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ATINER's Conference Paper Series
ARC2013-0758

Architectural and Structural Development of Tall Buildings

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URL Conference Papers Series: www.atiner.gr/papers.htm

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ISSN **2241-2891**
16/12/2013

An Introduction to ATINER's Conference Paper Series

ATINER started to publish this conference papers series in 2012. It includes only the papers submitted for publication after they were presented at one of the conferences organized by our Institute every year. The papers published in the series have not been refereed and are published as they were submitted by the author. The series serves two purposes. First, we want to disseminate the information as fast as possible. Second, by doing so, the authors can receive comments useful to revise their papers before they are considered for publication in one of ATINER's books, following our standard procedures of a blind review.

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President
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This paper should be cited as follows:

Alaghmandan, M., Pehlivan, N.A. and Elnimeiri, M. (2013) **"Architectural and Structural Development of Tall Buildings"** Athens: ATINER'S Conference Paper Series, No: **ARC2013-0758**.

Architectural and Structural Development of Tall Buildings

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Abstract

One of the main reasons for development and expansion of tall buildings around the world through the past decades was the cost efficiency of the construction of this type of building, particularly in dense cities. This growth could be due to the availability of more rental areas with less environmental damages, land use and more day lighting. In this paper, based on the technology development in architectural and structural realms, the expansion of tall buildings is studied from the appearance of this type of building (19th century) to the current situation (by the end of 2012) architecturally, structurally and historically. In this paper, regarding the previous studies, the history of tall buildings will be divided into three main categories; dominance of architecture, dominance of structure and re-dominance of architecture in tall buildings and based on the study about 73 tallest buildings built by the end of 2012, the future trend of architectural and structural considerations of tall buildings is predicted. In the part of the dominance of structure in tall buildings, the main lateral loads based structural systems are briefly illustrated and introduced.

(Because of apace limitation, it cannot be possible to have the buildings' figures explained in the paper.)

Key Words: Architectural development, Structural systems, Tall buildings,

Corresponding Author:

Introduction

With regard to increasing the number of tall buildings (Figure 1) through the years and regarding the growth of the average height of them (Figure 2), designing this type of building has been a critical issue. Since, studying and considering the history of the architectural and structural development of tall buildings can be important and inevitable criteria for future prediction of this realm of construction.

Figure 1. *Number of tall buildings (200 meter or taller) in the world*

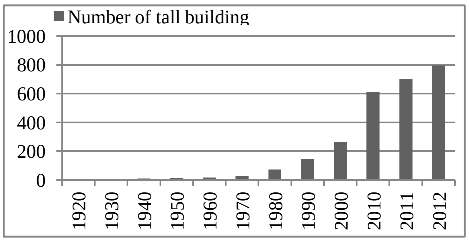
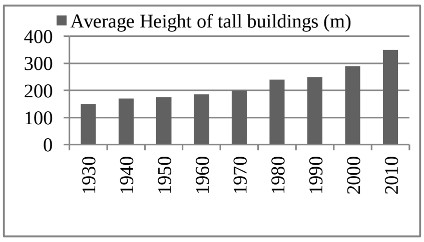


Figure 2. *The average height of the 100 tallest buildings in the world*

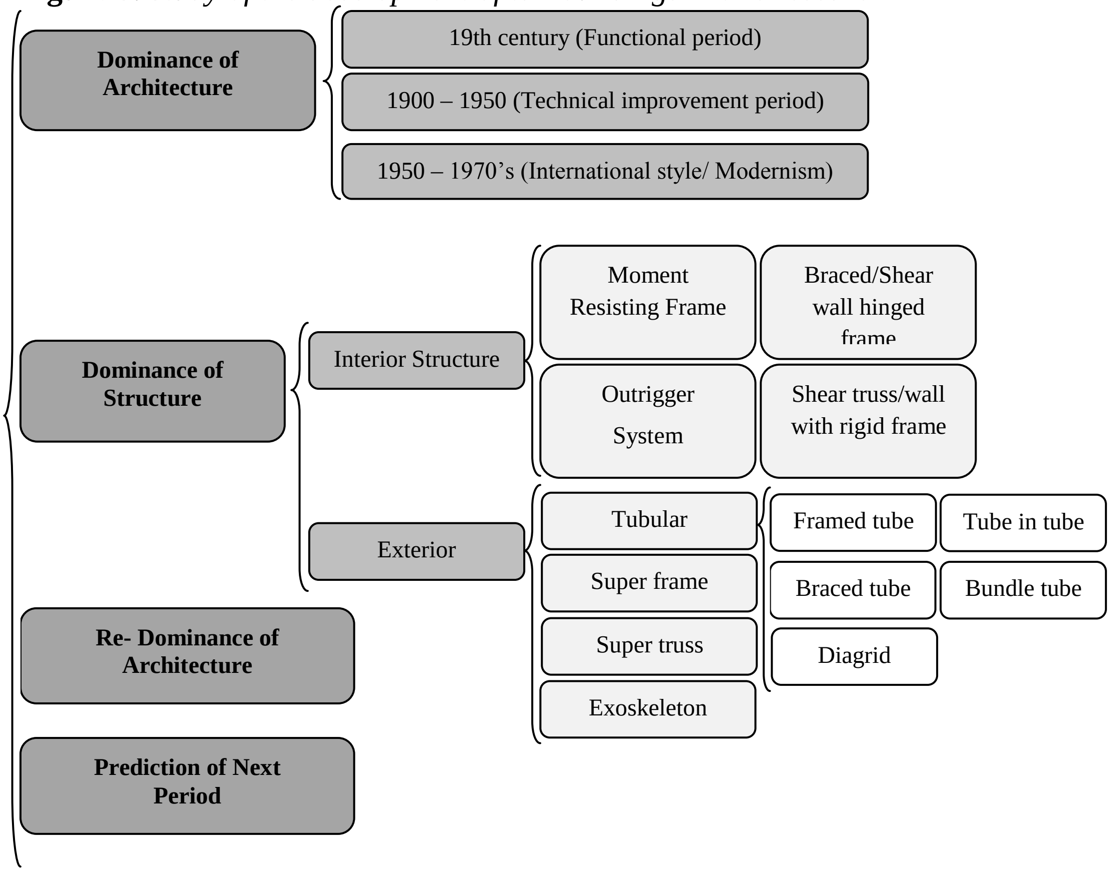


Development of tall buildings

Among the main parameters of the building technology development, the architectural and structural progress like fireproofing of steel and iron and vertical transportation technology (elevator) are the most effective ones. In this part, based on the technology development, the path of the expansion of tall buildings is briefly reviewed from the beginning of the appearance of this type of building architecturally, structurally and historically.

Previously, the development of tall buildings was categorized by a couple of studies. As (Pelli, 1982) categorized that period into four ages such as the functional phase, eclectic Phase, modern phase and postmodern phase; also (Bennett, 1995) divided the period into seven divisions such as the functional period, eclectic period, Art Deco period, international Period, super tall period, social skyscraper period and post modern period. In this paper, regarding the aforementioned studies, the history of tall buildings is divided into three main categories; dominance of architecture, dominance of structure and again re-dominance of architecture in tall building. Each of the periods has also a few subdivisions items. At the end, by considering the architectural and structural parameters in design of tall buildings and also regarding a data study of 73 tallest buildings built by the end of 2012, the future trend of tall building's path is predicted. (Figure 3)

Figure 3. *Study of the development of tall buildings in this research*



Dominance of Architecture in Tall Buildings

This period is about the period of the construction of the first tall building built in the U.S. (1884) until around the 1970. Basically, tall buildings appeared in the late nineteenth century in the United States of America and because of that it was so called "American Building Type".

19th Century

The story began from a very extensive fire. Most of the downtown area of Chicago destroyed because of the Chicago fire in 1871. On the time, architects and engineers participated in the rebuilding of the city by new ideas particularly against the next fire. Steel was chosen as one of the main material for this revolution. It had been used earlier in low industrial structures in the U.S. and also in Europe in bridge construction. Building with more than common height was also chosen as the new type of building. The true skyscraper was invented in Chicago in 1884 and spread through the cities in the U.S. very fast because of increasing rentable area by stacking office spaces vertically by less land use and much more natural light.

In order to serve this architectural-economic revolution, new technologies and knowledge were needed to construct and improve this type of building. The Home Insurance Building (1884) is actually considered as the first tall building with 10 stories and 138 ft (42 m) height, built in Chicago by William Le Baron Jenney as the architect and engineer of the building. In 1890, two additional floors were added on top of the original building. The majority of its structure was composed of cast and wrought iron. (Korom, 2008)

1900 – 1950 (Technical improvement period)

By 1904, elevators, electric lighting, plumbing and heating technology could serve and adaptable to almost any height. At the turn of twentieth century, the combination between decoration and ornament on tall buildings was clearly visible, simultaneously. The triangular shaped Flatiron Building (1903) in New York, designed by Daniel Burnham is one of the most significant examples of this period. In this building, using motifs came from European style like gothic and renaissance can be seen. (Korom, 2008)

Between 1920 until 1940, the Art Deco style also came to the same trend of inscribing to mix both classic and modernism style to impact on the skyscraper. (Bennett, 1995) The Chrysler building (1930) and Empire state tower (1931), both in New York, are two examples of this architectural style.

<u>1950 – 1970's (International style/ Modernism)</u>

The development of tall buildings necessitated the use of iron and later steel skeleton and glass skin. The iron-steel skeleton structure of tall buildings was the innovation of Chicago architects that was known as an international and modernism style in the late 19th century in the U.S. The Seagram Building (1958), a 35-story tall building, designed by Ludwig Mies van der Rohe in New York stands is one of the earliest examples of this style. (Korom, 2008)

Dominance of Structure in Tall Buildings

The second major part of the study of the development of tall buildings is about the majority of tall buildings from 1970 until the current trend of tall buildings. This period is basically about the time that structural strategies could overcome on the architectural aspects of tall buildings. Fairly, it is better to explain that, the structural concepts of tall buildings are more effective in the development of tall buildings than architectural strategies.

Regarding the effect of the lateral loads (wind & seismic) besides the gravity loads on design of tall buildings, the lateral loads based structural systems of tall buildings can be divided into: interior structures and exterior structures. This concept of division is based on the distribution of the components of the primary lateral load resisting over the building. It means that where the majority of the lateral loads resisting system is; interior or exterior of the building. (Ali & Moon, 2007)

Interior Structures

There are four main types of lateral load systems in the category of the interior structures which are moment resisting frames, braced/shear wall hinged frame, shear truss/wall with rigid frame system and core supported outrigger system. These systems are usually arranged as planar assemblies in two perpendicular directions; although they could be employed integrally as mixed structural systems. (Taranath, 2005)

Moment Resisting Frame (MRF)

The moment resisting frame (rigid frame system) is a system with column and girder plane frames with rigid or semi rigid connections in both steel and concrete. Moment resisting frame is based on the fact that the connections have enough rigidity to hold the nearly unchanged original angles between intersecting components. One of the most important advantages of this system is the speed of the construction because of easy modulation and fabrication. The Lever House (1952) with 21 stories and 307 ft (94 m) height is one of the good examples of this type of structural system built in New York. (Jayachandran, 2009)

Braced/Shear wall hinged frame

These two systems are configured by steel hinged frame with braced or concrete shear wall. Braced hinged frame is basically more efficient for low rise building around a 10 stories building. Two of the important advantages of this system are: 1) efficient resistance against lateral loads by axial forces in the shear truss members and also 2) using shallower beams compared with the rigid frames without diagonals. (Taranath, 2005)

Hinged frame by concrete shear wall is more common in comparison by braced hinged frame for tall buildings. The United Building (1992) in Chicago is one of the good examples of this structural system with 51 stories and 668 ft (204 m) height, designed by Ricardo Bofill.

Shear truss/wall with rigid frame system

In this system, the structure of tall building can laterally supported by vertical steel shear trusses which resist the majority of the lateral loads primarily through axial stiffness of the members with steel rigid frame. The steel shear trusses act like vertical cantilever trusses. This system can be designed with both steel and concrete in the core and also the perimeter of the building and it could be efficient for around a 50-story building. (Ali & Moon, 2007)

The Empire state tower (1931), with 1250 ft (381 m) height and 102 stories is the most famous tall building built with this system. This building designed in the distinctive art deco style by Shreve, Lamb and Harmon by employing moment resisting frames coupled with bracing system located around the building core. (Korom, 2008)

Outrigger system

Outrigger systems have been historically used by sailing ships. It transfers the overturning moment from the core that would act as a pure cantilever, to the perimeter columns through the outriggers to reduce the total moment. The Jin Mao Tower (1999) is an 88-story landmark tall building in Shanghai designed by the Skidmore, Owings & Merrill in postmodern style. The 88 floors (93 if the spire floors are counted) are divided into 16 segments, each of which is 1/8 shorter than the 16-storey base. Three sets of two-story high outrigger trusses connect the columns to the core at six of the floors to provide additional lateral support. (Sarkisian, 2011) This system can be considered on the border of the interior and exterior structural systems; because outriggers connect the interior system (shear walls) to the exterior system (mega columns) of tall buildings.

<u>Exterior Structures</u>

Unlike the interior structural systems, when the main part of the lateral load resisting components of the system located on the perimeter of the structure of the building, is called exterior structural system. However, it does not mean that there are no any minor components of the lateral load resisting system in the interior of the building. The main advantage of the exterior structural system is preparing free spaces from huge structural components particularly in office buildings. This system is mainly divided into four main systems: tube, space truss, super frame and exoskeleton systems.

<u>Tubular structural system</u>

Tubular system acts like a three dimensional cantilevered hollow tube perpendicular to the ground. Tubular forms have also several types based upon the structural efficiency such as frame, braced, bundled tube, tube in tube and diagrid systems. Each of the variations of tube systems was invented to make a better solution to resist lateral loads.

Framed tube System: Structurally, the perimeter of tall buildings is more important than any other types of buildings due to their tallness and slenderness to prepare more moment resistance; which means greater vulnerability to lateral forces, particularly wind loads. One of the most important tall buildings built with framed tube structural system is the Aon Center designed by architect firms Edward Durell Stone and The Perkins and Will partnership, completed in 1974 in Chicago as the Standard Oil Building with 83 floors and 1,136 ft (346 m) height with emphasis on vertical structural line.

Braced tube system: Instead of using closely spaced perimeter columns in the framed tube system, it is possible to stiffen the widely spaced columns by adding diagonal braces to create wall like characteristics. In addition to lateral loads, the braces can also collect gravity loads from floors to transfer to the ground and act as inclined columns. The significance of the braced tube system rather than frame tube system is that the diagonals of a trussed tube connected to columns at each joint effectively eliminate the effects of shear lag throughout the tubular framework. Shear lag phenomenon is the most important issue in design of tube systems. (Khan, 1967) In material, braced tube systems can be utilized in both steel and reinforced concrete. John Hancock Tower (1968) with 1,127 ft (344 m) tall is one of the famous tall buildings designed by this system in Chicago.

Tube in tube system: The stiffness of the framed tube system can also be increased by adding one or more cores to resist lateral loads. The core itself could be made up of another tube, braced tube or framed tube. Thus, the force path is through the floor diaphragm connecting the core and the outer tube to transfer the lateral load to both systems. One of the very important advantages of this system is that, the inner tube in this structural system can act as a second defense line against not only against lateral load but also works as a safe zone for evacuation; like a solid concrete core in the Twin World Trade Centers, completed in 1973 in New York designed by Minoru Yamasaki.

Bundled tube system: In this system, a building consists of several tubes tied together to resist the lateral forces and it is actually the series of the individual tubes connected together to act as a single unit (tube). It acts like a building that has interior columns along the perimeters of the tubes. This system developed because of very slender structures with a single framed tube that is basically not adequate for that; thus for this system the width of the building at its base should be large enough to maintain a reasonable slenderness (height to width ratio). In material, there are both steel and concrete examples of this system. The Willis Tower, formerly named as Sears Tower, with 110 stories with 1451 ft (422 m) in height, completed in 1974 in Chicago was the first bundled tube structure with nine steel framed tubes bundled at the base.

Diagrid system: This system can be considered as a tubular structural system by diagonal elements and also be considered as a braced tube system without vertical and horizontal structural elements. This system is a recently used as a new aesthetic architectural-structural concept for tall buildings. In material, this system is also configured with both steel and concrete. In general, this system is more appropriate for the circular or ellipse plan buildings or curved corners, because of the ability of transferring loads, continuously.

An early example of diagrid structure is the IBM Building built in 1963 in Pittsburgh; with its 13-story building height. St. Mary Axe in London, also known as the Swiss Re Building, completed by 2003 with 41 floors and 591 ft (180 m) tall designed by Norman Foster designed with this system. (www.Skyscraper.com, 2012)

This system can also be designed in a variation of different forms of members. Both the proposed COR Building in Miami, designed by Chad Oppenheim Architecture and Ysrael Seinuk of YAS Consulting Engineers with 25 stories and 380 ft (115 m) tall and the O-14 Building in Dubai designed by RUR Architecture with 335 ft (102 m) tall and 23 floors used reinforced concrete diagrid concept as their lateral load resisting systems built in 2010. (Wood, 2010)

This system is on the boundary of the dominance of structure and the re-dominance of architecture in tall building in the progressive review; because this system can be adapted with current trend of forms of tall buildings.

Super frame system

A super frame (mega frame) is a structural system with a number of huge columns at perimeter of the building to support the building for both gravity and lateral load. The concept of super frame is basically an exterior tubular system with wider span between columns and consequently more free view and day lighting. (Iyengar, 1986) One of the negative points of this system is the effect of the huge structural components on the architectural appearance of the building. The Parque Central Complex Twin Towers in Caracas, Venezuela with 56 stories and 738 ft (225 m) height designed by Daniel Fernández Shaw with this structural system. (www.Skyscraper.com, 2012)

Space truss system

Space truss structure is basically a kind of braced tube or diagrid system; but in space truss system, diagonal elements connect the exterior and the interior of the building together. In a typical braced tube structure, all the diagonal members are located on the plane parallel to the facades at the exterior of the building. In material this system configured with steel with a height limit around 150 stories. The positive point of this structural system is the efficient resistance of lateral shear by axial forces in the space truss members. The Bank of China Tower 1990 designed by I. M. Pei in Hong Kong with this aesthetic structural system. This building with 1033.5 ft (315.0 m) height is the first building outside the U.S. with more than 1,000 ft. (www.Skyscraper.com, 2012)

Exoskeleton System

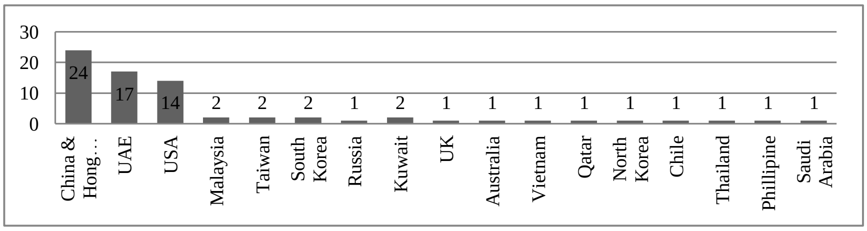
In exoskeleton structures, the main part of the lateral load resisting system is located outside the building away from the facade. Due to the compositional characteristics, the system acts as a primary building characteristic. Since, thermal contraction and fire proofing of the structural components should be carefully considered during the design process. (Ali & Moon, 2007) Hotel de las Artes designed by Skidmore, Owings & Merrill with 505 ft (154 m) tall built in 1994 in Barcelona is one of the buildings with this structural system. (www.Skyscraper.com, 2012)

Study on 73 tallest buildings (Built by 2012)

After a brief illustration about the basic architectural and structural parameters of tall buildings, for studying the next generation of tall buildings, finding out the important and also the most common parameters and data of tallest buildings seems to be essential and inevitable. The results of the study of 73 tallest buildings built by 2012 based on the data of CTBUH will be shown in the following.

Location: One of the most important parameters is the location of the buildings. The (Figure 4) categorizes the tall buildings based on the country. As can be seen, regarding to this chart, there are three main countries, China and Hong Kong (as one country), UAE and USA actually have around %77 of the total number of tallest buildings of the world.

Figure 4. *The number of tall buildings regarding to the location (Author)*



Height: This factor is also another important factor that will be shown in (Figure 5). It should be mentioned that the Burj Al Khalifa is the only tall building with 828 (m) tall. Also because there is no any considerable tall building between 550 and 800 (m) tall built by 2012, in this chart the number of buildings in this part is 0. It is clear that around %64 of the tall buildings are categorized between 300 to 350 (m) heights. Also, it seems to be essential to show the growth of this type of buildings during the past periods of time. (Figure 6) confirms the growth of tall buildings particularly after 2000 during past decades. In the past decade, the growth of the construction of the buildings with 300-349 (m) tall is rapidly increased through the world. These figures show the importance of the study of this height scope of tall buildings.

Figure 5. *The number and the rate of tall buildings regarding to the height*

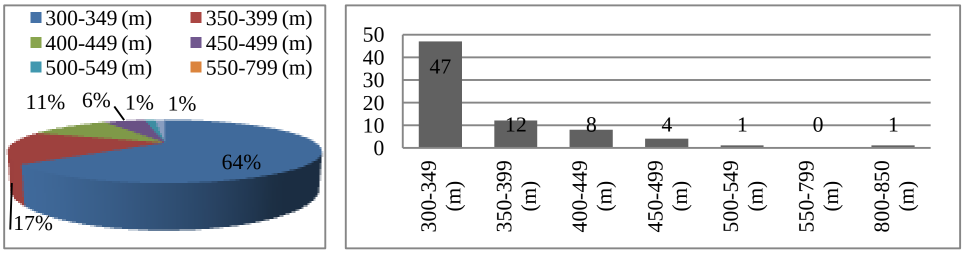
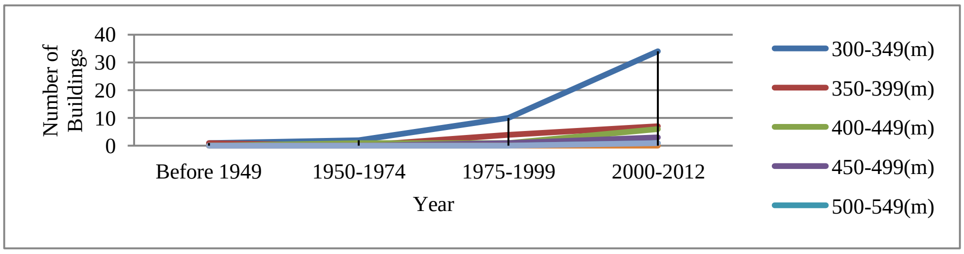


Figure 6. *The growth of tall buildings during past decades based on the height*



Function: The other significant parameter of the research on tall buildings is the function. The (Figure 7) shows the most common functions of tall buildings during the time. As can be seen, the majority of the function of tall buildings are mixed use and office and then residential. Mixed use and office tall buildings, as two main functions, are basically around %77 of the total number of tall buildings. In addition to the number of tall buildings' function, the real path of the growth of this factor can also be important and effective for the future prediction. (Figure 8) shows the most common functions in different periods of time. The growth of the number of tall buildings with mixed use, office and residential function can clearly show us a light for the next generation.

Figure 7. *The number and the rate of tall buildings regarding to the function*

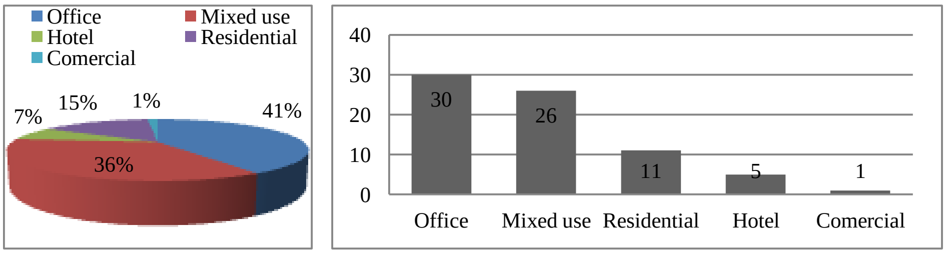
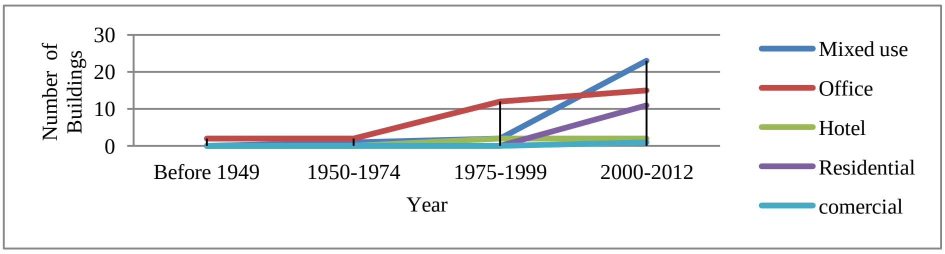


Figure 8. *The growth of tall buildings based on the function (Author)*



Re-Dominance of Architecture in Tall Buildings (Future Prediction)

To show the re-dominance of architecture in the realm of tall buildings there are a few examples with irregular and iconic shapes and forms such as Daniel Libeskind's Fiera Milano Tower and Morphosis' Phare Tower in La Defense and Hadid's Dancing Tower in Dubai.

Basically, the supporting structural system of tall buildings varies depending on the project and its specific situation, but in reality the diagrid system is often employed as a primary structural system for these types of tall buildings. It seems that diagrid system is a structural system can be matched well for this path of design. As can be seen, most of the aerodynamic and free forms of tall buildings are designed with this system and as previously mentioned, this system act as a joint for the two periods of dominance of architecture and structure in tall building but it cannot be necessarily the most efficient structural system for all types of buildings.

Conclusion

Regarding all the aforesaid parameters and recent forms of tall buildings, it can be seen that the form of the super tall buildings are and will not limited into rectangular prisms and the complexity of them are going to be increased because of the development of the technology and structural progressive systems and the ability of engineers. However, in some cases the form of tall buildings has to be dependent on the basic structural parameters like lateral and gravity loads because of the importance and the effectiveness of them. The most important issue that has to be criticized by all the design team members is the efficiency. It seems it is not worth to build a super tall building without considering the efficient parameters, architecturally and structurally. The gross and rentable floor area as the architectural and the weight of the structural material as the structural efficient parameters will be achieved by a comprehensive collaboration among design team.

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