a peak. On the other hand, reinforced concrete followed a more stable trendline particularly between 1996 and 2016; while it seems to gain acceleration in the coming years.
- For all the structural systems of supertall buildings except mega column/core category, *composite* shows a great dominance; whereas *steel* is the least preferred structural material. 3 out of every 4 of the supertalls with outriggered frame system benefit from the merits of composite. On the other hand, steel is mostly used in tube systems among the structural systems of the supertalls.
- Owing to its superiority over tube systems in the matter of panoramic view and ease of construction, outriggered frame system is the most preferred structural system; whereas mega core and mega column systems are rarely utilized.
- *Outriggered frame systems* built with tapered and free forms are mostly used for the supertall buildings with height range between *300-600m*; while *tube systems* built with simple and free forms are dominantly utilized for the supertall buildings with height range between *300-400m*. On the other hand, mega *column/core and shear-frame systems* are generally employed for the supertall buildings *up to 350m high*. In *megatall* construction, *outriggered frame system* is the most preferred structural system.
- Between the periods of *1980 and 2022*, there are mostly completions of supertall buildings with the height range between *300-650m*. After 2010, a dramatic rise has been observed in density of construction, and by 2019, the number of supertall buildings to be built will reach a peak, 46 as declared by CTBUH.

Overall, as a design guideline for the architects, in the light of the results above, Figure 5.1 shows the number of supertall buildings (Appendix-A) for each type of building forms in relation to structural system and structural material; while Figure 5.2 indicates the number of supertall buildings (Appendix-A) for each type of building forms in relation to structural system and aspect ratio. On the other hand, Figure 5.3 demonstrates the number of supertall buildings (Appendix-A) for each type of building forms in relation to structural system and building height.

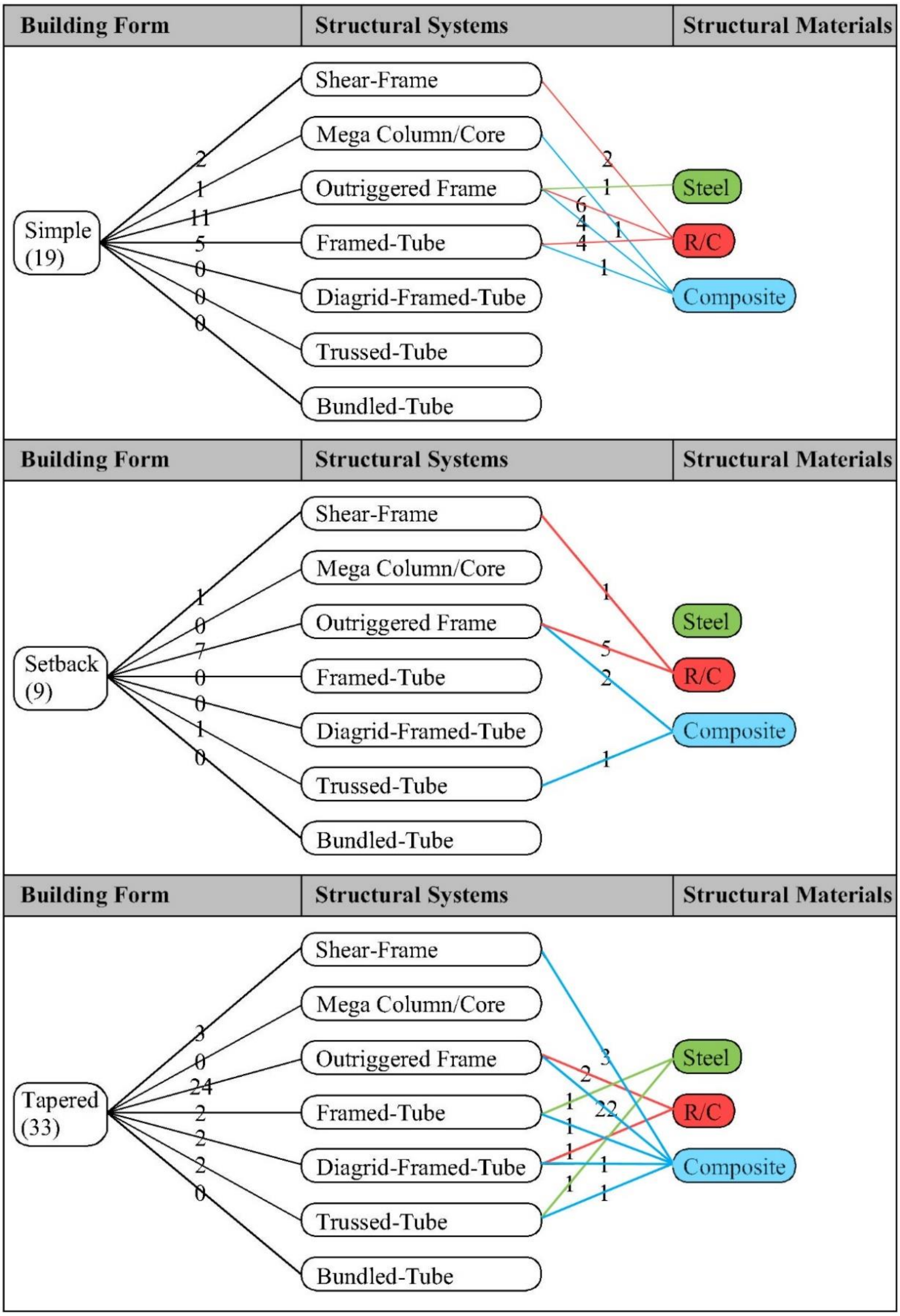


Figure 5.1 Interrelation of structural system with building form and structural material (Appendix-A)

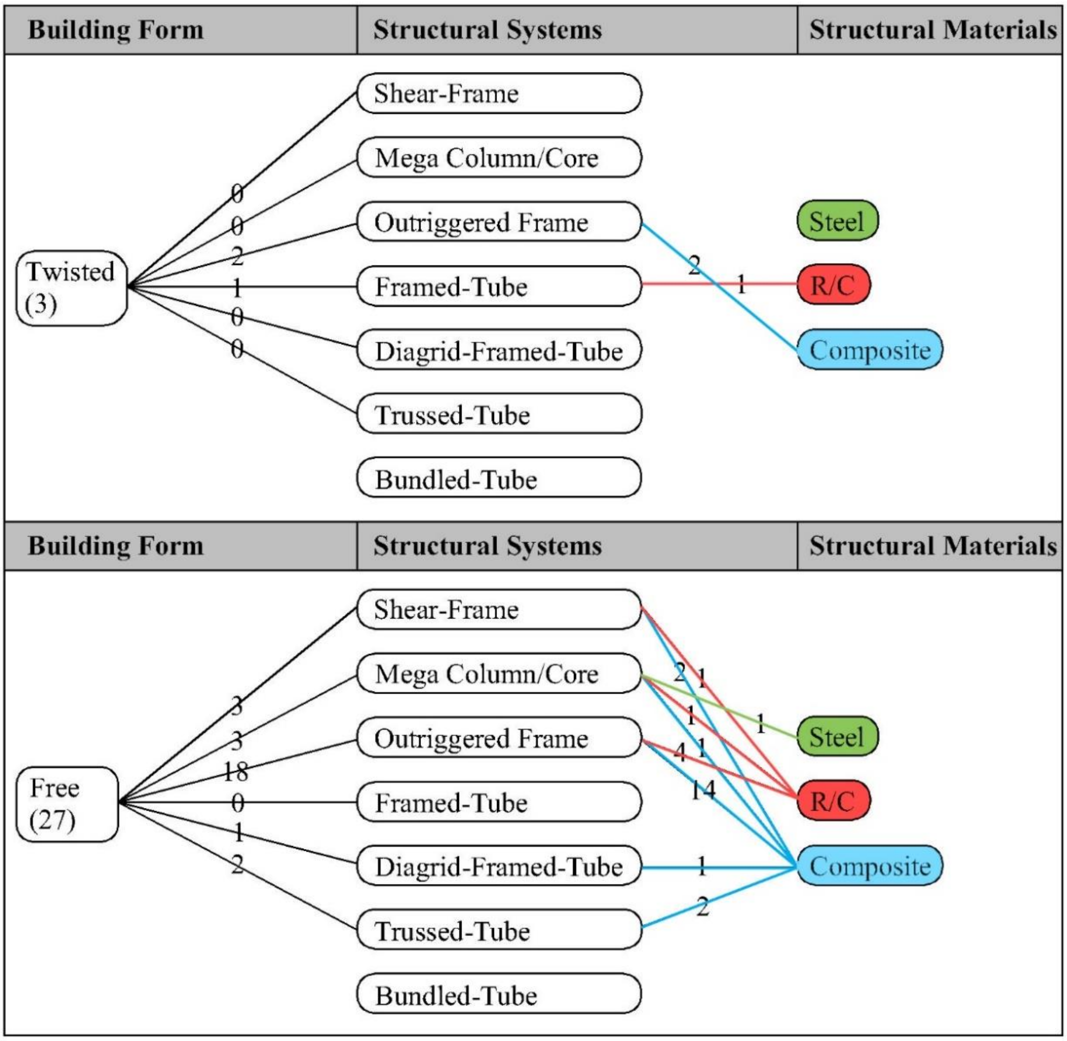


Figure 5.1 Continued

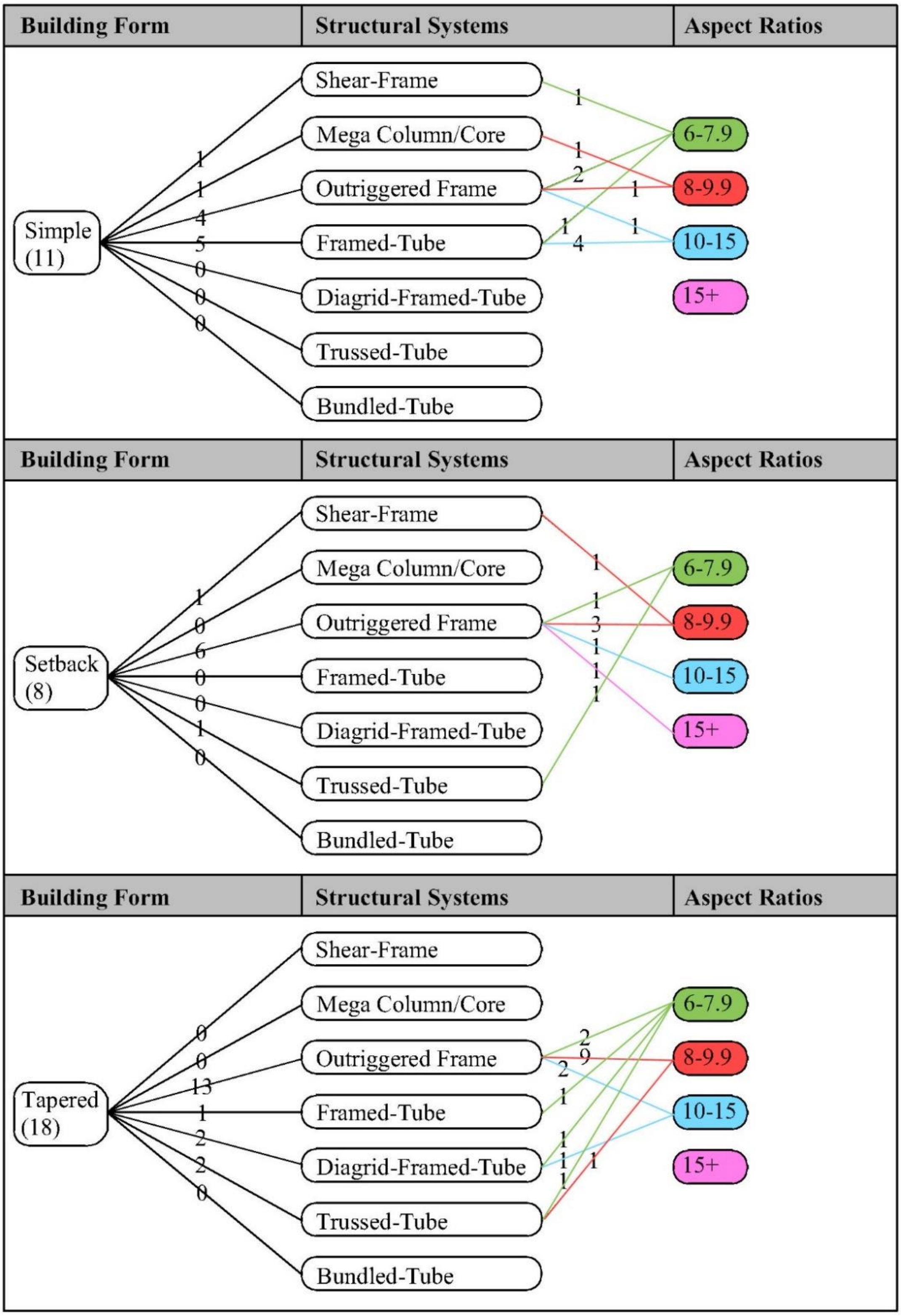


Figure 5.2 Interrelation of structural system with building form and aspect ratio (Appendix-A)

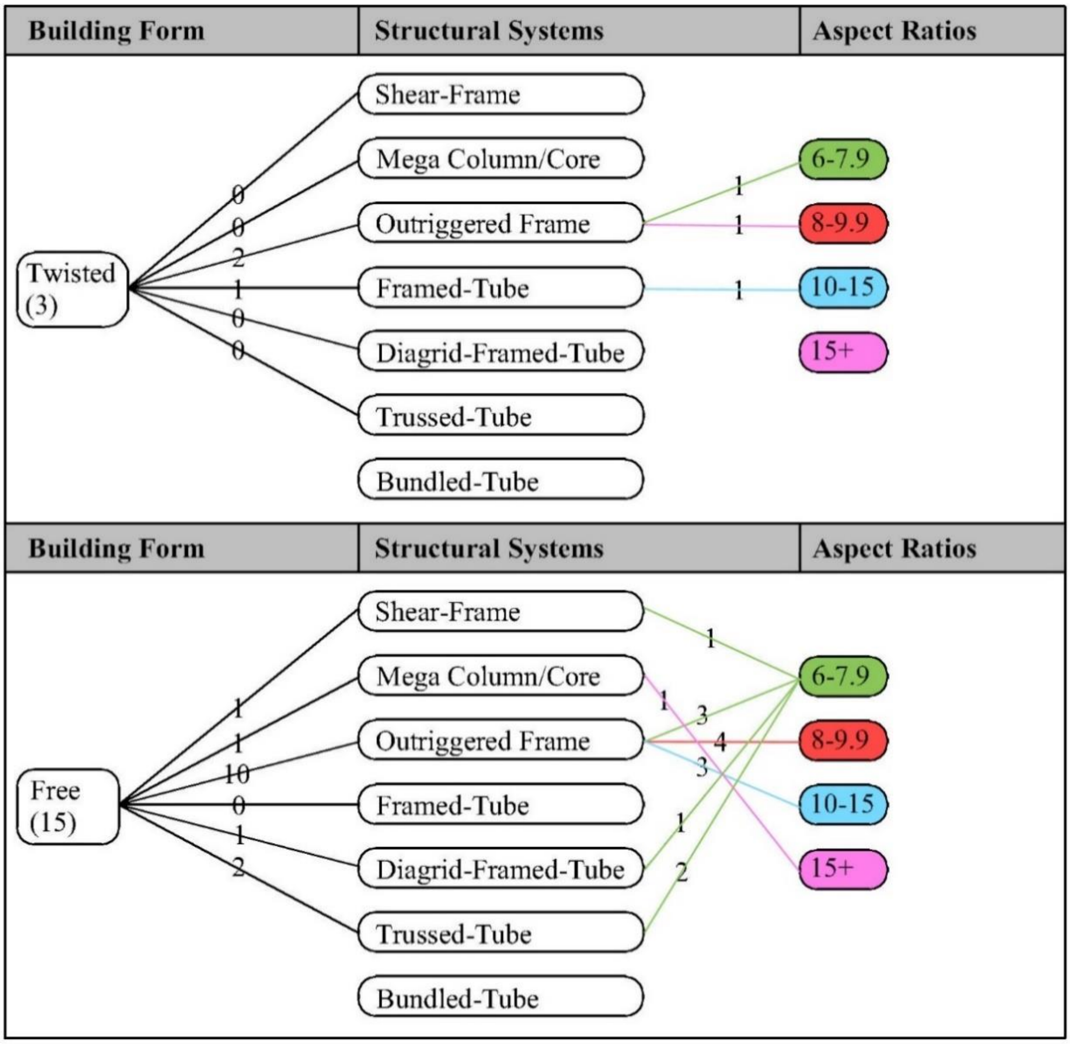


Figure 5.2 Continued

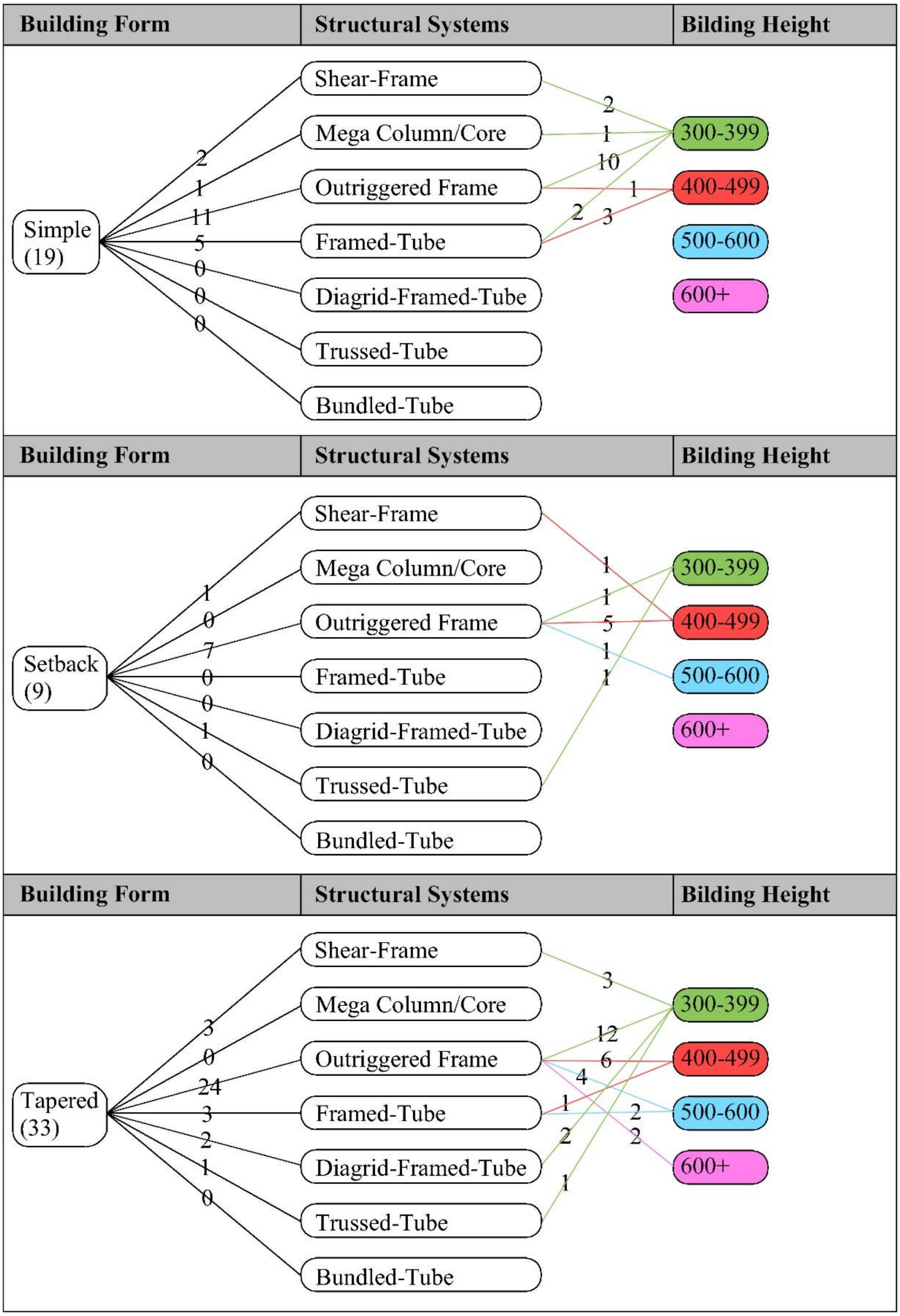


Figure 5.3 Interrelation of structural system with building form and building height (Appendix-A)

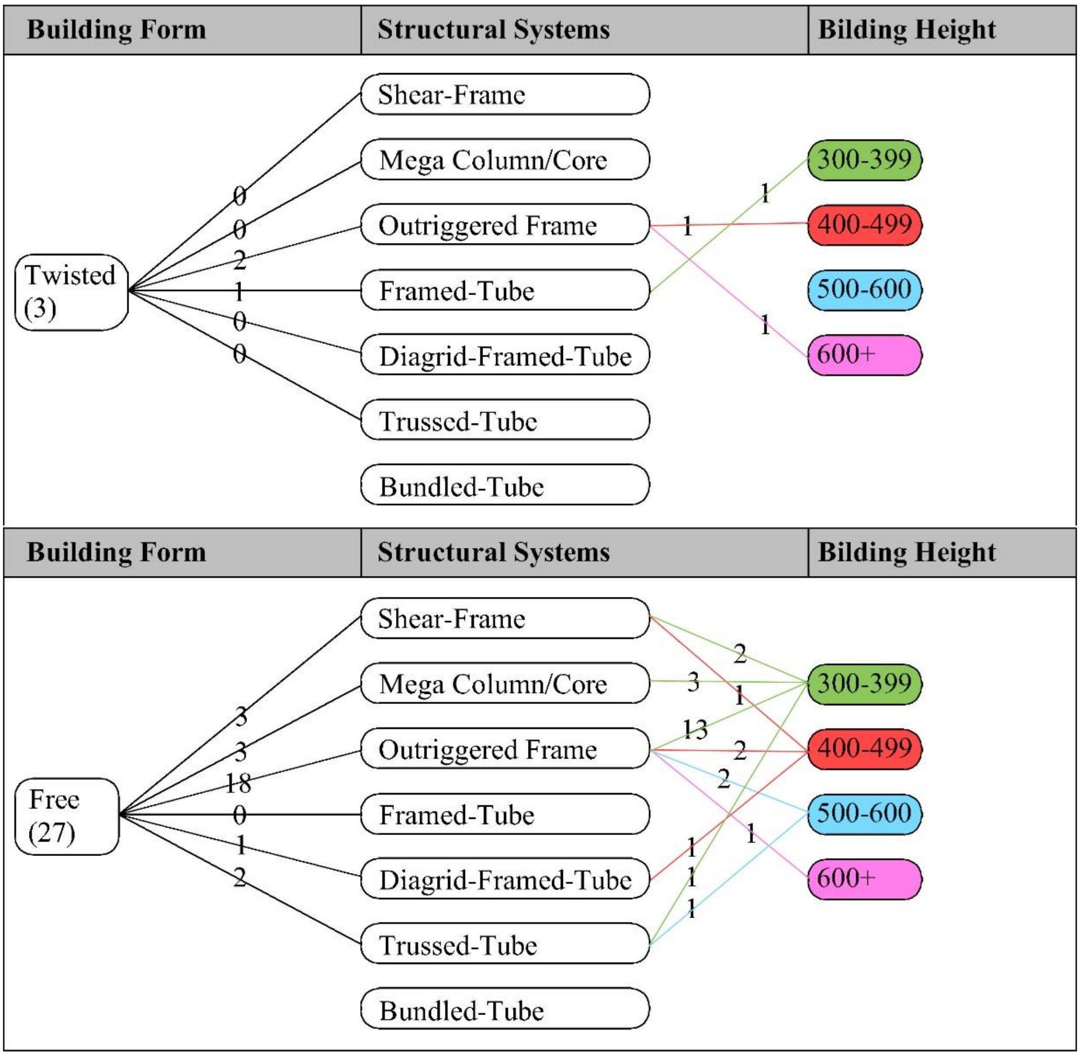


Figure 5.3 Continued

5.2 Research Limitations

The main determinant factor for the sample group of the supertalls is availability of the data presented in (Appendix-A), since the difficulty in data collection process has been experienced owing to security issues of tall buildings especially in the United States after the tragedy of WTC Twin Towers at September 11th 2001.

Because of this reason, the analyses of particularly, interrelations of structural systems and other design considerations could be based on 91 out of 286 supertall buildings from CTBUH database. Moreover, this number has been decreased up to 55 for the analyses on the aspect ratios due to the similar difficulties in obtaining of ground floor plan with its necessary dimensions.

5.3 The Future Trend of Architectural Form

Based on the data collected in this research (Appendix-A), it is sensible to believe that architectural trend for the next generation of supertall buildings seems to create an overall architectural form totally integrated with aerodynamic concerns, namely *aerodynamically adaptive architectural forms.*

Regarding the effect of the wind on supertall buildings, the fact is worth stating to endorse the reason of this expected trend. Escaping from wind, architecturally, can diminish the effect of wind on supertall buildings. This statement shows the significance of the effect of *aerodynamic architectural design (major modifications)* including *aerodynamic form* and plan variation, particularly *tapered forms.* Hence, numerous of the most well-known and the tallest supertall buildings as in the case of

- 1000+m high *Jeddah Tower* with tapered form,
- 828m high *Burj Khalifa* with setback form,
- 636m high *Wuhan Greenland Center* with tapered and aerodynamic form,
- 632m high *Shanghai Tower* with aerodynamic form (twisted),
- 599m high *Ping An Finance Center* with tapered form,
- 597m high *Goldin Finance 117* with tapered form,
- 555m high *Lotte World Tower* with tapered form,
- 541m high *One World Trade Center* with tapered form, and
- 530m high *Guangzhou CTF Finance Center* with aerodynamic form -

have been utilizing such major aerodynamic modifications.

5.4 Future Studies

Due to the state-of-art supertall building technology and construction, many new areas could be explored to apply the findings presented in this study. The following items could be considered as potential study areas:

1. The effects of advanced technologies on planning and development criteria of supertall buildings
2. Exploring the aesthetic potentials of the supertall's structural systems
3. Evolution of structural systems of supertall buildings in conjunction with architectural forms and aesthetics
4. Developing innovative structural systems for the next generation of sustainable megatall buildings
5. The development of supertall building projects at Middle East Technical University according to the design guideline developed in this research
6. Identification of other potentially innovative design factors related to supertall building projects

7. Architectural solutions for planning and development of supertall building regarding architectural form and structural system
8. Influence of codes and regulations in supertall building development in Turkey
9. Relationships between structural elements and building aesthetics
10. Optimizing structural materials use regarding supertall building design

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APPENDIX A

SUPERTALL BUILDING LIST (91 BUILDINGS)

Table A.1. Supertall Building List (91 buildings)

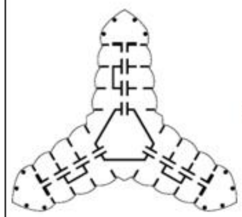
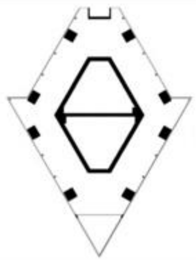
#	Building Name Location Height / Number of Floors Completion Date Architect Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m²)	Aver. Fl. Ar. (m2) / Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
SUPERTALL BUILDINGS WITH COMPLETED AND UNDER CONSTRUCTION STATUS													
1	**Jeddah Tower** Jeddah (SA) 1000+ m / 167 2021 Adrian Smith + Gordon Gill Architecture LEED Gold			243.866	~1460 ~2100*		~6,7*	Tapered (Aerodynamically Adaptive)	Central	Residential	10	Outriggered Frame / Reinforced Concrete	Tapered
2	**Burj Khalifa** Dubai (AE) 828m / 163 2010 Skidmore, Owings & Merril LLP (SOM) LEED Gold			309.473	~1898 ~6500*		~13,4*	Setback (Aerodynamically Adaptive)	Central	Hotel Residential Office	~10,5*	Outriggered Frame / Reinforced Concrete	Setback
3	**PNB118** Kuala Lumpur (MY) 644m / 118 2021 Fender Katsalidis Arch.; RSP Arch. Sdn Bhd LEED			292.000	~2474 ~2985*		~11,8*	Free	Central	Hotel Office	6,7	Outriggered Frame / Composite	Wind Opening

Table A.1. Continued

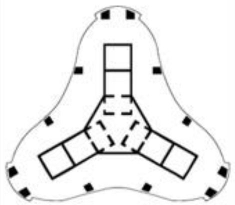
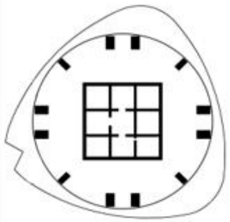
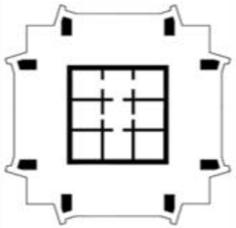
#	Building Name / Location / Height / Number of Floors / Completion Date / Architect / Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m²)	Aver. Fl. Ar. (m2) / Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
	SUPERTALL BUILDINGS WITH COMPLETED AND UNDER CONSTRUCTION STATUS												
4	**Wuhan Greenland Center** Wuhan (CN) 636m / 126 2019 Adrian Smith + Gordon Gill Architecture LEED Gold			303.275	~2407 ~3340*		~14*	Non-continuous Tapered (Aerodynamically Adaptive)	Central	Hotel Residential Office	~8,8	Outriggered Frame / Composite	Aerodynamic Form & Tapered & Corner Modification
5	**Shanghai Tower** Shanghai (CN) 632m / 128 2015 Gensler LEED Platinum			420.000	~3281 ~4754*	~30 x ~30	~23,2*	Twisted (Aerodynamically Adaptive)	Central	Hotel Office	8,8	Outriggered Frame / Composite	Twisted
6	**Ping An Finance Center** Shenzhen (CN) 599m / 115 2017 Kohn Pedersen Fox Associates (KPF) LEED Gold			459.187	~3993 ~4070*	~32.3 x 32.3	~17*	Non-continuous Tapered (Aerodynamically Adaptive)	Central	Office	8,3*	Outriggered Frame / Composite	Tapered & Corner Modification

Table A.1. Continued

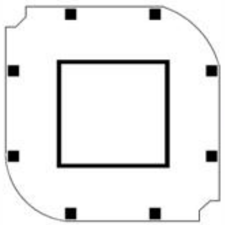
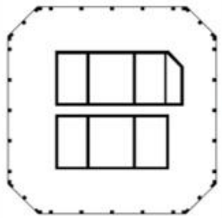
#	Building Name / Location / Height / Number of Floors / Completion Date / Architect / Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m²)	Aver. Fl. Ar. (m2) / Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
7	**Goldin Finance 117** Tianjin (CN) 597m / 128 Architecturally topped out P & T Group LEED Platinum			370.000	~2890 ~3984*	34 x 32	~13*	Non-continuous Tapered (Aerodynamically Adaptive)	Central	Hotel Office	9,5	Trussed-Tube / Composite	Tapered
8	**Lotte World Tower** Seoul (KR) 555m / 123 2017 Kohn Pedersen Fox Associates LEED Gold			304.081	~2472 ~4800*	36 x 36	~17,5*	Non-continuous Tapered (Aerodynamically Adaptive)	Central	Hotel Office	7,9	Outriggered Frame / Composite	Tapered
9	**One World Trade Center** New York City (US) 541m / 94 2014 Skidmore, Owings & Merril LLP (SOM) LEED Gold			325.279	~3460 ~4400*	~35,2 x ~36	13,5*	Tapered (Aerodynamically Adaptive)	Central	Office	8,6	Outriggered Frame / Composite	Tapered

Table A.1. Continued

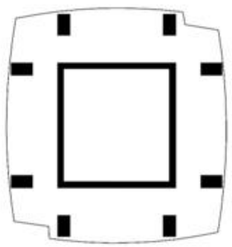
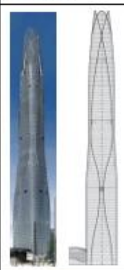
#	Building Name / Location / Height / Number of Floors / Completion Date / Architect / Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m²)	Aver. Fl. Ar. (m2) / Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
	SUPERTALL BUILDINGS WITH COMPLETED AND UNDER CONSTRUCTION STATUS												
10	**Guangzhou CTF Finance Centre** Guangzhou (CN) 530m / 111 2016 Kohn Pedersen Fox Associates (KPF) LEED (in progress)			398.000	~3585 ~3500*	~30 x ~30	~16*	Tapered (Aerodynamically Adaptive)	Central	Hotel Residential Office	8,5	Outriggered Frame / Composite	Aerodynamic Form & Tapered
11	**Tianjin CTF Finance Centre** Tianjin (CN) 530m / 97 2020 Skidmore, Owings & Merril LLP (SOM) LEED Gold			252.144	~2599 ~3970*	33 x 33	~15*	Tapered (Aerodynamically Adaptive)	Central	Hotel Office	~7,3*	Framed-tube / Composite	Tapered & Corner Modification
12	**Citic Tower** Beijing (CN) 528m / 108 2018 Kohn Pedersen Fox Associates (KPF) LEED Gold (in progress)			437.000	~4046 ~6000*	39 x 39	~19,5*	Free	Central	Office	6,8*	Trussed-Tube / Composite	Aerodynamic Form

Table A.1. Continued

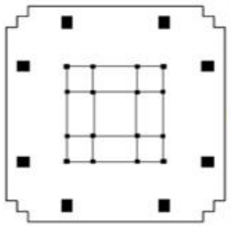
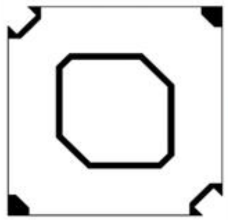
#	Building Name / Location / Height / Number of Floors / Completion Date / Architect / Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m^2)	Aver. Fl. Ar. (m2)	Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
13	**Evergrande IFC 1** Hefei (CN) 518m / 112 2021 Gensler			322.000	~2875	~3040*	32,9 x 33,3	~11,4*	Modulated and Repetitive Free	Central	Hotel Residential Office	~9,2	Outriggered Frame / Composite	
14	**TAIPEI 101** Taipei (TW) 508m / 101 2004 C.Y. Lee & Partners Architects/Planners LEED Platinum			198.347	~1964	~4032*	22,5 x 22,5	~20,5*	Modulated and Repetitive Free (Aerodynamically Adaptive)	Central	Office	9	Outriggered Frame / Composite	Setback & Tapered & Corner Modification
15	**Shanghai World F. C.** Shanghai (CN) 492m / 101 2008 Kohn Pedersen Fox Associates (KPF) LEED Gold (Pre-certified)			381.600	~3778	~3360*	~32 x ~32	~13*	Tapered (Aerodynamically Adaptive)	Central	Hotel Office	8,5	Outriggered Frame / Composite	Tapered & Aerodynamic Top & Wind Opening

Table title: SUPERTALL BUILDINGS WITH COMPLETED AND UNDER CONSTRUCTION STATUS

Table A.1. Continued

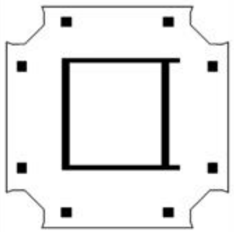
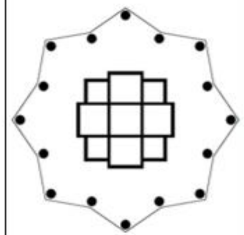
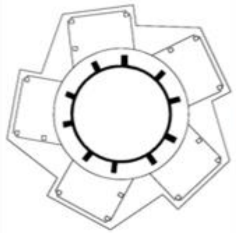
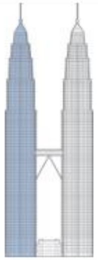
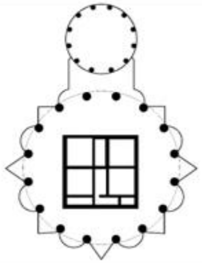
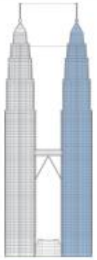
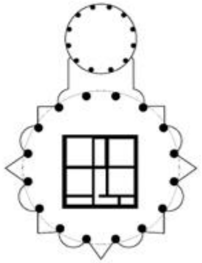
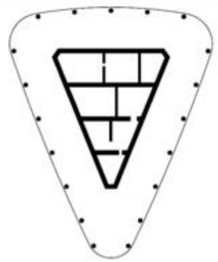
#	Building Name / Location / Height / Number of Floors / Completion Date / Architect / Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m²)	Aver. Fl. Ar. (m2) / Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
	SUPERTALL BUILDINGS WITH COMPLETED AND UNDER CONSTRUCTION STATUS												
16	**International Commerce Centre** Hong Kong (CN) 484m / 108 2010 Kohn Pedersen Fox Associates (KPF) LEED Certified			274.064	~2537 ~3730*	~34 x ~33	~16*	Tapered (Aerodynamically Adaptive)	Central	Hotel Office	9	Outriggered Frame / Composite	Tapered & Corner Modification
17	**Chengdu Greenland Tower** Chengdu (CN) 468m / 101 2019 Adrian Smith + Gordon Gill Architecture			220.534	~2183 ~2715*	28 x 28	17	Tapered	Central	Hotel Office	7,5*	Outriggered Frame / Composite	Aerodynamic Form
18	**Lakhta Center** St.Petersburg (RU) 462m / 86 2018 Gorproject LEED (Pre-certified)			330.000	~3837 ~2545*	27m (in diameter)	~13,8*	Twisted	Central	Office	~7,8*	Outriggered Frame / Composite	

Table A.1. Continued

#	Building Name Location Height / Number of Floors Completion Date Architect Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m^2)	Aver. Fl. Ar. (m2)	Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
19	**Petronas Twin Tower 1** Kuala Lumpur (MY) 452m / 88 1998 Cesar Pelli & Associates			197.500	~2244	~2900*	22,9 x 22,9	11,7	Setback (Aerodynamically Adaptive)	Central	Office	8,6	Outriggered Frame / Reinforced Concrete	Setback & Aerodynamic Top
20	**Petronas Twin Tower 2** Kuala Lumpur (MY) 452m / 88 1998 Cesar Pelli & Associates			197.500	~2244	~2900*	22,9 x 22,9	11,7	Setback (Aerodynamically Adaptive)	Central	Office	8,6	Outriggered Frame / Reinforced Concrete	Setback & Aerodynamic Top
21	**Zifeng Tower** Nanjing (CN) 450m / 66 2010 Skidmore, Owings & Merril LLP (SOM) LEED Silver			137.529	~2084	~2760*		~17,5*	Free	Central	Hotel Office	~6*	Outriggered Frame / Composite	

Title row of the table: **SUPERTALL BUILDINGS WITH COMPLETED AND UNDER CONSTRUCTION STATUS**

Table A.1. Continued

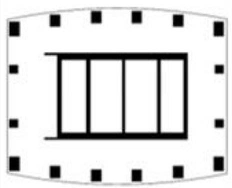
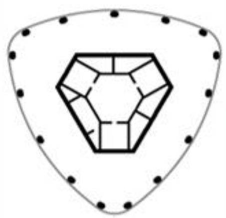
#	Building Name / Location / Height / Number of Floors / Completion Date / Architect / Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m²)	Aver. Fl. Ar. (m2) / Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
	SUPERTALL BUILDINGS WITH COMPLETED AND UNDER CONSTRUCTION STATUS												
22	**KK 100** Shenzhen (CN) 442m / 100 2011 TFP Farrels LEED Gold			220.000	~2200 ~2850*	~37 x ~24,3	13,5	Non-continuous Tapered	Central	Hotel Office	9,6	Outriggered Frame / Composite	
23	**Guangzhou IFC** Guangzhou (CN) 439m / 103 2010 WilkinsonEyre LEED Platinum			250.095	~2428 ~2885*		11,9	Amorphous Free (Structurally & Aerodynamically Adaptive)	Central	Hotel Office	7,7	Diagrid-Framed-Tube / Composite	Aerodynamic Form
24	**Wuhan Center Tower** Wuhan (CN) 438m / 88 2018 East China Architectural Design & Research Institute			343.900	~3908			Non-continuous Tapered	Central	Hotel Residential Office		Outriggered Frame / Composite	

Table A.1. Continued

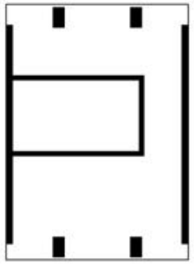
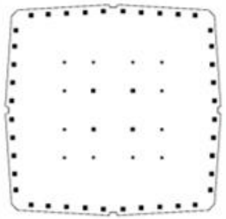
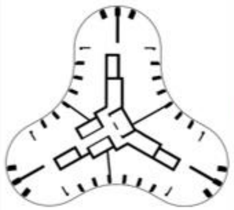
#	Building Name Location Height / Number of Floors Completion Date Architect Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m²)	Aver. Fl. Ar. (m2) / Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
25	**111 West 57th Street** New York City (US) 435m / 82 2019 SHoP Architects			29.357	~358 ~415*	~13 x ~8	~9	Setback	Peripheral	Residential	24	Outriggered Frame / Reinforced Concrete	
26	**Akhmat Tower** Grozny (RU) 435m / 102 2020 Adrian Smith + Gordon Gill Architecture			261.678	~2565			Tapered	Central	Hotel Residential Office		Framed-Tube / Steel	Corner Modification
27	**World One** Mumbai (IN) 442m / 117 _ Pei Cobb Freed & Partners LEED Gold targeted			164.000	~1400 ~1890*		~11	Setback	Central	Residential	9,2*	Shear Walled Frame / Reinforced Concrete	

Table A.1. Continued

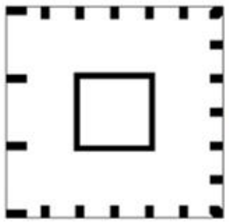
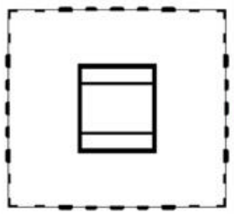
#	Building Name Location Height / Number of Floors Completion Date Architect Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m²)	Aver. Fl. Ar. (m2) / Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
28	**Haikou Tower 1** Haikou (CN) 428m / 94 2020 HENN			387.423	~4121			Tapered (Aerodynamically Adaptive)	Central	Hotel Residential Office		Outriggered Frame / Composite	Tapered & Corner Modification
29	**432 Park Avenue** New York City (US) 426m / 85 2015 Rafael Viñoly Architects LEED			65.497	~770 ~805*	10,6 x 10,6	~8,9	Simple (Structurally Adaptive)	Central	Residential	15	Framed-Tube / Reinforced Concrete	Air Passes
30	**Marina 101** Dubai (AE) 425m / 101 2017 National Engineering Bureau			120.706	~1195 ~1160*	12,8 x 14,9*	~11*	Articulated Simple Form with Architectural Top	Central	Hotel Residential	~12*	Framed-tube / Reinforced Concrete	

Table A.1. Continued

SUPERTALL BUILDINGS WITH COMPLETED AND UNDER CONSTRUCTION STATUS

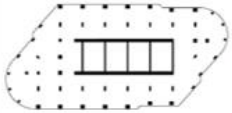
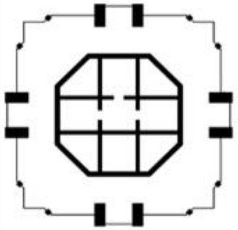
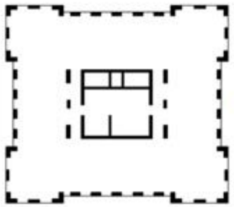
#	Building Name Location Height / Number of Floors Completion Date Architect Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m^2)	Aver. Fl. Ar. (m2) / Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
31	**Trump International Hotel & Tower** Chicago (US) 423m / 98 2009 Skidmore, Owings & Merril LLP (SOM)			241.548	~2465 ~3280*	~41,2 x ~14,9	~22*	Setback (Aerodynamically Adaptive)	Central	Hotel Residential	8	Outriggered Frame / Reinforced Concrete	Setback
32	**Jin Mao Tower** Shanghai (CN) 421m / 88 1999 Skidmore, Owings & Merril LLP (SOM) LEED Gold			289.500	~3290 ~2516*	~27,5 x ~27,5	~13	Unmodulated and Repetitive Free	Central	Hotel Office	7,9*	Outriggered Frame / Reinforced Concrete	Aerodynamic Building Top
33	**Princess Tower** Dubai (AE) 413m / 101 2012 Eng. Adnan Saffarini			171.175	~1694 ~1200*	~11,9 x ~11,9*	~9,9*	Articulated Simple Form with Architectural Top	Central	Residential	~10,9*	Framed-tube / Reinforced Concrete	

Table A.1. Continued

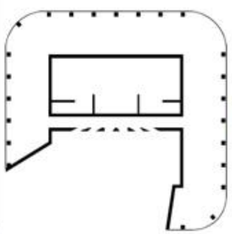
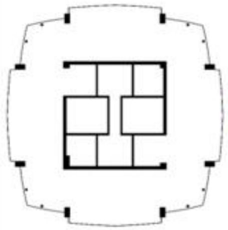
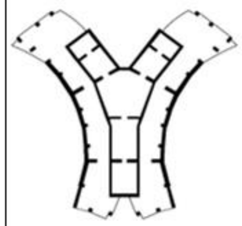
#	Building Name / Location / Height / Number of Floors / Completion Date / Architect / Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m²)	Aver. Fl. Ar. (m2)	Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
	SUPERTALL BUILDINGS WITH COMPLETED AND UNDER CONSTRUCTION STATUS													
34	**Al Hamra Tower** Kuwait City (KW) 413m / 80 2011 Skidmore, Owings & Merril LLP (SOM)			178.061	~2226	~2285*	~36 x ~18	11,4*	Sculptural Free (Aerodynamically Adaptive)	Central	Office	~7*	Shear Walled Frame / Composite	Aerodynamic Form
35	**Two IFC** Hong Kong (CN) 412m / 88 2003 Cesar Pelli & Associates LEED Gold			185.805	~2103	~3220*	29 x 27	15	Setback	Central	Office	7,2	Outriggered Frame / Composite	Aerodynamic Top & Corner Modification (Saw-tooth)
36	**LCT Landmark Tower** Busan (KR) 412m / 101 2020 Samoo Architects & Engineers & SOM								Articulated Simple Form with Architectural Top	Central	Hotel Residential		Outriggered Frame / Reinforced Concrete	

Table A.1. Continued

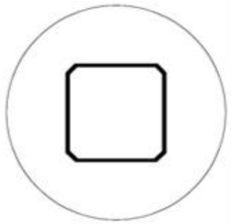
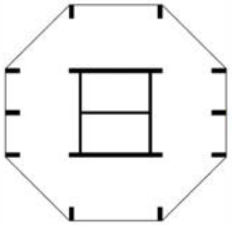
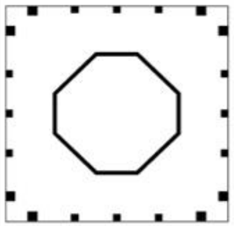
#	Building Name / Location / Height / Number of Floors / Completion Date / Architect / Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m²)	Aver. Fl. Ar. (m2) / Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
37	**China Resources Headquarters** Shenzhen (CN) 393m / 67 2018 Kohn Pedersen Fox Associates (KPF)			268.713	~4010 ~3350*	30 x 30	~17*	Tapered (Structurally & Aerodynamically Adaptive)	Central	Office	~6,6*	Diagrid-Framed-Tube / Composite	Aerodynamic Form & Tapered
38	**23 Marina** Dubai (AE) 392m / 88 2012 Hafeez Contractor; KEO International Consultants			139.596	~1586 ~1460*	~17,7 x ~17,1*	~14*	Articulated Simple Form with Architectural Top	Central	Residential	~9,5*	Outriggered Frame / Reinforced Concrete	
39	**CITIC Plaza** Guangzhou (CN) 390m / 80 1996 Kohn Pedersen Fox Associates (KPF)			205.239	~2565 ~2850*		11,3*	Simple Form with Architectural Top	Central	Office	~7,4*	Shear Walled Frame / Reinforced Concrete	

Table A.1. Continued

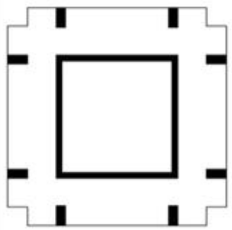
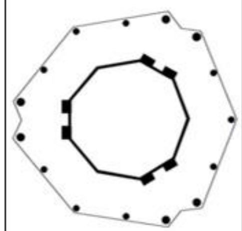
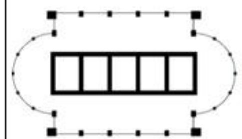
#	Building Name / Location / Height / Number of Floors / Completion Date / Architect / Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m^2)	Aver. Fl. Ar. (m2) / Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
40	**Shum Yip Upperhills Tower 1** Shenzhen (CN) 388m / 80 2019 Skidmore, Owings & Merril LLP (SOM)				~3000 ~3050*	31 x 31	12	Simple	Central	Hotel Office	7,2	Outriggered Frame / Composite	
41	**Capital Market Authority Tower** Riyadh (SA) 385m / 76 2018 HOK, Inc.; Omrania & Associates LEED Gold			213.300	~2806		~10*	Free (Structurally & Aerodynamically Adaptive)	Central	Office	~6,9	Trussed-Tube / Composite	Aerodynamic Form
42	**Shun Hing Square** Shenzhen (CN) 384m / 69 1996 HOK, Inc.; Omrania & Associates			280.000	~4058 ~2000*	43,5 x 12	12,5	Amorphus Free	Central	Office	8	Outriggered Frame / Composite	Aerodynamic Form

Table A.1. Continued

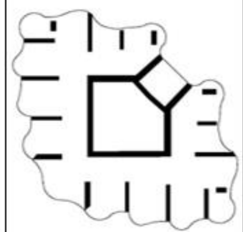
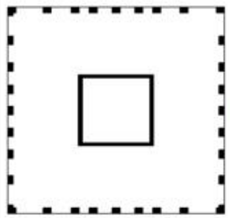
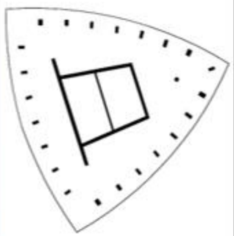
#	Building Name / Location / Height / Number of Floors / Completion Date / Architect / Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m²)	Aver. Fl. Ar. (m2) / Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
43	**Burj Mohammed Bin Rashid** Abu Dhabi (AE) 381m / 88 2014 Foster + Partners							Amorphus Free (Aerodynamically Adaptive)	Central	Residential	13	Outriggered Frame / Reinforced Concrete	Aerodynamic Form
44	**Elit Residance** Dubai (AE) 380m / 87 2012 Eng. Adnan Saffarini			140.013	~1609 ~1410*	12,8 x 11,8		Articulated Simple Form with Architectural Top	Central	Residential	~10.3*	Framed-tube / Reinforced Concrete	
45	**Federation Tower** Moscow (RU) 374m / 93 2016 Rimax Design; SPEECH			442.915	~4762			Amorphus Free	Central	Residential Office		Outriggered Frame / Composite	

Table A.1. Continued

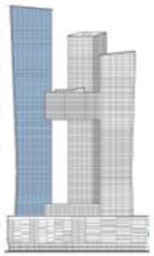
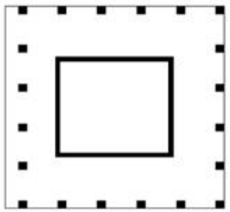
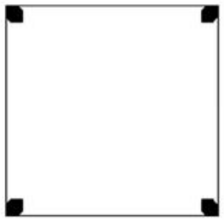
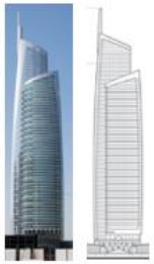
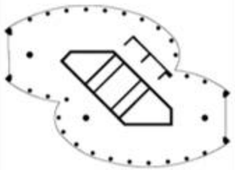
#	Building Name / Location / Height / Number of Floors / Completion Date / Architect / Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m^2)	Aver. Fl. Ar. (m2)	Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
46	**Golden Eagle Tiandi Tower A** Nanjing (CN) 368m / 76 2019 East China Architectural Design & Research Institute								Tapered (inverse)	Central	Hotel Office		Outriggered Frame / Composite	
47	**Bank of China Tower** Hong Kong (CN) 367m / 72 1990 I.M. Pei & Partners			135.000	~1875	2704		~10	Setback (Structurally & Aerodynamically Adaptive)	Central split	Office	~7*	Trussed-Tube / Composite	Setback
48	**Almas Tower** Dubai (AE) 360m / 68 2008 Atkins			160.000	~2353			~13	Amorphous Free	Central	Office	~9,2	Outriggered Frame / Composite	

Table A.1. Continued

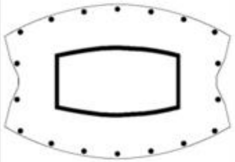
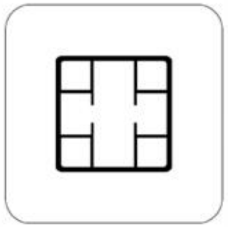
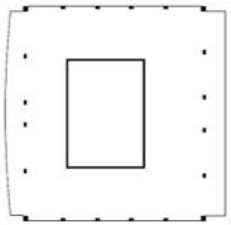
#	Building Name Location Height / Number of Floors Completion Date Architect Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m²)	Aver. Fl. Ar. (m2) Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
	SUPERTALL BUILDINGS WITH COMPLETED AND UNDER CONSTRUCTION STATUS							**Architectural Design Considerations**					
49	**Greenland Group Suzhou Center** Suzhou (CN) 358m / 77 2019 Skidmore, Owings & Merril LLP (SOM) LEED Silver targeted			284.828	~3699 			Free	Central	Hotel Office		Outriggered Frame / Composite	Air Passes
50	**Sino Steel International Plaza T2** Tianjin (CN) 358m / 83 _ MAD Architects			225.370	~2715 ~2440*	~26,2 x ~26,2	~13,4*	Simple	Central	Office	6,9	Framed-Tube / Composite	
51	**Raffles City Chongqing T3N** Chongqing (CN) 355m / 79 2019 Chongqing Architecture and Design Institute LEED Gold (Pre-certified)					~13 x ~19	~8*	Non-continuous Tapered	Central	Residential	9,5	Outriggered Frame / Composite	

Table A.1. Continued

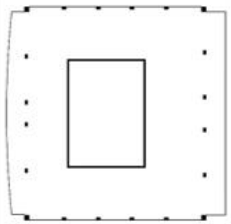
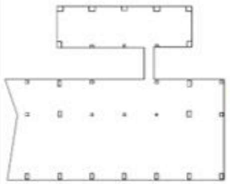
#	Building Name / Location / Height / Number of Floors / Completion Date / Architect / Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m²)	Aver. Fl. Ar. (m2)	Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
	SUPERTALL BUILDINGS WITH COMPLETED AND UNDER CONSTRUCTION STATUS													
52	**Raffles City Chongqing T4N** Chongqing (CN) 355m / 79 2019 Chongqing Architecture and Design Institute LEED Gold (Pre-certified)						~13 x ~19	~8*	Non-continuous Tapered	Central	Hotel Office	9,5	Outriggered Frame / Composite	
53	**Hanking Center Tower** Shenzhen (CN) 350m / 73 2018 Morphosis LEED Gold			185.806	~2545				Tapered (Structurally Adaptive)	External	Office	7,3	Trussed-Tube / Steel	
54	**T&C Tower** Kaohsiung (TW) 348m / 85 1997 C.Y. Lee & Partners Architects/Planners			306.337	~3604				Free	Atrium	Hotel Office		Mega Column (Mega Frame) / Steel	

Table A.1. Continued

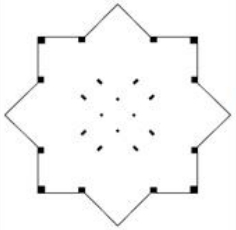
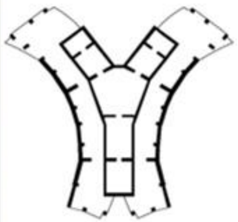
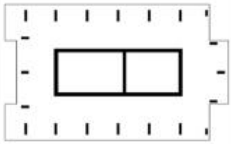
#	Building Name / Location / Height / Number of Floors / Completion Date / Architect / Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m^2)	Aver. Fl. Ar. (m2) / Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
55	**The Center** Hong Kong (CN) 346m / 73 1998 Dennis Lau & Ng Chun Man Arch & Eng (HK) Ltd. (DLN) 			130.032	~1781 /	~25 x ~25	~20*	Simple Form with Architectural Top	Central	Office	8,2	Mega Column / Composite	
56	**LCT Residential Tower A** Busan (KR) 339m / 85 2020 Samoo Architects & Engineers Skidmore, Owings & Merrill LLP 							Articulated Simple Form with Architectural Top	Central	Residential		Outriggered Frame / Reinforced Concrete	
57	**NEVA TOWERS 2** Moscow (RU) 338m / 77 2020 FXFOWLE; SPEECH; HOK, Inc. LEED (in progress)					~9,2 x ~10,7	~10	Simple Form with Architectural Top	Central	Residential	11,3	Outriggered Frame / Reinforced Concrete	

Table A.1. Continued

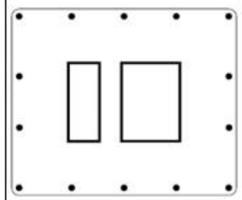
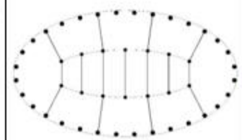
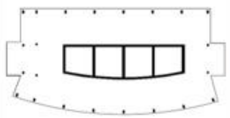
#	Building Name Location Height / Number of Floors Completion Date Architect Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m^2)	Aver. Fl. Ar. (m2)	Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
58	**Tianjin Modern City Office Tower** Tianjin (CN) 338m / 65 2016 Skidmore, Owings & Merril LLP (SOM)								Tapered	Central	Office		Outriggered Frame / Composite	
59	**Tianjin World Financial Center** Tianjin (CN) 337m / 75 2011 East China Architectural Design & Research Institute; SOM			203.953	~2719				Non-continuous Tapered	Central	Office		Outriggered Frame / Composite	
60	**Wilshire Grand Center** Los Angeles (US) 335m / 62 2017 East China Architectural Design & Research Institute; SOM LEED Gold targeted			377.035	~6081				Tapered	Central	Hotel Office		Outriggered Frame / Composite	

Table title row: SUPERTALL BUILDINGS WITH COMPLETED AND UNDER CONSTRUCTION STATUS

Table A.1. Continued

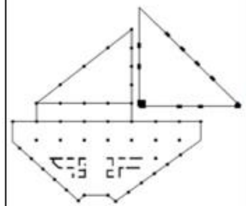
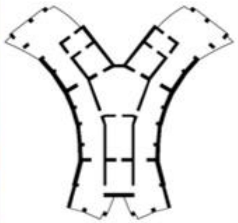
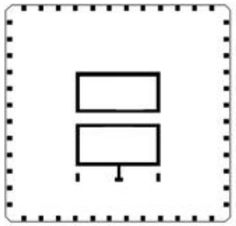
SUPERTALL BUILDINGS WITH COMPLETED AND UNDER CONSTRUCTION STATUS								Architectural Design Considerations					
#	Building Name Location Height / Number of Floors Completion Date Architect Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m²)	Aver. Fl. Ar. (m2) Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
61	Shimao International Plaza Shanghai (CN) 333m / 60 2016 Ingenhoven Overdiek und Partners			91.600	~1526			Amorphous free	Central	Hotel Office		Mega Column / Composite	
62	LCT Residential Tower B Busan (KR) 333m / 85 2020 Samoo Architects & Engineers Skidmore, Owings & Merrill LLP							Articulated Simple Form with Architectural Top	Central	Residential		Outriggered Frame / Reinforced Concrete	
63	China World Tower Beijing (CN) 330m / 74 2010 Skidmore, Owings & Merril LLP (SOM) LEED Gold	 		280.000	~3784			Tapered	Central	Hotel Residential		Outriggered Frame / Composite	

Table A.1. Continued

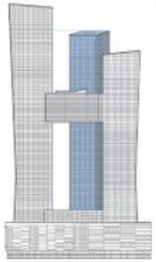
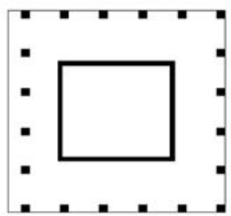
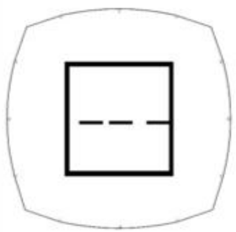
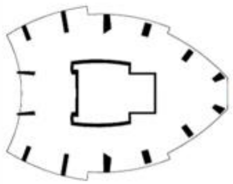
#	Building Name Location Height / Number of Floors Completion Date Architect Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m^2)	Aver. Fl. Ar. (m2)	Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
64	**Golden Eagle Tiandi Tower B** Nanjing (CN) 328m / 68 2019 East China Architectural Design & Research Institute								Tapered (inverse)	Central	Office		Outriggered Frame / Composite	
65	**Salesforce Tower** San Francisco (US) 326m / 61 2018 Pelli Clarke Pelli Architects LEED Platinum targeted				~3600		~33,3 x ~31,6	~16,3	Non-continuous Tapered	Central	Office		Shear Walled Frame / Composite	
66	**Q1 Tower** Gold Coast (AU) 323m / 78 2005 Innovarchi; Sunland Group			107.510	~1378				Articulated Simple Form with Architectural Top	Central	Residential		Shear Walled Frame / Reinforced Concrete	

Table A.1. Continued

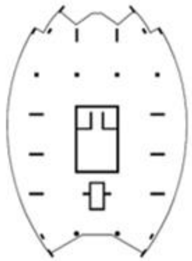
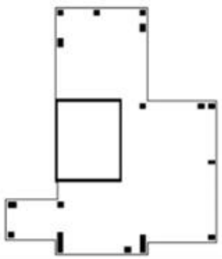
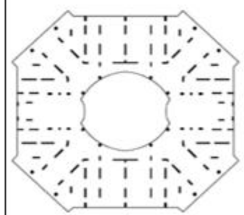
#	Building Name / Location / Height / Number of Floors / Completion Date / Architect / Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m²)	Aver. Fl. Ar. (m2) / Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
67	Burj Al Arab Dubai (AE) 321m / 56 1999 Atkins LEED Silver			120.000	~2143			Amorphous Free (Aerodynamically Adaptive)	Central	Hotel		Shear Walled Frame / Composite	Aerodynamic Form
68	53 West 53rd New York City (US) 320m / 77 2019 Ateliers Jean Nouvel							Non-continuous Tapered	Peripheral	Residential	12	Diagrid-Framed-Tube / Reinforced Concrete	
69	Palais Royale Mumbai (IN) 320m / 88 _ Talati Panthaky Associates LEED Platinum							Articulated Simple Form	Central	Residential		Outriggered Frame / Reinforced Concrete	

Table A.1. Continued

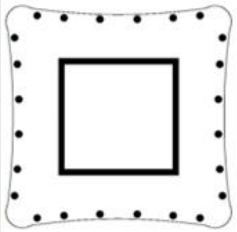
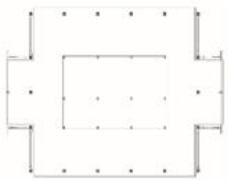
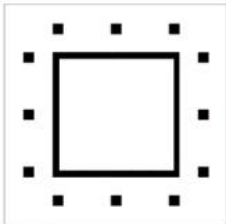
#	Building Name Location Height / Number of Floors Completion Date Architect Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m^2)	Aver. Fl. Ar. (m2) Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
								SUPERTALL BUILDINGS WITH COMPLETED AND UNDER CONSTRUCTION STATUS					
70	**Sinar Mas Center 1** Shanghai (CN) 320m / 65 2017 Skidmore, Owings & Merril LLP (SOM) LEED Gold (Pre-certified)							Amorphous Free	Central	Office		Outriggered Frame / Composite	
71	**New York Times Tower** New York (US) 319m / 52 2007 FXFOWLE; Renzo Piano Building Workshop			143.601	~2761 ~2320*	~28 x ~20	~13,8	Articulated Simple Form with Architectural Top	Central	Office	6,8	Outriggered Frame / Steel	
72	**MahaNakhon** Bangkok (TH) 314m / 75 2016 Office for Metropolitan Architecture			121.782	~1624 ~1521*	22 x 22	14	Amorphous Free	Central	Hotel Residential	13,6	Outriggered Frame / Reinforced Concrete	

Table A.1. Continued

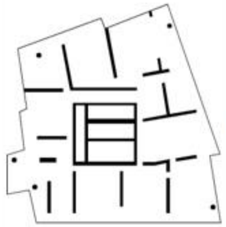
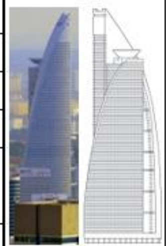
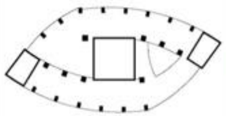
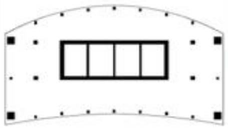
#	Building Name Location Height / Number of Floors Completion Date Architect Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m²)	Aver. Fl. Ar. (m2) Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
73	**Ocean Heights** Dubai (AE) 310m / 83 2010 Aedas			113.416	~1366 ~1000*	~10,5 x ~10,5*	~9*	Tapered	Central	Residential	~11,5*	Outriggered Frame / Reinforced Concrete	
74	**Menara TM** Kuala Lumpur (MY) 310m / 55 2001 Hijjas Kasturi Associates			148.643	~2702			Amorphous Free	Central	Office		Outriggered Frame / Reinforced Concrete	
75	**Pearl River Tower** Guangzhou (CN) 309m / 71 2013 Skidmore, Owings & Merril LLP (SOM) LEED Platinum			165.840	~2336 ~2845*	38 x 14	18,5	Amorphous Free (Aerodynamically Adaptive)	Central	Office	11,7	Outriggered Frame / Composite	Aerodynamic Form

Table title: SUPERTALL BUILDINGS WITH COMPLETED AND UNDER CONSTRUCTION STATUS

Table A.1. Continued

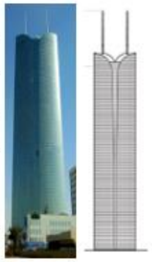
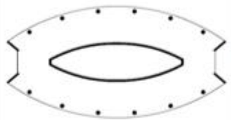
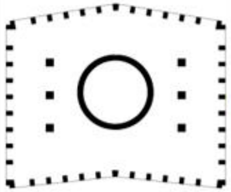
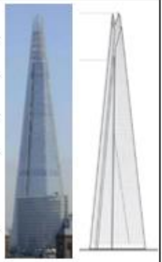
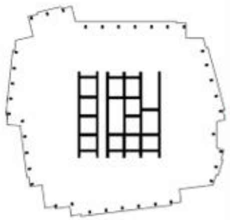
#	Building Name / Location / Height / Number of Floors / Completion Date / Architect / Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m^2)	Aver. Fl. Ar. (m2) / Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
76	**Burj Rafal** Riyadh (SA) 308m / 68 2014 P & T Group			92.626	~1362			Articulated Simple Form with Architectural Top	Central	Hotel Residential		Outriggered Frame / Composite	
77	**Cayan Tower** Dubai (AE) 306m / 73 2013 Skidmore, Owings & Merril LLP (SOM) LEED Certified			111.000	~1520 ~1142*	13,7m (in diameter)	13	Twisted (Structurally Adaptive & Aerodynamically Adaptive)	Central	Residential	10,8	Framed-Tube / Reinforced Concrete	Twisted
78	**The Shard** London (GB) 306m / 73 2013 Renzo Piano Building Workshop BREEAM Excellent			127.489	~1746 ~4822*	22 x 20	12,5	Tapered (Aerdynamically Adaptive)	Central	Hotel Residential Office	~4,7*	Shear Walled Frame / Composite	Tapered

Table A.1. Continued

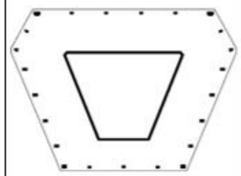
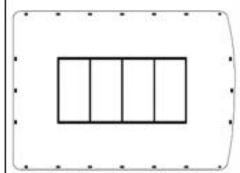
#	Building Name / Location / Height / Number of Floors / Completion Date / Architect / Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m^2)	Aver. Fl. Ar. (m2) / Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
79	**Northeast Asia Trade Tower** Incheon (KR) 305m / 68 2011 Kohn Pedersen Fox Associates LEED Silver			140.000	~2059			Tapered	Central	Hotel Residential Office		Outriggered Frame / Composite	
80	**Wuxi Maoye City - Marriott Hotel** Wuxi (CN) 304m / 68 2014							Simple	Central	Hotel		Outriggered Frame / Composite	
81	**One Manhattan West** New York (US) 303m / 67 2019 Skidmore, Owings & Merril LLP (SOM) LEED Gold targeted			171.000	~2552			Non-continuous Tapered	Central	Office		Shear Walled Frame / Composite	

Table A.1. Continued

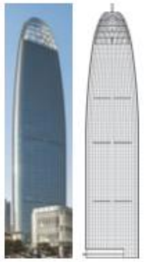
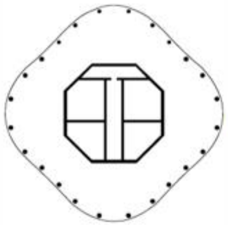
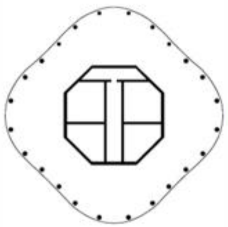
#	Building Name / Location / Height / Number of Floors / Completion Date / Architect / Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m²)	Aver. Fl. Ar. (m2) / Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
	SUPERTALL BUILDINGS WITH COMPLETED AND UNDER CONSTRUCTION STATUS							Architectural Design Considerations					
82	**Greenland Puli Center** Jinan (CN) 303m / 61 2014 Skidmore, Owings & Merril LLP (SOM)			111.064	~1821			Non-continuous Tapered	Central	Office		Outriggered Frame / Composite	
83	**Jiangxi N. G. Central Plaza, Parcel A** Nanchang (CN) 303m / 59 2015 Skidmore, Owings & Merril LLP (SOM)			110.000				Free (Aerodynamically Adaptive)	Central	Office		Outriggered Frame / Composite	Aerodynamic Form & Corner Modification
84	**Jiangxi N. G. Central Plaza, Parcel B** Nanchang (CN) 303m / 59 2015 Skidmore, Owings & Merril LLP (SOM)			110.000				Free (Aerodynamically Adaptive)	Central	Office		Outriggered Frame / Composite	Aerodynamic Form & Corner Modification

Table A.1. Continued

SUPERTALL BUILDINGS WITH COMPLETED AND UNDER CONSTRUCTION STATUS

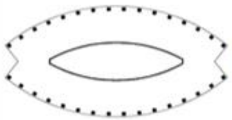
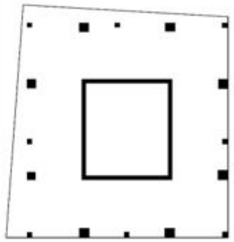
#	Building Name / Location / Height / Number of Floors / Completion Date / Architect / Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m²)	Aver. Fl. Ar. (m2) / Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
85	**Kingdom Centre** Riyadh (SA) 302m / 41 2002 Ellerbe Becket; Omrania & Associates			185.000	~4512			Free (Aerodynamically Adaptive)	Central	Hotel Residential Office		Shear Walled Frame / Reinforced Concrete	Aerodynamic Form & Wind Opening
86	**Capital City Moscow Tower** Moscow (RU) 302m / 76 2010 NBBJ							Modulated & Repetitive Free	Central	Residential		Outriggered Frame / Reinforced Concrete	
87	**Shenzhen Zhongzhou Holdings F. C.** Shenzhen (CN) 301m / 61 2015 Adrian Smith + Gordon Gill Architecture							Simple	Atrium	Hotel Office		Outriggered Frame / Composite	

Table A.1. Continued

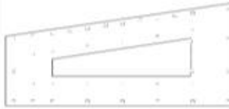
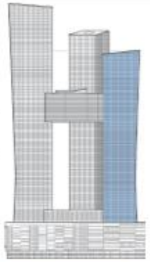
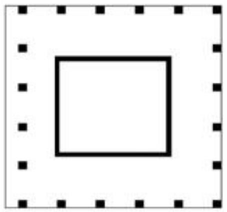
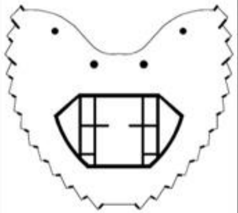
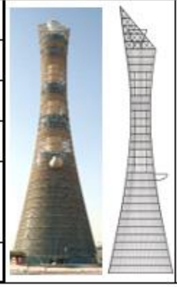
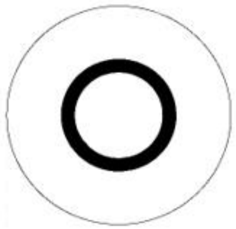
#	Building Name Location Height / Number of Floors Completion Date Architect Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m^2)	Aver. Fl. Ar. (m2) / Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
	SUPERTALL BUILDINGS WITH COMPLETED AND UNDER CONSTRUCTION STATUS							Architectural Design Considerations					
88	**Abeno Harukas** Osaka (JP) 300m / 60 2014 Takenaka Corporation			212.000	~3533 /			Setback (Aerodynamically Adaptive)	Central	Hotel Office		Outriggered Frame / Composite	Setback
89	**Golden Eagle Tiandi Tower C** Nanjing (CN) 300m / 60 2019 East China Architectural Design & Research Institute							Tapered (inverse)	Central	Office		Outriggered Frame / Composite	
90	**NBK Tower** Kuwait City (KW) 300m / 59 2018 Foster + Partners LEED Gold targeted							Free	Central	Office		Outriggered Frame / Composite	

Table A.1. Continued

#	Building Name / Location / Height / Number of Floors / Completion Date / Architect / Energy Label	Photo & Image	Typical Floor Plan	Tower Gross Floor Area (m²)	Aver. Fl. Ar. (m2) / Ground Fl. Ar. (m2)	Core Dimensions (m x m)	(Max.) Lease Span (m)	Architectural Design Considerations: Building Form	Core Type	Function	Aspect Ratio	Structural System / Structural Material	Aerodynamic Design Considerations
91	**Aspire Tower** Doha (QA) 300m / 36 2007 Hadi Simaan 			35.000	 ~1294*	18m (in diameter)	11,3	Free	Central	Hotel Office	16,6*	Mega Core / Reinforced Concrete	Air Passes

SUPERTALL BUILDINGS WITH COMPLETED AND UNDER CONSTRUCTION STATUS

* Calculated by the author.

APPENDIX B

SUPERTALL BUILDING LIST (286 BUILDINGS)

Table A.2. Supertall Building List (286 buildings)

#	Building name	Location	Height (m)	Structural Material	Building Form	Building Function
1	Jeddah Tower	SA	1000+	Composite	Tapered	Residential
2	Burj Khalifa	AE	828	RC	Setback	Multi-function
3	Merdeka PNB 118	MY	644	Composite	Free	Multi-function
4	Shanghai Tower	CN	632	Composite	Twisted	Multi-function
5	Grand Rama 9 Tower	TH	615	-	Free	Multi-function
6	Makkah Royal Clock Tower	SA	601	-	Simple	Hotel
7	Ping An Finance Center	CN	599	Composite	Tapered	Office
8	Global Financial Center Tower 1	CN	568	Composite	Tapered	Office
9	Lotte World Tower	KR	555	Composite	Tapered	Multi-function
10	One World Trade Center	US	541	Composite	Tapered	Office
11	Guangzhou CTF Finance Center	CN	530	Composite	Tapered	Multi-function
12	Tianjin CTF Finance Center	CN	530	Composite	Tapered	Multi-function
13	Citic Tower	CN	528	Composite	Free	Office
14	Skyfame Center Landmark Tower	CN	528	-	Tapered	-
15	Evergrande International Center T1	CN	518	Composite	Free	Multi-function
16	TAIPEI 101	TW	508	Composite	Free	Office
17	Shanghai World Financial Center	CN	492	Composite	Tapered	Multi-function
18	International Commerce Centre	CN	484	Composite	Tapered	Multi-function
19	Central Park Tower	US	472	RC	Setback	Multi-function
20	Chengdu Greenland Tower	CN	468	Composite	Tapered	Multi-function
21	Lakhta Center	RU	462	Composite	Twisted	Multi-function
22	Vincom Landmark 81	VN	461	Composite	Setback	Multi-function

#	Building name	Location	Height (m)	Structural Material	Building Form	Building Function
23	Changsha IFS Tower T1	CN	452	Composite	Simple	Multi-function
24	Petronas Twin Tower 1	MY	452	RC	Setback	Office
25	Petronas Twin Tower 2	MY	452	RC	Setback	Office
26	Suzhou IFS	CN	450	Composite	Free	Multi-function
27	Zifeng Tower	CN	450	Composite	Free	Multi-function
28	The Exchange 106	MY	446	-	Tapered	Office
29	KK 100	CN	442	Composite	Tapered	Multi-function
30	Guangzhou International Finance Center	CN	439	Composite	Free	Multi-function
31	Wuhan Center Tower	CN	438	Composite	Tapered	Multi-function
32	Review Plaza A1	CN	436	Composite	Tapered	Multi-function
33	111 West 57th Street	US	435	RC	Setback	Residential
34	Multifunctional Highrise Complex-Akhmat Tower	RU	435	Steel	Tapered	Multi-function
35	Diamond Tower	SA	432	-	Twisted	Residential
36	Chongqing Tall Tower	CN	431	RC	Tapered	Multi-function
37	Haikou Tower 1	CN	428	Composite	Tapered	Multi-function
38	Shandong IFC	CN	428	-	-	Multi-function
39	One Vanderbilt	US	427	Composite	Tapered	Office
40	Dongguan International Trade Center 1	CN	427	Composite	Tapered	Office
41	432 Park Avenue	US	426	RC	Simple	Residential
42	Marina 101	AE	425	RC	Simple	Multi-function
43	Trump International Hotel & Tower	US	423	RC	Setback	Multi-function
44	Jin Mao Tower	CN	421	Composite	Free	Multi-function

#	Building name	Location	Height (m)	Structural Material	Building Form	Building Function
45	Princess Tower	AE	413	RC	Simple	Residential
46	Al Hamra Tower	KW	413	RC	Free	Office
47	Two International Finance Centre	CN	412	Composite	Setback	Office
48	LCT Landmark Tower	KR	412	RC	Simple	Multi-function
49	Dongfeng Plaza Landmark Tower	CN	407	-	Tapered	-
50	Nanning China Resources Tower	CN	403	Composite	Tapered	Multi-function
51	Guiyang International Financial Center T1	CN	401	-	Free	Multi-function
52	China Resources Headquarters	CN	393	Composite	Tapered	Office
53	23 Marina	AE	393	RC	Simple	Residential
54	CITIC Plaza	CN	390	Composite	Simple	Office
55	Shum Yip Upperhills T1	CN	388	Composite	Simple	Multi-function
56	30 Hudson Yards	US	387	-	Free	Office
57	La Maison by HDS	AE	387	-	Simple	Residential
58	Capital Market Authority Tower	SA	385	Composite	Free	Office
59	Shun Hing Square	CN	384	Composite	Free	Office
60	Eton Place Dalian Tower 1	CN	383	Composite	Free	Multi-function
61	Abu Dhabi Plaza	KZ	382	Composite	Setback	Multi-function
62	Nanning Logan Century 1	CN	381	Composite	Simple	Multi-function
63	Burj Mohammed Bin Rashid	AE	381	RC	Free	Residential
64	Elite Residence	AE	381	RC	Simple	Residential
65	Guiyang World Trade Center	CN	380	RC	Tapered	Multi-function
66	Shenzhen Center	CN	376	Composite	Tapered	Multi-function
67	Central Plaza	CN	374	RC	Simple	Office

#	Building name	Location	Height (m)	Structural Material	Building Form	Building Function
68	Federation Tower	RU	374	RC	Free	Multi-function
69	Coronation Square Tower 1	MY	370	-	-	-
70	Fairmont Kuala Lumpur T1	MY	370	-	-	Multi-function
71	The Address Boulevard	AE	370	RC	Setback	Multi-function
72	Xujiahui Center Tower 1	CN	370	-	-	Office
73	Hai Tian Center Tower 2	CN	369	Composite	Free	Multi-function
74	Golden Eagle Tiandi Tower A	CN	368	Composite	Tapered	Multi-function
75	Bank of China Tower	CN	367	Composite	Setback	Office
76	Guiyang Financial Center Tower 2	CN	367	-	-	-
77	Bank of America Tower	US	366	Composite	Free	Office
78	VietinBank Business Center Office	VN	363	Composite	Simple	Office
79	Vista Tower	US	363	RC	Free	Multi-function
80	Three Sixty West Tower B	IN	361	RC	Simple	Residential
81	Almas Tower	AE	360	RC	Free	Office
82	Greenland Group Suzhou Center	CN	358	Composite	Free	Multi-function
83	Gevora Hotel	AE	356	-	Simple	Hotel
84	Il Primo T1	AE	356	RC	Setback	Residential
85	S Residence by Immo	AE	356	RC	Free	Residential
86	JW Marriot Marquis Hotel Dubai Tower 1	AE	355	RC	Free	Hotel
87	JW Marriot Marquis Hotel Dubai Tower 2	AE	355	RC	Free	Hotel
88	Emirates Tower One	AE	355	Composite	Free	Office
89	Raffles City Chonqging T3N	CN	355	Composite	Tapered	Residential
90	Raffles City Chonqging T4N	CN	355	Composite	Tapered	Multi-function

#	Building name	Location	Height (m)	Structural Material	Building Form	Building Function
91	OKO - Residential Tower	RU	354	RC	Simple	Multi-function
92	The Torch	AE	352	RC	Setback	Residential
93	Forum 66 Tower 1	CN	351	Composite	Tapered	Multi-function
94	The Pinnacle	CN	350	RC	Simple	Office
95	Icon Tower 1	ID	350	Composite	-	Multi-function
96	Xi An Glory International Financial Center	CN	350	Composite	Simple	Office
97	Hanking Center Tower	CN	350	Composite	Tapered	Office
98	Agricultural Development Center Tower 1	CN	350	-	-	-
99	Spring City 66	CN	349	Composite	Free	Office
100	Hengfeng Guiyang Center Tower 1	CN	349	Composite	-	Multi-function
101	Huiyun Center	CN	348	Composite	-	Office
102	T & C Tower	TW	348	Steel	Free	Multi-function
103	Shimao Hunan Center	CN	347	Composite	Setback	Office
104	The Center	CN	346	Composite	Simple	Office
105	Xiamen Cross Strait Financial Centre	CN	344	Composite	Simple	Office
106	Four Seasons Place	MY	343	RC	Simple	Multi-function
107	ADNOC Headquarters	AE	342	RC	Simple	Office
108	Comcast Technology Tower	US	342	Composite	Setback	Multi-function
109	One Shenzhen Bay Tower 7	CN	341	Composite	Free	Multi-function
110	Oxley Tower 1	MY	341	-	Free	Hotel
111	Uptown Dubai Tower 2	AE	340	-	Free	-
112	45 Broad Street	US	340	-	Free	Residential
113	LCT Landmark Tower A	CN	340	RC	Simple	Residential
114	Wuxi International Finance Square	CN	339	Composite	Simple	Multi-function

#	Building name	Location	Height (m)	Structural Material	Building Form	Building Function
115	Heartland 66 Office Tower	CN	339	-	Free	Office
116	Chongqing World Financial Center	CN	339	Composite	Simple	Multi-function
117	Mercury City Tower	RU	339	RC	Setback	Multi-function
118	NEVA TOWERS 2	RU	338	RC	Simple	Residential
119	Suning Plaza Tower 1	CN	338	Composite	Free	Multi-function
120	Tianjin Modern City Office Tower	CN	338	Composite	Tapered	Office
121	Parc1 Tower A	KR	338	Composite	Free	Office
122	Wanling Global Center	CN	337	-	-	-
123	Tianjin World Financial Center	CN	337	Composite	Tapered	Office
124	Hengqin International Finance Center	CN	337	Composite	Free	Multi-function
125	WOW Hotel & Hotel Apartments	AE	336	RC	Free	Hotel
126	DAMAC Heights	AE	335	RC	Free	Residential
127	Wilshire Grand Center	US	335	Composite	Tapered	Multi-function
128	Twin Tower Guiyang, East	CN	335	Composite	Simple	Office
129	Twin Tower Guiyang, West	CN	335	Composite	Simple	Multi-function
130	Shengjing Finance Plaza T2	CN	334	Composite	-	Multi-function
131	Thamrin Nine Tower 1	ID	334	Composite	Free	Multi-function
132	Shimao International Plaza	CN	333	RC	Free	Multi-function
133	LCT Residential Tower B	KR	333	RC	Simple	Residential
134	Mandarin Oriental T - A	CN	333	-	Free	Multi-function
135	Rose Rayhaan by Rotana	AE	333	Composite	Free	Hotel

#	Building name	Location	Height (m)	Structural Material	Building Form	Building Function
136	Jinan Center Financial City A5-3	CN	333	Composite	Free	Office
137	A Tower	AE	333	-	-	Residential
138	Jiujiang IFC	CN	333	Composite	Free	Office
139	The Address Residence Fountain	AE	331	RC	Setback	Hotel
140	Minsheng Bank Building	CN	331	Steel	Simple	Office
141	China World Tower	CN	330	Composite	Tapered	Multi-function
142	Guangxi Financial Investment Center	CN	330	-	Free	Multi-function
143	Shimao Qianhai Project T-1	CN	330	Composite	Twisted	-
144	Yuexiu Fortune Center T-1	CN	330	Composite	Free	Office
145	The Skyscraper	AE	330	-	Free	Office
146	Changsha A9 Financial District	CN	330	-	Simple	Multi-function
147	Wuhan Yangtze River Shipping Center	CN	330	Composite	-	Multi-function
148	Zhenru Center	CN	330	Composite	Simple	Office
149	Huaguouuan Zone D	CN	330	Composite	-	-
150	Huaguouuan Zone N	CN	330	Composite	-	-
151	One Zaabeel Tower 1	AE	330	-	Simple	Office
152	Hon Kwok City Center	CN	330	Composite	Simple	Multi-function
153	3 World Trade Center	US	329	Composite	Setback	Office
154	Zhuhai Tower	CN	329	Composite	Tapered	Multi-function
155	Keangnam Hanoi Landmark T.	VN	329	RC	Setback	Multi-function
156	Longxi International Hotel	CN	328	Composite	Free	Multi-function
157	Al Yaqoub Tower	AE	328	RC	Setback	Multi-function

#	Building name	Location	Height (m)	Structural Material	Building Form	Building Function
158	Golden Eagle Tiandi Tower B	CN	328	Composite	Tapered	Office
159	Wuxi Suning Plaza 1	CN	328	Composite	Simple	Multi-function
160	Bianjiang IFC Tower 1	CN	328	Composite	-	Office
161	Global Financial Center Tower 2	CN	328	Composite	Tapered	Multi-function
162	Baoneng Center	CN	327	Composite	Tapered	Office
163	Qingdao Landmark Tower	CN	327	-	Tapered	Multi-function
164	Huaqiang Golden Corridor City	CN	327	Composite	Tapered	Multi-function
165	Salesforce Tower	US	326	Composite	Tapered	Office
166	The Index	AE	326	RC	Tapered	Multi-function
167	Dongfeng Plaza Tower 2	CN	326	-	Tapered	-
168	Qianhai Horoy Tower	CN	325	-	Free	Multi-function
169	9 DeKalb Avenue	US	325	RC	Setback	Multi-function
170	The Landmark	AE	324	RC	Free	Multi-function
171	Deji Plaza	CN	324	Composite	Free	Multi-function
172	Yantai Shimao No.1	CN	323	Composite	Free	Multi-function
173	Q1 Tower	AU	323	RC	Simple	Residential
174	Wenzhou Trade Center	CN	322	RC	Tapered	Multi-function
175	The One Colombo T - A	LK	322	-	-	Multi-function
176	Guangxi Finance Plaza	CN	321	Composite	Tapered	Multi-function
177	Burj Al Arab	AE	321	RC	Free	Hotel
178	Nina Tower	CN	320	RC	Setback	Multi-function
179	53 West 57rd	US	320	RC	Tapered	Residential
180	Palais Royale	IN	320	RC	Simple	Residential
181	Shenzhen Bay Innovation	CN	320	-	-	Office
182	Huijin Center 1	CN	320	Composite	Tapered	Office
183	Junchao Plaza	CN	320	-	-	Office

#	Building name	Location	Height (m)	Structural Material	Building Form	Building Function
184	The Pinnacle Tower	KE	320	RC	Tapered	Multi-function
185	Sinar Mas Center	CN	320	Composite	Free	Office
186	Xinchu Qingtian Plaza Tower 1	CN	319	Composite	-	Office
187	Global City Square	CN	319	Composite	Free	Office
188	New York Times Tower	US	319	Steel	Simple	Office
189	Foshan Suning Plaza Tower 1	CN	318	-	Tapered	Multi-function
190	Jiuzhou International Tower	CN	318	Composite	Setback	Office
191	Nanning World Trade Center T1	CN	318	Composite	Tapered	Multi-function
192	OCT Xian International Culture Tower	CN	318	-	Setback	Multi-function
193	Fanya International Finance – North	CN	318	-	Tapered	Office
194	Fanya International Finance – South	CN	318	-	Tapered	Office
195	HHHR Tower	AE	318	RC	Free	Residential
196	Australia 108	AU	317	RC	Tapered	Residential
197	M101 Skywheel	MY	317	-	Setback	Multi-function
198	Chonqging IFS T1	CN	316	Composite	Simple	Multi-function
199	Magnolias Waterfront Residences T1	TH	315	RC	-	Residential
200	Walsin Centro	CN	315	-	-	Multi-function
201	Changsha IFS Tower 2	CN	315	Composite	Setback	Office
202	Nanning International Youth Cultural	CN	315	Composite	Tapered	Multi-function
203	MahaNakhon	TH	314	RC	Free	Multi-function
204	FIVE Jumeirah Village Dubai	AE	314	RC	Free	Multi-function
205	TEDA IFC 1	CN	313	-	Setback	Office

#	Building name	Location	Height (m)	Structural Material	Building Form	Building Function
206	CITIC Financial Center Tower 1	CN	312	-	Tapered	Multi-function
207	Bank of America Plaza	US	312	Composite	Simple	Office
208	Poly Pazhou C2	CN	311	Composite	Tapered	Office
209	Moi Center Tower A	CN	311	Composite	Simple	Office
210	Guangxi Wealth Financial Center	CN	311	Composite	-	Office
211	US Bank Tower	US	310	Steel	Setback	Office
212	Ocean Heights	AE	310	RC	Tapered	Residential
213	Greenland Center 1	CN	310	-	Tapered	Multi-function
214	Greenland Center 2	CN	310	-	Tapered	Multi-function
215	Nameste Tower	IN	310	RC	Tapered	Hotel
216	Menara TM	MY	310	RC	Free	Office
217	Varso Tower	PL	310	-	Setback	Office
218	Xinchu Qunqtian Plaza Tower 2	CN	310	Composite	Simple	-
219	Pearl River Tower	CN	309	Composite	Free	Office
220	Fortune Center	CN	309	Composite	Tapered	Office
221	Chengdu Poly International Plaza	CN	309	Composite	Tapered	Multi-function
222	Emirates Tower Two	AE	309	RC	Simple	Hotel
223	Stalnaya Vershina	RU	309	Composite	Setback	Multi-function
224	Kempinski Hotel & Residences	MY	309	RC	-	Multi-function
225	Guangfa Securities Headquarters	CN	308	Composite	Tapered	Office
226	Burj Rafal	SA	308	RC	Simple	Multi-function
227	35 Hudson Yards	US	308	RC	Setback	Residential
228	Amna Tower	AE	307	RC	Simple	Residential
229	Noora Tower	AE	307	RC	Simple	Residential
230	The Franklin-North Tower	AE	307	RC	Setback	Office
231	Cayan Tower	AE	306	RC	Twisted	Residential
232	The One	CA	306	-	Simple	Residential

#	Building name	Location	Height (m)	Structural Material	Building Form	Building Function
233	One 57	US	306	-	Setback	Multi-function
234	East Pacific Center Tower A	CN	306	Composite	Simple	Residential
235	The Shard	GB	306	Composite	Tapered	Multi-function
236	JPMorgan Chase Tower	US	305	Composite	Simple	Office
237	Etihad Towers T2	AE	305	RC	Tapered	Residential
238	Northeast Asia Trade Tower	KR	305	Composite	Tapered	Multi-function
239	International Trade Center	CN	305	-	-	Multi-function
240	Shenzhen CFC Changfu Center	CN	304	Composite	Tapered	Office
241	Balyoke Tower II	TH	304	RC	Setback	Hotel
242	KAFD World Trade Center	SA	304	RC	Free	Office
243	Wuxi Mayoe City	CN	304	Composite	Simple	Hotel
244	One Manhattan West	US	303	Composite	Tapered	Office
245	Two Prudential Plaza	US	303	RC	Setback	Office
246	Suzhou ICC	CN	303	-	Free	Multi-function
247	Diwang International Fortune Center	CN	303	Composite	Tapered	Multi-function
248	Indonesia 1-North Tower	ID	303	-	Simple	Multi-function
249	Global Trade Center	CN	303	Composite	Free	Office
250	Greenland Puli Center	CN	303	Composite	Tapered	Office
251	Indonesia 1-North Tower	ID	303	-	Simple	Multi-function
252	Jiangxi Nanchang Greenland 1	CN	303	Composite	Simple	Office
253	Jiangxi Nanchang Greenland 2	CN	303	Composite	Tapered	Office
254	Leatop Plaza	CN	303	Composite	Tapered	Office
255	Wells Fargo Plaza	US	302	Steel	Free	Office

#	Building name	Location	Height (m)	Structural Material	Building Form	Building Function
256	Kingdom Center	SA	302	-	Free	Multi-function
257	The Address	AE	302	RC	Free	Multi-function
258	Al Wasl Tower	AE	302	RC	Free	Multi-function
259	Gate to the East	CN	302	Composite	Free	Multi-function
260	Capital City Moscow Tower	RU	302	RC	Free	Multi-function
261	International Commerce Financial Centre	CN	301	Composite	Free	Multi-function
262	Jumeriah Gate	AE	301	RC	Free	Multi-function
263	Merkez Ankara Office Tower	TR	301	RC	Tapered	Office
264	Greenland Center North Tower	CN	301	Composite	Tapered	Multi-function
265	Greenland Center South Tower	CN	301	Composite	Tapered	Office
266	Shenzhen Zhongzhou Holdings FC	CN	301	Composite	Tapered	Multi-function
267	50 Hudson Yards	US	300	RC	Setback	Office
268	Doosan Haeundae Tower A	CN	300	RC	Free	Residential
269	Supernova Spira	IN	300	RC	Tapered	Multi-function
270	Il Primo Tower 2	AE	300	RC	Setback	Residential
271	Centralcon Shangsha P1	CN	300	-	-	-
272	Centralcon Shangsha P2	CN	300	-	-	-
273	Huachuang International Plaza Tower 1	CN	300	Composite	Simple	Multi-function
274	Huangpu Dongjiadu 1	CN	300	-	-	Multi-function
275	Torre Costenera	CL	300	RC	Tapered	Office
276	Abeno Harukas	JP	300	RC	Setback	Multi-function
277	Arraya Tower	KW	300	Composite	Free	Office

#	Building name	Location	Height (m)	Structural Material	Building Form	Building Function
278	Golden Eagle Tiandi Tower C	CN	300	Composite	Tapered	Office
279	OCT Tower	CN	300	Composite	Tapered	Office
280	NBK Tower	KW	300	Composite	Tapered	Office
281	Shenglog Global Center	CN	300	Composite	Tapered	Office
282	Aspire Tower	QA	300	Composite	Free	Multi-function
283	Baoneng FC 1	CN	300	-	Tapered	-
284	Baoneng FC 2	CN	300	-	Tapered	-
285	Baoneng FC 3	CN	300	-	Tapered	-
286	Wenling Sheraton	CN	300	-	Tapered	Hotel

CURRICULUM VITAE

H. EMRE ILGIN
Architect *(M.Sc., Ph.D. Candidate)*

PERSONAL INFORMATION

Date of Birth / Place	16.06.1981 / Ankara, TURKEY
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EDUCATION

Institution	Date from - date to	Degree(s) or Diploma(s) obtained
MIDDLE EAST TECHNICAL UNIVERSITY Graduate School of Natural and Applied Sciences Department of Architecture / Building Science *(Thesis Subject: **Potentials and Limitations of Supertall Building Structural Systems**)*	(2006 - Present)	Ph.D. Candidate *(3.44 / 4)* (Ph.D. Q. Exam is satisfied in 2010) (Ph.D. proposal is satisfied in 2017)
MIDDLE EAST TECHNICAL UNIVERSITY Graduate School of Natural and Applied Sciences Department of Architecture / Building Science *(Thesis Subject: **A Study on Tall Buildings and Aerodynamic Modifications against Wind Excitation**)*	(2003 - 2006)	M.Sc. *(3.86 / 4)*
MIDDLE EAST TECHNICAL UNIVERSITY Department of Architecture	(1998 - 2003)	B.A. *(2.77 / 4)*
KIRIKKALE SCIENCE HIGH SCHOOL	(1995 - 1998)	

LANGUAGE SKILLS / Indicate competence on a scale of 1 to 5 (1 - Basic; 5 - Excellent)

Language	Reading	Speaking	Writing
Turkish	Mother Tongue		
English	5	5	5
German	1	1	1

COMPUTER SKILLS / Indicate competence on a scale of 1 to 5 (1 - Basic; 5 - Excellent)

Program	Level
Full Computer Literacy (MS Office, MS Word, Excel, Power-Point, Adobe Photoshop etc.)	5
CAD/CAM Programs (AutoCAD, Architectural Desktop)	5
3D Studio Max, ArchiCAD	4
Internet Applications	5

MEMBERSHIP OF PROFESSIONAL BODIES

Organization	Registration number
Chamber of Architects	38322

PROFESSIONAL EXPERIENCE

Date from - date to	Location	Company / Organization/ Institution	Position	Description
11 / 2016 - Present	Ankara / Turkey	**MINISTRY OF HEALTH** General Directorate of Healthcare Investment Department of Consultancy and Supervision (PPP Projects/Integrated Health Campuses)	Architectural Site Inspector / Ass. Healthcare Specialist	Some important projects: • ***Ankara Etlik Integrated Health Campus (~3600-bed)*** *(Investor/Contractor: TURKERLER & ASTALDI JV)* • ***Turkish Public Health Agency and the Turkish Pharmaceutical and Medical Devices Agency Campus (~415.000 m²)*** *(Investor/Contractor: CCN Holding)* • ***Kayseri Integrated Health Campus (~1500-bed)*** *(Investor/Contractor: YDA Group)* • ***Konya Integrated Health Campus (~1300-bed)*** *(Investor/Contractor: YDA Group)* • ***Isparta Integrated Health Campus (~800-bed)*** *(Investor/Contractor: Akfen Holding)*
10 / 2014 -11 / 2016	Ankara / Turkey	**MINISTRY OF HEALTH** General Directorate of Healthcare Investment Department of Project (PPP Projects/Integrated Health Campuses)	Chief of Architectural Project Office / Ass. Healthcare Specialist	Some important projects: • ***Ankara Bilkent Integrated Health Campus (~3600-bed)*** • ***Ankara Etlik Integrated Health Campus (~3600-bed)*** • ***İzmir Bayraklı Integrated Health Campus (2060-bed)*** • ***Kocaeli Integrated Health Campus (1080-bed)*** • ***Bursa Integrated Health Campus (1355-bed)***
10 / 2010 - 10 / 2014	Ankara / Turkey	**MINISTRY OF HEALTH** Department of Construction and Maintenance Research & Project Branch Office	Project Coordinator	Some important projects: • ***Van 500-bed hospital (~110.000 m²)*** • ***Gumushane 200-bed hospital (~33.000 m²)*** • ***Giresun-Bulancak 100-bed hospital + renovation (~30.000 m²)*** • ***Rize 400-car parking garage (~21.000 m²)*** • ***Erzincan-Refahiye 50-bed hospital (~8.000 m²)*** • ***Artvin-Borçka 50-bed hospital (~8.500 m²)*** • ***Artvin-Murgul 10-bed hospital (~3.000 m²)*** • ***Adana 40-unit ADSM renovation + Adm. building(~6300 m²)***
11 / 2007 - 04 / 2010	Ankara / Turkey	**MINISTRY OF INTERIOR** The General Directorate of Security Department of Construction and Property Research & Project Branch Office	Chief of Architectural Project Office	Some important projects: • ***The Reception Centers for Asylum Seekers and Refugees & Removal Centers for Illegal Immigrants (~150.000 m²)*** *(European Union Founded Project, 3.000.000 € budget)* • ***Kırıkkale Police School of Higher Education (~35.000 m²)*** • ***Karabuk Police Department (~10.000 m²)*** • ***Renovation Project of Police Academy Gölbaşı Campus***
05 / 2005 - 10 / 2005	Ankara /Turkey	**PROKON MUHENDISLIK VE MUSAVIRLIK A.S.**	Architect	Renovation Project of Social Complex for the Central Bank in Ankara
01 / 2005 - 04 / 2005	Ankara /Turkey	**DALOKAY & GÜZER MİM. LTD. ŞTİ.**	Architect	Several Residential Projects

ACADEMIC EXPERIENCE

Date from - date to	Location	Company / Organization/ Institution	Position	Description (Courses)
2014- 2017	Ankara / Turkey	**BAŞKENT UNIVERSITY** Faculty of Fine Arts, Design and Architecture Department of Architecture	Part-time Instructor	• **ARCH 223** Building Materials (Undergraduate Must Course) • **ARCH 224** Statics and Strength (Undergraduate Must Course) • **ARCH 225** Building Systems I (Undergraduate Must Course) • **ARCH 226** Building Systems II (Undergraduate Must Course) • **ARCH 325** Building Technologies I (Undergraduate Must Course) • **ARCH 326** Building Technologies II (Undergraduate Must Course)
2007 - 2012	Ankara / Turkey	**MIDDLE EAST TECHNICAL UNIVERSITY** Faculty of Architecture Department of Architecture	Part-time Instructor	**BS 536** Studies on Tall Building: Design Considerations (Graduate Elective Course)
09 / 2006 - 10 / 2007	Ankara / Turkey	**ÇANKAYA UNIVERSITY** Faculty of Eng. & Arch. Department of Interior Architecture	Research Assistant / Ph.D. Scholarship	• **INAR 233** Construction I (Undergraduate Must Course) • **INAR 234** Construction II (Undergraduate Must Course) • **INAR 237** Structural Systems (Undergraduate Must Course) • **INAR 281** Introduction to CAD (Undergraduate Must Course) • **INAR 282** Advanced CAD (Undergraduate Must Course) • **INAR 344** Environmental Control II: Natural & Artificial Lighting (Undergraduate Must Course) • **INAR 405** Research in Interior Architecture (Undergraduate Must Course)
07 / 2006 - 07 / 2007	Ankara / Turkey	**THE SCIENTIFIC AND TECHNOLOGICAL RESEARCH COUNCIL OF TURKEY (TÜBİTAK) /** **MIDDLE EAST TECHNICAL UNIVERSITY**	Researcher	***"The Analysis of Solar and Wind (Access) Rights and A Proposal for Turkey in the Context of Urban Planning Criteria"*** TÜBİTAK PROJECT (105M151)
07 / 2005 - 07 / 2006	Ankara / Turkey	**THE SCIENTIFIC AND TECHNOLOGICAL RESEARCH COUNCIL OF TURKEY (TÜBİTAK) /** **MIDDLE EAST TECHNICAL UNIVERSITY**	Researcher	***"Wind Energy and Architectural Integration into Tall Buildings"*** TÜBİTAK PROJECT (105M014)

BOOKS / DISSERTATIONS

Books / Dissertations
Ilgın, H.E., ***Fire Safety in Hospitals: Encountered Problems and Remedies About Passive Fire Precautions in Hospitals,*** Healthcare Specialist Thesis, General Directorate of Healthcare Investment, Ministry of Health.
Günel, M.H. and **Ilgın, H.E.**, ***Yuksek Binalar: Tasıyıcı Sistem & Aerodinamik Form,*** MIDDLE EAST TECHNICAL UNIVERSITY, Publication of Faculty of Architecture, Ankara, December 2014. (ISBN: 978-975-429-278-7) (2nd edition)
Günel, M.H. and **Ilgın, H.E.**, ***Tall Buildings: Structural System and Aerodynamic Form,*** Routledge, 2014 (ISBN: 978-1-138-02177-8) (METU Development Foundation Book Award)
Günel, M.H. and **Ilgın, H.E.**, ***Yüksek Binalar: Tasıyıcı Sistem & Aerodinamik Form,*** MIDDLE EAST TECHNICAL UNIVERSITY, Publication of Faculty of Architecture, Ankara, 2010. (ISBN: 978-975-429-278-7)
Günel, M.H., **Ilgın, H.E.** and Sorguç, A.G., ***Ruzgâr Enerjisi ve Bina Tasarımı,*** MIDDLE EAST TECHNICAL UNIVERSITY, Publication of Faculty of Architecture, Ankara, 2007. (ISBN: 975-429-255-8)
Ilgın, H.E., ***A Study on Tall Buildings and Aerodynamic Modifications Against Wind Excitation.*** Unpublished M.Sc. Thesis. Ankara: MIDDLE EAST TECHNICAL UNIVERSITY, January 2006.

PROJECTS of THE SCIENTIFIC AND TECHNOLOGICAL RESEARCH COUNCIL OF TURKE (TUBITAK)

Projects
The Analysis of Solar and Wind (Access) Rights and A Proposal for Turkey in the Context of Urban Planning Criteria, TUBİTAK PROJECT, Engineering Research Grant Committee MAG-HD-06 (105M151), 2007.
Wind Energy and Architectural Integration into Tall Buildings, TUBİTAK PROJECT, Engineering Research Grant Committee MAG-HD-06 (105M014), 2006.

INTERNATIONAL PUBLICATIONS

International Publications
Selçuk, S.A. and **Ilgın, H.E.**, ***Performative Approaches in Tall Buildings: Pearl River Tower,*** Eurasian Journal of Civil Engineering and Architecture, Vol. 1, Issue 2, p. 11-20, December 2017.
Gunel, M.H. and **Ilgın, H.E.**, ***A Proposal for the Classification of Structural Systems of Tall Buildings***, *Building and Environment*, Vol. 42, p. 2667-2675, 2007. (TÜBİTAK Publication Encouragement Award)
Ilgın, H.E. and Gunel, M.H., ***The Role of Aerodynamic Modifications in the Form of Tall Buildings against Wind Excitation***, *METU JFA*, Vol. 24, No. 2, p. 17-25, 2007.

NATIONAL PUBLICATIONS

National Publications
Ilgın, H.E. and Yücel, O., ***Encountered Problems and Remedies About Passive Fire Precautions in Healthcare Buildings***, Uzman Yaklaşım, Vol. 2, p. 64-67, October 2017. (ISSN: 2564-7369)
Ilgın, H.E., ***Hidden Danger in Hospitals: Noise***, Uzman Yaklasım, Vol. 1, p. 32-35, April 2017. (ISSN: 2564-7369)
Kazımov, T., Selçuk, S.A., and **Ilgın, H.E.**, ***Performative Design in High Buildings: The Shanghai Tower Case,*** Yapı Dergisi, Vol: 428, p. 118-125, June, 2017.
Ilgın, H.E. and Günel, M.H., ***Ne Zamana Kadar En Yuksek?,*** *Ege Mimarlık*, p. 26-27, 2008/4-67.
Ilgın, H.E. and Günel, M.H., ***Yuksek Binalarda Yanal Kuvvetlere Karşı Strukturel Yaklaşımlar***, *Ege Mimarlık*, p. 20-25, 2008/4-67.
Günel, M.H and **Ilgın, H.E.**, ***Bir Mimari Tasarım Kriteri Olarak Ruzgâr Enerjisi Kullanımı***, *Ege Mimarlık*, p. 6-11, 2008/2-65.
Günel, M.H. and **Ilgın, H.E.**, ***Degisim Ruzgârı***, *Tasarım Merkezi Dergisi*, Vol: 4, March 2007, p. 101-105, 2007.

(INTER)NATIONAL CONFERENCES & SEMINARS

Conferences & Seminars
Ilgın, H.E. and Yucel, O., ***Encountered Problems and Remedies About Passive Fire Precautions in Hospitals,*** TUYAK 2017 International Fire Safety Symposium and Exhibition, 9-10 November 2017, Istanbul, Turkey, 2017.
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M.Sc. DISSERTATION EXAMINING COMMITTEE MEMBERSHIP

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Participant, TC in Estonia, Paunküla ***"Europe in Crises"***, 5th to 13th October 2016.
Participant, TC in Bulgaria, Varna ***"The Power of Non Formal Education"***, 27th April to 2nd May 2017.
Participant, TC in Armenia, Yerevan ***"Everyone has a story to tell"***, 3rd to 12th September 2017.