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# Developments of Structural Systems Toward Mile-High Towers

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**Abstract**

Tall buildings which began from about 40 m tall office towers in the late 19th century have evolved into mixed-use megatall towers over 800 m. It is expected that even mile-high towers will soon no longer be a dream. Structural systems have always been one of the most fundamental technologies for the dramatic developments of tall buildings. This paper presents structural systems employed for the world's tallest buildings of different periods since the emergence of supertall buildings in the early 1930s. Further, structural systems used for today's extremely tall buildings over 500 m, such as core-outrigger, braced mega-tube, mixed, and buttressed core systems, are reviewed and their performances are studied. Finally, this paper investigates the potential of superframed conjoined towers as a viable structural and architectural solution for mile-high and even taller towers in the future.

**Keywords:** Tall buildings, Tallest buildings, Core-outrigger systems, Braced megatubes, Mixed systems, Buttressed core systems, Superframed conjoined towers, Mile-high towers

## 1. Introduction

Tall buildings emerged in the late 19th century in New York and Chicago. Two critical technologies which must be employed for prototypes of early tall buildings were elevators and skeletal structures. In terms of multistory office buildings with passenger elevators, the seven-and-a-half-story tall Equitable Building of 1870 in New York is recognized as the first one. However, this building used masonry as its primary structural system especially for building perimeter, while iron columns and beams were used partially (Landau and Condit, 1996). In the 10-story Home Insurance Building of 1885 in Chicago, not only passenger elevators but also an early version of iron/steel skeletal structural systems was employed for the major portion of the building for the first time, while masonry was used only partially on the contrary (Leslie, 2013). Since then, the primitive skeletal structure developed further into moment resisting frames often in combination with lateral wind bracings. With the two essential technologies of tall buildings for their structures and vertical transportations, the new building type developed rapidly.

Symbolic power of tall buildings being recognized, the height race began from the turn of the century starting from the Park Row Building in New York which had already reached 30 stories in 1899. The threshold height of supertall buildings, 300 m, was first reached by the 319 m tall 77-story Chrysler Building of 1930 in New York, and the height race was culminated with the 381 m tall 102-story Empire State Building of 1931 also in New York. Due to the Great Depression and Second World War, developments of tall buildings slowed down for years. When it resumed after the war, more economical tall buildings usually not taller than 50-60 stories were predominantly built mostly in the International Style.

During the late 1960s and 1970s, new structural concepts of various tubular systems were developed, and this produced supertall buildings with more efficient and economical structures. Notable examples at that time include the 343 m tall 100-story John Hancock Center (now called 875 North Michigan Avenue) of 1969 in Chicago, the demolished 417 m tall 110-story One World Trade Center of 1972 and 415 m tall 110-story Two World Trade Center of 1973 both in New York as twin towers, and the 442 m tall 108-story Sears Tower (now called Willis Tower) of 1974 in Chicago.

Toward the end of the 20th century, the region of major tall building developments shifted from the U.S. to Asian countries, which reflects their rapid economic growth. The title of the tallest in the world was also taken by twin supertalls in Asia for the first time. The 452 m tall 88-story Petronas Towers of 1998 in Kuala Lumpur exceeded the architectural height of the Sears Tower which still held the title of the tallest occupied floor then. In 2004, the 508 m tall 101-story Taipei 101 in Taipei finally eclipsed the both architectural and occupied heights of the Sears Tower.

More recently in the 21st century, the Middle East also jumped into the height race and the 828 m tall 163-story Burj Khalifa of 2010 in Dubai took the title with a very large margin. Further, the Jeddah Tower at its expected

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height over 1 km in Jeddah is under construction at present to surpass the Burj Khalifa soon. Based on the oil wealth, the Middle East has rapidly become a new region for tall, supertall and megatall (over 600 m) buildings.

At the time of the completion of the Empire State Building, there were only two supertall buildings in the world. Both of them were in New York. When the Sears Tower was constructed, the number of supertall buildings increased to seven, four in New York and three in Chicago. Today, there are more than 100 supertall buildings in the world. While majority of tall buildings are built in Asian and Middle Eastern countries, new tall buildings are also continuously soaring up in the U.S. as well as many other parts of the world in recent years. Indeed, tall buildings are now a global architectural phenomenon.

There are many reasons why the number of tall buildings is continuously increasing and they are becoming ever taller. The world population grows continuously, and today more people live in urban areas than in rural areas. Only 30% of the world's population was urban in 1950; at present 55% of the world's population resides in urban areas in 2018; and the urban population will be further increased to about 70% by 2050 according to the Population Division of the United Nations Department of Economic and Social Affairs. Tall buildings are one of the most viable solutions to deal with this global phenomenon (Al-Kodmany and Ali, 2012).

Certainly, developments of tall buildings are not always based on their necessity and/or feasibility. Some tall buildings are developed taller than necessary to express the city's and/or country's growing economic power. Some other tall buildings are built as corporate or individual aspirations. And there are many other non-feasibility-based cases of tall building developments. Nonetheless, tall buildings are still one of the most essential building types for the rapidly-urbanizing future world with dense cities; more tall buildings will be built continuously to accommodate ever-growing urban population; and they will become taller and taller to redistribute the urban density toward the limitless space in the sky (Ali and Moon, 2007; 2018). Indeed, one of the greatest architects of all time Frank Lloyd Wright already proposed a mile-high (1.6 km) tower about 60 years ago as a visionary project (Wright, 1957). With a tower over 1 km already under construction, visionary mile-high and even taller buildings will perhaps no longer be only a dream.

There are many design issues to be considered to build extremely tall buildings not only regarding the towers themselves but also about the infrastructures around them. While all of the interrelated design issues should be holistically orchestrated, one of the most fundamental design considerations for exceedingly tall buildings is their structural systems which make their physical existence possible. Though many structural systems have been developed, no mile-high towers have actually been built yet. This paper presents developments of tall building structural systems toward mile-high towers. It reviews first the structural systems for the world's tallest buildings of different periods beginning from the emergence of supertall buildings in the early 1930s to the present. It also studies performances of some of the major structural systems for extremely tall contemporary buildings over 0.5 km and up to about 1 km. Finally, this paper investigates the potential of superframed conjoined towers for mile-high and even taller buildings.

## 2. Structural Developments in Supertall Buildings

The Empire State Building of 1931 structured with the braced moment resisting frames, the only available structural system for supertalls and already conventional at the time of its construction, held the title of the world's tallest for longer than 40 years. Beginning from the mid-1960s and 1970s, various new structural systems more efficient than the traditional braced moment resisting frames were continuously developed for an ever-increasing number of supertall buildings. Today, some of the structural systems efficiently produce even megatall buildings.

### 2.1. Structural Systems for Tallest Buildings

Table 1 shows structural systems used for tallest buildings in the world during different periods since the Empire State Building. The moment resisting frame with lateral wind bracings around the building's core was the predominantly used structural system for tall buildings including the Empire State Building before the development of the tubular concept by Fazlur Khan in the 1960s. Though the shear truss-frame interaction behavior was not fully understood at that time (Ali, 2001), engineers still recognized the efficiency of adding diagonal bracings around the core which together with the orthogonal moment resisting frames acted as vertical trusses. Therefore, tall buildings with these braced moment resisting frames could be constructed more efficiently compared to those structured only with moment resisting frames. The structural steel use for the 102-story Empire State Building was 42.2 psf (206 kg/$m^2$). It is noted that though no 100-story tall building was ever built only with moment resisting frames, Khan estimated the steel use of about 65 psf (317 kg/$m^2$) for this imaginary case in his "premium for height" diagram (Khan, 1970).

The framed tube as the firstly conceived tube system was employed for the first time in a reinforced concrete building, the 43-story Dewitt-Chestnut Apartments of 1966 in Chicago. Soon after, the system was employed for the new tallest building in steel, the demolished 110-story One World Trade Center which initiated the new supertall era 41 years after the construction of the Empire State Building. Only two years after the completion of the One World Trade Center, the 25 m taller 108-story Sears Tower (now called Willis Tower) was built with the bundled tube sys-

**Table 1.** Structural systems for tallest buildings in the world since 1931

| Building | City | Tallest Period | Height (m) | Story | Structural System |
|---|---|---|---|---|---|
| Empire State Building | New York | 1931-1972 | 381 | 102 | Braced Moment Resisting Frame |
| One World Trade Center, Demolished | New York | 1972-1974 | 417 | 110 | Framed Tube |
| Sears Tower (now Willis Tower) | Chicago | 1974-1998 | 442 | 108 | Bundled Tube |
| Petronas Towers | Kuala Lumpur | 1998-2004 | 452 | 88 | Tube-in-Tube |
| Taipei 101 | Taipei | 2004-2010 | 508 | 101 | Core-Outrigger |
| Burj Khalifa | Dubai | 2010-present | 828 | 163 | Buttressed Core |
| Jeddah Tower | Jeddah | 2021, expected - ? | 1000+ | 167 | Buttressed Core |

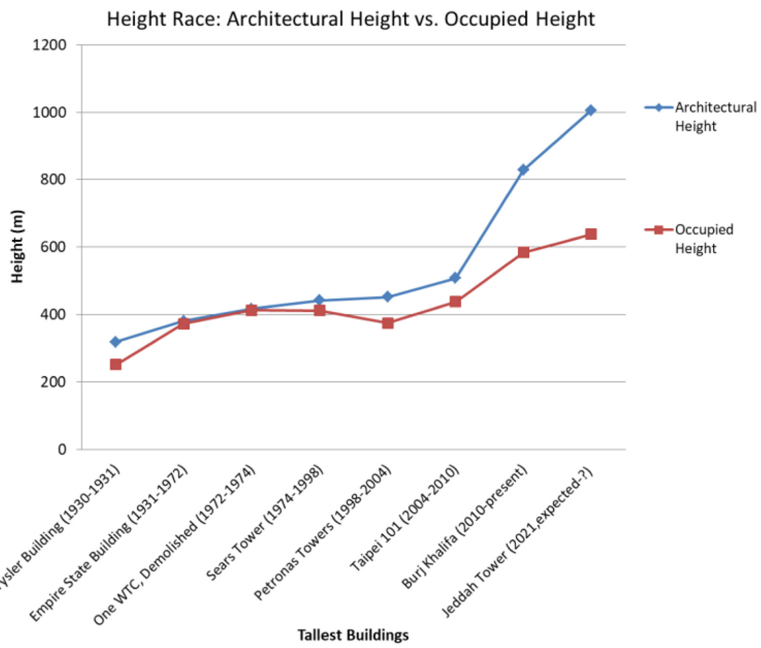


**Figure 1.** Height race: architectural heights vs. occupied heights of the tallest buildings.

tem which reduced the shear-lag induced inefficiency of the framed tube system. The steel uses for the One World Trade Center and Sears Tower were 37.0 psf (181 kg/m$^2$) and 33.0 psf (161 kg/m$^2$) respectively (Schueller, 1990). These developments of tubular systems resulted in more efficient tallest building structures compared to the Empire State Building. Another important tube system is the braced tube employed for the 100-story John Hancock Center of 1969 in Chicago. This building used only 29.7 psf (145 kg/m$^2$) structural steel. Though the braced tube, more efficient than the framed or bundled tube in general, is in fact one of the most efficient structural systems for tall buildings, interestingly, it was never used for the tallest building of any period.

Since the completion of the Sears Tower in 1974 no supertall buildings were built in any place of the world until the construction of the 367 m tall Bank of China of 1990 in Hong Kong. This is about the time when the most active tall building development region moved from the U.S. to Asian countries. Since the 1990s, many tall and supertall buildings have been built in Asia. The tallest building was also built in Asia for the first time. The 452 m tall 88-story Petronas Towers of 1998 in Kuala Lumpur exceeded the architectural height of the Sears Tower by 10 m. However, one of the most fundamental architectural design criteria is to provide occupiable spaces for people, and it is noted that the tallest building in that regard was still Sears Tower with its tallest occupied height 38 m taller than that of the Petronas Towers. The world's tallest height of the Petronas Towers was accomplished by designing and constructing the spires as integral parts of the main structures of the towers.

In terms of structural materials, unlike all the other previous tallest buildings structured with steel, the Petronas Towers were built with reinforced concrete and steel resulting in composite structures. Since the beginning of the Asian era of tall buildings, reinforced concrete alone or in combination with steel has widely been used for structural systems of tall buildings not only in Asia but globally. The primary lateral load resisting system for the Petronas Towers is the tube-in-tube composed of the reinforced concrete core and perimeter framed tube. Due to the diversity in materials use, direct efficiency comparisons between tall building structures have become inappropriate. In 2004, the 508 m tall 101-story Taipei 101 finally reached the height of 0.5 km for the first time. With its tallest occupied height at 438 m, it also exceeded the tallest occupied height of the Sears Tower by 20 m. The core-outrigger system, which became very popular from the 1990s, was employed for Taipei 101 using reinforced concrete and steel, resulting in composite structure.

In addition to Asia, Middle East has even more recently become one of the most active regions of tall building developments. Dubai alone with its 37 supertall buildings either completed or under construction at present is the city having the largest number of supertalls in the world. Almost all of the supertalls already in use in Dubai were completed in the 21st century including the current world's tallest Burj Khalifa. With its height of 828 m, it exceeded the height of the previous tallest Taipei 101 by a significant margin of 320 m. The Y-shaped plan form-integrated reinforced concrete "buttressed core" system was employed for the Burj Khalifa to reach the unprecedented enormous height.

However, it is also noted that the tallest occupied height difference between the Burj Khalifa and Taipei 101 is only 147 m. As the height of the tallest building becomes greater, the gap between the architectural and occupied heights also becomes larger. The Jeddah Tower, which also employs the buttressed core system, will finally become the first tallest building exceeding the height of 1 km. It took about 120 years for tall buildings to reach the height of 0.5 km. However, it is expected that additional 0.5 km will be reached within less than just 20 years. As the difference between the architectural and occupied heights is becoming larger for the tallest buildings, it will be only about 50 m between the Burj Khalifa and Jeddah Tower.

### 2.2. Structural Systems for Tall Buildings over 500 m

Taipei 101 reached the height of 500 m for the first time in 2004; the Burj Khalifa reached the height of 800 m in 2010; and finally the Jeddah Tower will exceed the height of 1 km soon. As the accelerated height race has been occurring so fast in recent years, many tall buildings have been built, under construction, or proposed in the height range between Taipei 101's about 500 m and Burj Khalifa's 800 m. It is important to take a close look at these buildings' structural systems together with the recent tallest buildings to better understand major lateral load resisting systems for the group of these exceedingly tall contemporary buildings over 500 m.

Table 2 shows most 500+ m tall buildings completed, under construction or on hold, based on the database by Council on Tall Buildings and Urban Habitat (CTBUH). Only four towers in the considered height range and status are omitted due to an inadequate amount of available structural information on them. The table also includes one proposed tower whose structural design has well been developed instead. With these 16 towers, several major structural systems employed for today's supertall and megatall buildings of this extreme height range are identified.

The core-outrigger system has been one of the most prevalently used structural systems for the height range up to about 700 m either alone or in combination with other systems. The braced megatube is also a very recent trend employed for 500+ m tall buildings mostly under construction in combination with core or core-outrigger structures. The buttressed core system is used especially for recent megatall buildings over 600 m and up to 1 km. The subse-

**Table 2.** Structural systems for 500+ m tall buildings

| Building | City | Year | Height (m) | Story | Structural System |
|---|---|---|---|---|---|
| Jeddah Tower | Jeddah | Under Constr. | 1000+ | 167 | Buttressed Core + Fin Walls |
| Burj Khalifa | Dubai | 2010 | 828 | 163 | Buttressed Core + Fin Walls (w/ Outrigger) |
| Suzhou Zhongnan Center | Suzhou | On Hold | 729 | 137 | Core-Outrigger + Megaframe |
| Merdeka PNB118 | Kuala Lumpur | Under Constr. | 644 | 118 | Core-Outrigger + Braced Megatube |
| Signature Tower | Jakarta | Proposed | 638 | 113 | Core-Outrigger + Megaframe |
| Wuhan Greenland Center | Wuhan | Under Constr. | 636 | 126 | Buttressed Core-Outrigger |
| Shanghai Tower | Shanghai | 2015 | 632 | 128 | Core-Outrigger |
| Ping An Finance Center | Shenzhen | 2016 | 599 | 115 | Core-Outrigger + Braced Megatube |
| Goldin Finance 117 | Tianjin | Under Constr. | 597 | 128 | Braced Megatube + Core |
| Lotte World Tower | Seoul | 2017 | 555 | 123 | Core-Outrigger |
| One World Trade Center | New York | 2014 | 541 | 94 | Core + Perimeter Moment Resisting Frame |
| Guangzhou CTF Finance Centre | Guangzhou | 2016 | 530 | 111 | Core-Outrigger |
| Tianjin CTF Finance Centre | Tianjin | Under Constr. | 530 | 97 | Core + Perimeter Sloped Column Frame |
| Citic Tower (formerly China Zun) | Beijing | Under Constr. | 528 | 108 | Braced Megatube + Core |
| Evergrande IFC T1 | Hefei | Under Constr. | 518 | 112 | Core-Outrigger + Megaframe |
| Taipei 101 | Taipei | 2004 | 508 | 101 | Core-Outrigger |

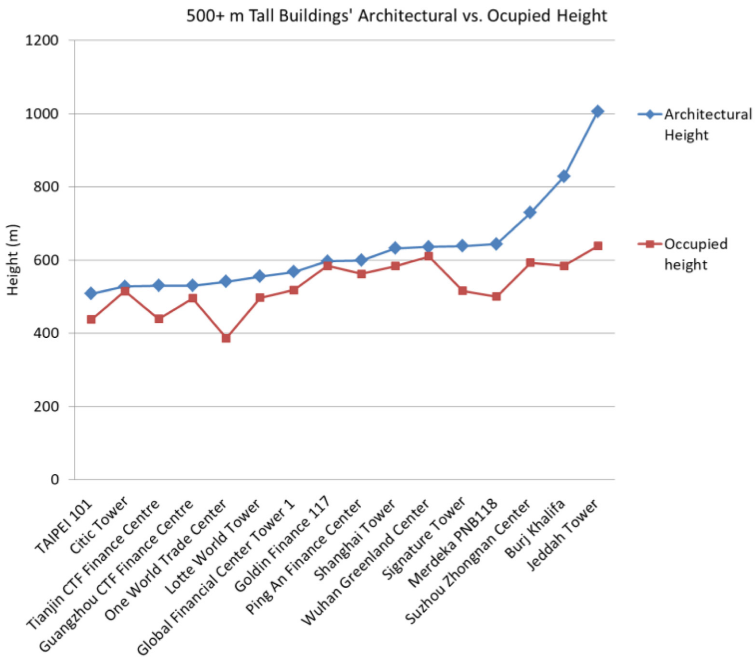


**Figure 2.** Architectural heights vs. occupied heights of 500+ m tall buildings.

quent sections of this paper discuss these structural systems in more detail. There are also some secondary systems such as perimeter megaframes and moment resisting frames.

The substantial differences between the architectural and occupied heights are also well observed in the 500+ m tall buildings. While their architectural heights range from about 500 m to 1000 m, their occupied heights range from about 400 m to only 600 m. The differences between the highest architectural and occupied heights become even larger as buildings become taller as owners wish to extend the height of their buildings with so-called "vanity heights" by employing integrally built structural spires (Ali and Moon, 2018). In this era of pluralism in architectural design, many recent supertall heights are often more monumental than practical compared to those of the 1970s before the postmodern period.

## 3. Core-Outrigger, Braced Megatube, and Mixed Systems

As presented in the previous section, the core-outrigger and braced megatube systems are two major structural systems employed for tall buildings over 500 m. In Table 2, the core-outrigger and braced megatube appear nine and four times respectively either alone or in combination with other systems. Further, the core-outrigger and braced megatube systems are sometimes directly combined together with shared perimeter megacolumns, resulting in a mixed system. This section studies further these structural systems frequently used for extremely tall buildings up to about 700 m.

### 3.1. Core-Outrigger Systems

Compared with structural cores with no outriggers, core-outrigger systems carry wind-induced overturning moments more efficiently with greater structural depth by connecting perimeter megacolumns to stiff building cores through outriggers. Though core-outrigger structures are also possible by only connecting regular perimeter columns with belt trusses at the outrigger levels, supertall and megatall outrigger structures almost always employ megacolumns for greater efficiency. The core-outrigger system's lateral load carrying mechanism is conceptually explained in Fig. 3. The overturning moment ($M_o$) caused by wind loads ($W$) is reduced due to the counteracting moment ($M_c$) provided by the megacolumns. The counteracting moment $M_c$ can be expressed in terms of the building width and cross-sectional area of the megacolumns as shown in Eq. (1) (Moon, 2016).

$$M_c = 2b^2 AE\chi \quad (1)$$

$A$ is the cross-sectional area of the megacolumns; $b$ is the distance between the center of the core and perimeter megacolumns on the outrigger plane; $E$ is the modulus of elasticity of steel; and $\chi$ is the curvature of the structure as a vertical cantilever bending beam. In steel structures, for example, since the modulus of elasticity of steel is constant regardless of its strength, the outrigger structure's bending stiffness is a function of the square of the distance between the center of the core and perimeter megacolumns

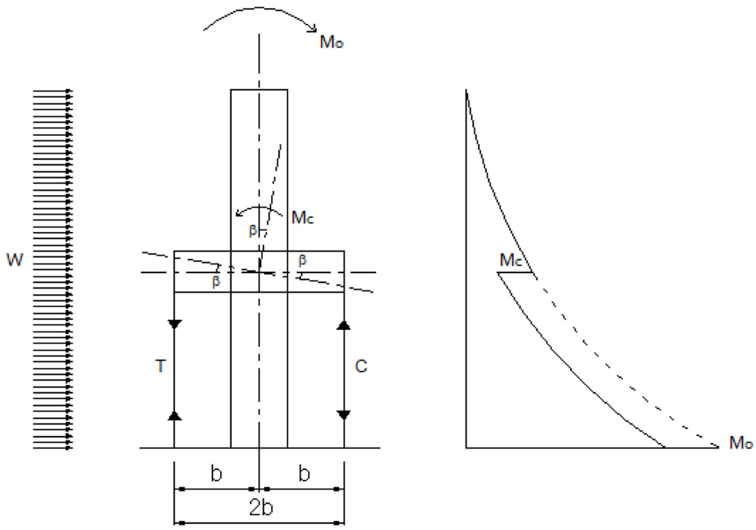


**Figure 3.** Simplified load carrying mechanism of the core-outrigger system.

as well as cross-sectional area of the megacolumns.

The outriggers, generally in the form of trusses in steel structures or walls in reinforced concrete structures, effectively act as stiff headers inducing a tension-compression couple in the perimeter megacolumns. Optimal locations of outriggers to minimize the lateral deformation have been investigated by many researchers and engineers. For the optimum performance, the outrigger in a one outrigger structure should be at about half height; the outriggers in a two outrigger structure should be at about one-third and two-thirds heights; the outriggers in a three outrigger structure should be at about one-quarter, one-half, and three-quarters heights, and so on (McNabb and Muvdi, 1975; Smith and Coull, 1991).

One of the earliest applications of the core-outrigger system with perimeter megacolumns can be found in the 190 m tall 47-story Place Victoria Building (now called Stock Exchange Building) of 1964 in Montreal. The outrigger system also appeared in Fazlur Khan's structural systems charts for steel tall buildings (Khan, 1973). However, he recommended the system for tall buildings up to only about 60 stories as the outriggers stretching from the core to the perimeter megacolumns as an alternate to only belt trusses with regular perimeter columns were not yet fully investigated at that time, despite that the Place Victoria Building had already been constructed with megacolumns.

Today, core-outrigger structures have been applied for much taller supertall and megatall buildings as shown in Table 2. At present, the tallest building structured with the core-outrigger system is the 632 m tall 128-story Shanghai Tower in Shanghai (Fig. 4). Furthermore, the system has already been applied to an even taller building currently on hold, the 729 m tall 137-story Suzhou Zhongnan Center in Suzhou (Shen, 2014). These heights are significantly

**Figure 4.** Shanghai Tower during construction showing central core, belt trusses and perimeter megacolumns (photograph by Kyoung Sun Moon).

taller than Khan's suggested height. There are multiple reasons for this. As already discussed, today's outrigger structures typically use perimeter megacolumns for greater efficiency instead of simply connecting regular perimeter columns with belt trusses. In addition, the efficiency of the system is further increased economically in many cases by using steel and reinforced concrete composite

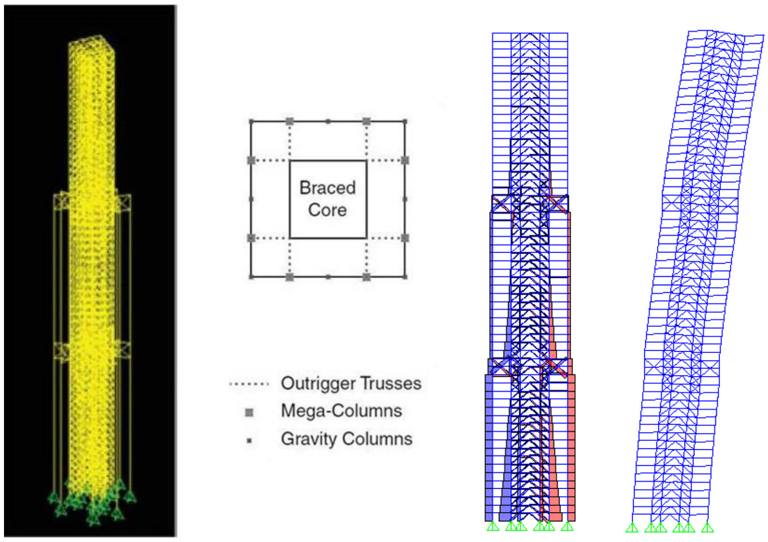


**Figure 5.** Axial force diagram and deformed shape of core-outrigger system subjected to wind loads.

structures for both the interior core and megacolumns. Moreover, structural optimization in terms of the number and locations of outriggers, etc., using today's specialized parametric engineering software increases the system's efficiency. Nonetheless, the structural efficiency of the core-outrigger system cannot exceed that of some of the most efficient tube type structures such as braced tubes and diagrids. However, another reason why the core-outrigger system is used for very tall buildings sometimes even taller than those tube type structures is that it is architecturally more flexible on façade design.

Fig. 5 shows lateral performance of a 60-story outrigger structure with two outriggers at one-third and two-thirds heights of the building. As the vertically cantilevered braced core bends due to lateral loads, outrigger trusses connected to the core and the perimeter megacolumns provides resistance against the bending deformation. Curvature reversals around the outrigger truss locations shown in the deformed shape clearly show this resistance. As can be seen from the figure, the performance of the core-outrigger system greatly relies on the core whose structural depth is much narrower than that of the building width. Therefore, the structural efficiency of the core-outrigger system cannot exceed that of the braced tubes or diagrids which use the entire building width as their structural depths and carry wind loads by axial actions of the perimeter tube members.

Fig. 6 shows comparative lateral efficiency of the core-outrigger, braced tube and diagrid systems based on design studies with 60-, 80-, and 100-story tall buildings structured with these three different structural systems (Moon, 2014). Braced megatube which will be discussed in more detail later is a modified version of the braced tube for greater efficiency. Though not appearing in Table 2, diagrids are another prevalently used structural system for today's tall buildings. The 555-m tall Lotte Tower in Seoul shown in the table was once proposed as a diagrid structure before its design was changed to the core-outrigger system.

The studied buildings' plan dimensions are 36 m × 36 m with 18 m × 18 m central cores, and their typical story height is 3.9 m. The height-to-width aspect ratios of the 60-, 80-, and -100 story buildings are 6.5, 8.7, and 10.8, respectively. All the required lateral stiffness of the braced tube and diagrid structures is allocated to the perimeter braced tubes and diagrids, and the core structures are designed to carry only gravity loads. In the outrigger structures, the core structures are steel braced frames, which carries not only gravity but also lateral loads. Outrigger trusses are located at every 20 stories over the building height except at the top.

The document, SEI/ASCE 7, Minimum Design Loads for Buildings and Other Structures, is used to establish the wind load. The buildings are assumed to be in Chicago and the basic wind speed of 40.2 meters per second (90 miles per hour) is used. One percent damping is assumed for the calculation of the gust effect factor. Stiffness-based design is performed for each structure to meet the target maximum allowable lateral displacement of a five hundredth of the building height. Structural steel is used for all three systems in this simplified comparative design study though reinforced concrete or composite structures are also very commonly used in today's tall buildings.

As buildings become taller, there is a "premium for height" due to lateral loads and the demand on the structural system increases not linearly but exponentially. Fig. 6, which shows the required amount of structural steel for the 60-, 80- and 100-story buildings of the core-outrigger, braced tube, and diagrid structures, clearly illustrates this phenomenon. Though outrigger structures are efficient

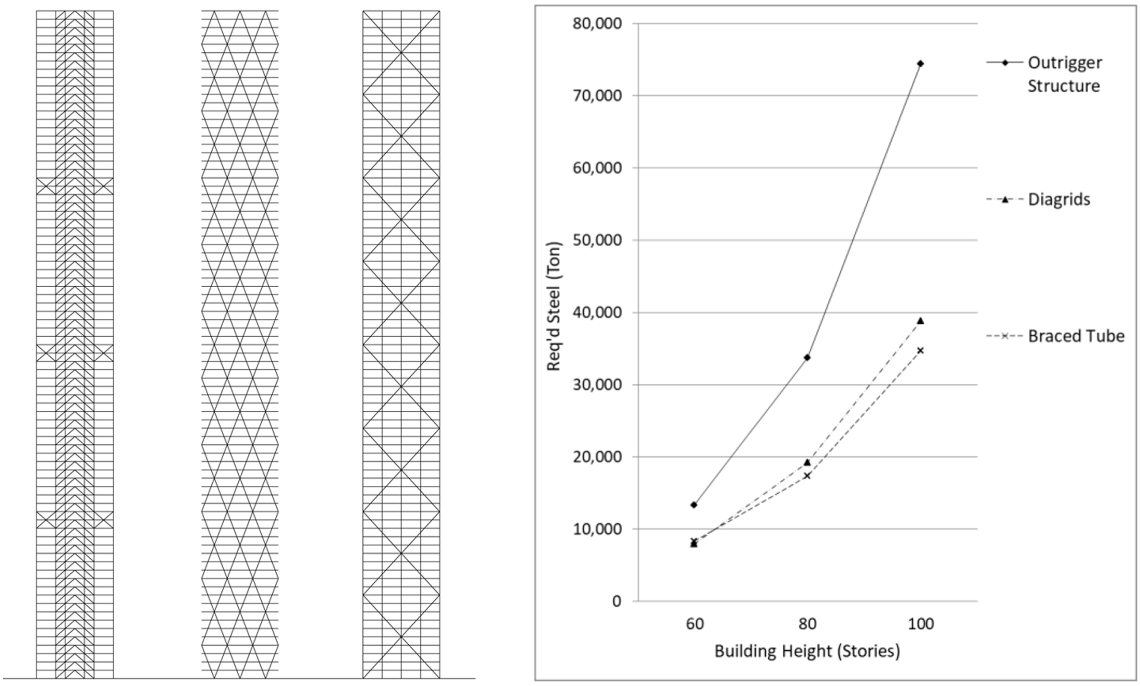


**Figure 6.** Required amount of structural steel for 60-, 80- and 100-story tall buildings of core-outrigger, diagrid and braced tube structures.

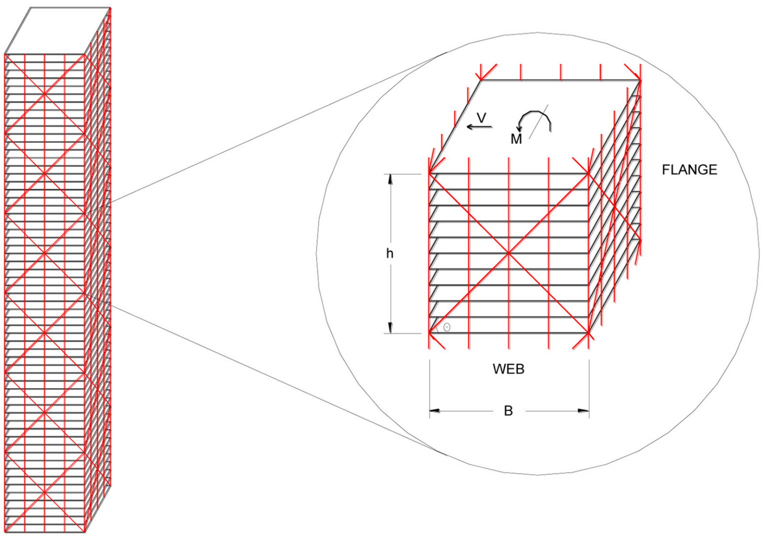


**Figure 7.** Braced tube structure composed of 10-story modules.

structural systems for tall buildings, the all-steel outrigger structures studied here are clearly less efficient than the tube type structures with large perimeter diagonals. The reasons why the core-outrigger structures are still even more prevalently used for supertall and megatall buildings than the tube type structures have already been discussed. Certainly, efficiency alone is not what determines the structural systems for tall buildings. Many other design issues should carefully be considered holistically.

### 3.2. Braced Megatubes

Braced tube structural systems are typically configured with evenly spaced columns and large diagonals on the building perimeter. Fig. 7 shows a 60-story building structured with the braced tube system composed of 10-story tall modules in which $V$ is wind-induced lateral shear force and $M$ is overturning moment applied to the modules. Eq. (2) expresses the typical braced tube module's bending stiffness based on the perimeter columns on both the flange and web frames (Moon, 2010).

$$K_B = (N_{c,f} + \delta)\frac{B^2 A_c E}{2h} \quad (2)$$

$K_B$ is bending stiffness; $N_{c,f}$ is number of columns on each flange frame (frame perpendicular to wind); $\delta$ is contribution of columns on web frames (frame parallel to wind) for bending stiffness; $B$ is building width in the direction of wind; $A_c$ is cross-sectional area of each column; $E$ is modulus of elasticity of steel; $h$ is module height.

In braced tubes, overturning moments and lateral shear forces due to wind loads are primarily carried by the perimeter columns and diagonal bracings respectively. Therefore, as the column arrangement is changed, the bending stiffness of the braced tube is also changed. Fig. 8 shows 100-story braced tube structures whose perimeter columns are configured in four different ways. Compared to the braced tube structures with their plan dimensions of 36 m × 36 m studied in the previous section, the plan dimensions in this study are increased to 54 m × 54 m in order to better study design alternatives with various column spacings. All the other design conditions are the same as before. Case 1, 2 and 3 in Fig. 8 show three different column spacing cases. In Case 1, the column spacing is gradually increased toward the building corner; in Case 2, the columns are evenly spaced at every 9 meters; in Case 3, the column spacing is gradually reduced toward the building corner. The value of $\delta$ for Case 1, 2 and 3 is 0.7, 1.1 and 1.6, respectively. As the column arrangement becomes denser toward the building corner, the web frame columns' contribution to the bending stiffness increases, and vice versa. This phenomenon has a direct impact on the lateral displacement of each tower. The maximum lateral displacements at the top of Case 1, 2 and 3 are 78.2 cm, 76.0 cm and 73.4 cm respectively, based on SAP2000 analyses.

William LeMessurier's study on supertall structures dealt with a similar topic (Rastorfer, 1985). Regarding overturning moments, the configuration with only four corner megacolumns produces the greatest bending stiffness than any other column configurations when the same amount of structural materials are used for each different alternative. LeMessurier's theoretical study of the 207-story tall Erewhon Center used four corner megacolumns in combination with X bracings between them. This configuration shown as Case 4 in Fig. 8 is conceptually the most extreme version of Case 3. While Case 1, 2 and 3 are composed of 24 perimeter columns on each floor, Case 4 has only four corner megacolumns. The cross-sectional area of each column of Case 4 is six times larger than that of each perimeter column of the other cases on each floor. Therefore, the amount of structural materials used for all four cases are identical. Case 4, as the most extreme version of Case 3, is much stiffer than the other cases. The maximum lateral displacement of Case 4 with four corner megacolumns is only 58.0 cm, about 25% smaller than

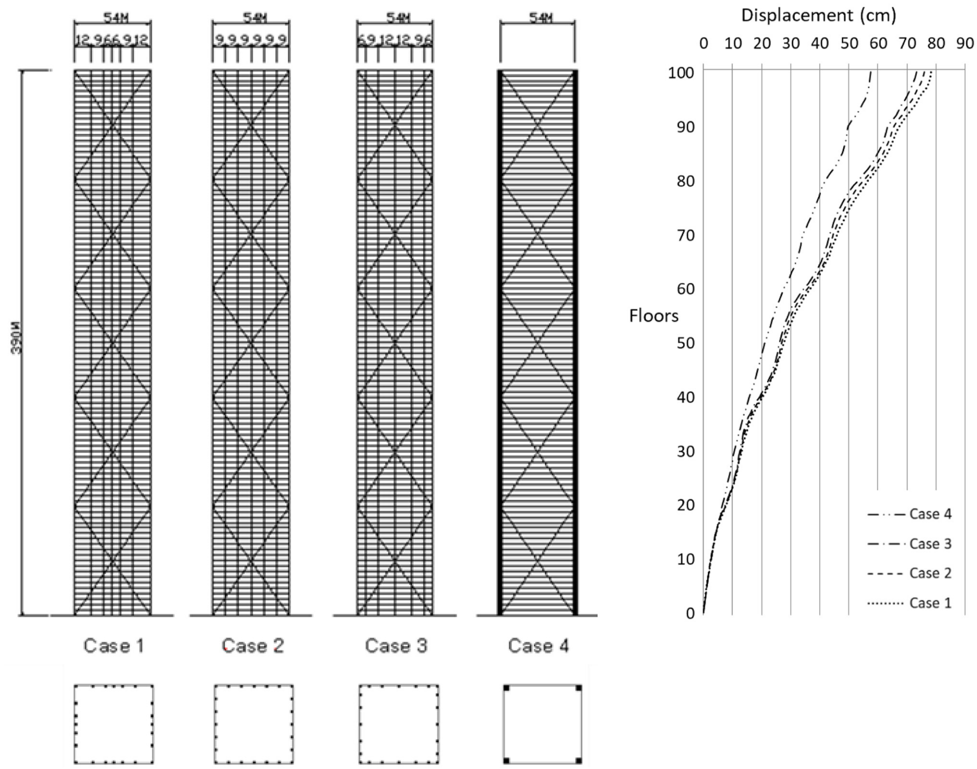


**Figure 8.** Maximum lateral displacements of braced tube structures of various column configurations.

that of Case 2 with 24 evenly spaced columns. Though Case 4 provides greater lateral stiffness based on higher bending rigidity, however, one important issue of this case is that it requires a more sophisticated gravity load resisting system because the dead and live loads of each floor must be carried also by the four corner megacolumns spaced at 54 meters in this particular example.

"The ultimate possible improvement of the structural efficiency is to go from a multi-column concept to a square tower having only four large corner columns. …… This then is the ultimate high-rise steel building. It means that at every 20 floors or so there would be transfer trusses ……, thereby guaranteeing that all gravity loads in the building flow into the four corner columns."

Fazlur Khan, 1972

Khan, who engineered the first braced tube supertall John Hancock Center of 1969, already envisioned a structural configuration similar to what is shown in Case 4 of Fig. 8 as "the ultimate possible improvement of the structural efficiency." Further, he also conceived the idea of transfer trusses between the corner megacolumns to carry gravity loads (Khan, 1972).

This idea of a modified braced tube with corner megacolumns and a reasonably good solution for transferring gravity loads has been employed for recent supertall buildings, and they are classified as braced megatubes in this paper. In the 597-m tall 128-story Goldin Finance 117 currently under construction in Tianjin, four corner megacolumns in conjunction with large perimeter diagonal bracings carry lateral loads very efficiently (Fig. 9). In terms of carrying gravity loads, there are additional small gravity columns between the corner megacolumns. The gravity loads in these gravity columns are transferred to the megacolumns through the belt trusses installed between the megacolumns at every about 15 stories in relation to the structure's module height as similarly predicted by Khan. The connections between the gravity columns and transfer belt trusses are made in such a way that the progressive collapse can be prevented when some of the gravity columns within the module are seriously damaged. The gravity columns between the transfer belt trusses are provided with vertically slotted connections with the top trusses. Therefore, these columns supported by the bottom trusses carry the floor loads entirely by compression in normal cases, but some of the columns toward the top trusses change to tension columns when any column failure occurs within the module (Liu et at., 2012).

While the arrangement of corner megacolumns establishes one of the most efficient lateral load- resisting systems, it could be obstructive for viewing from the interior corner spaces often the most desired in the building. In the 528-m tall 108-story Citic Tower (formerly known as China Zun), currently under construction in Beijing, the braced megatube concept was also used. However, the corner megacolumns of the Citic Tower are split into two following the rounded square-shaped floor plans on almost all levels to provide column-free corner space, except for only several lowest levels near the base where the maximum overturning moments are applied (Fig. 10). Though the configuration with paired megacolumns around the corners does not provide the same level of stiffness prov-

**Figure 9.** Goldin Finance 117 under construction showing the braced megatube composed of corner megacolumns, large perimeter X-bracings, gravity columns and transfer belt trusses (photographs in public domain).


**Figure 10.** Citic Tower under construction showing single corner megacolumns on several lowest levels and split paired corner megacolumns on typical levels (photograph in public domain).

ided by single corner megacolumns when the same amounts of structural materials are used, it produces more desirable architectural result. The configuration of the gravity columns and transfer belt trusses in the Citic Tower is very similar to that in the Goldin Finance 117.

### 3.3. Mixed Systems

Combining two (or possibly more) lateral load resisting systems in tall buildings is not new. Different from the traditional combined systems such as shear wall (or shear truss)-frame interaction system and tube-in-tube system, however, in some of the new supertall and megatall structural systems, major components of the lateral load-resisting systems combined are shared, resulting in mixed systems in which the shared components consequently carry out dual functions to meet project-specific design requirements. Such systems are often produced in recent tall buildings when the previously studied core-outrigger and braced megatube systems are directly combined with shared megacolumns by the both systems.

When common squarish floor plans are considered, a core-outrigger system is typically configured with two megacolumns on each of four sides totaling eight, while a braced megatube is designed with four corner megacolumns as shown in Fig. 11. Therefore, some adjustments are often necessary to mix these two systems by sharing the megacolumns. Fig. 11 also shows a mixed system with four corner megacolumns and diagonally rearranged outriggers as is the case with the Shanghai World Financial Center shown in Fig. 12. Alternatively, the mixed system can be designed with eight megacolumns. In this case, the outriggers can be configured orthogonally as usual, but the bracings should be placed between the eight megacolumns, which results in some edge bracings directly meeting at the corners. An example of this case is the Ping An Financial Center shown in Fig. 13.

The 492-m tall 101-story Shanghai World Financial Center of 2008 in Shanghai is one of the earliest mixed system examples. This building, originally designed as a 460-m tall, had been structured with a tube-in-tube system with the reinforced concrete core and steel framed tube system, and foundation piles had already been in place based on this design when its design was changed to a 492-m tall building with larger plan dimensions. To accommodate these changes without reconstructing the existing foundation system, more efficient structural system had to be developed for not overloading the foundation. As a solution, the perimeter framed tube was changed to a more efficient braced megatube, and consequently, the thickness of the concrete core walls and hence the weight could be reduced. In addition, outrigger trusses were added that connected the core and corner megacolumns diago-

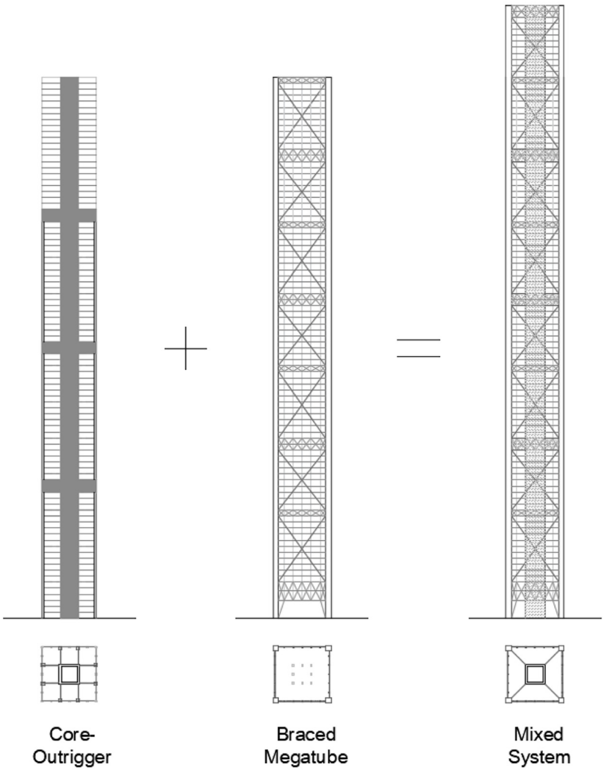


**Figure 11.** Concept of mixed system composed of typical core-outrigger and braced megatube systems with shared corner megacolumns and diagonally rearranged outriggers.

**Figure 12.** Shanghai World Financial Center during construction showing central core, corner megacolumns, perimeter diagonals, and belt trusses; diagonally arranged outriggers are hidden inside (photograph in public domain).

nally (Katz and Robertson, 2008). As a result, an unprecedented mixed system was developed with the core-outrigger and braced megatube systems, two major lateral load resisting systems for very tall buildings with shared megacolumns.

Since the construction of the Shanghai World Financial

**Figure 13.** Ping An Finance Center during construction showing central core, two megacolumns on each side, perimeter diagonals, and belt trusses; outriggers are hidden inside (photograph in public domain).

Center, some of the supertall buildings have employed a similar structural system. These buildings include the 599-m tall 115-story Ping An Financial Center of 2016 in Shenzhen and the 644-m tall 118-story Merdeka PNB118 which is currently under construction in Kuala Lumpur (Fender et al., 2016). The performance of this type of mixed system composed of the two major tall building structural systems is greatly influenced by stiffness distribution between them. It could be designed as a core-outrigger-system-dominant structure with supplemental stiffness provided by the braced megatube as is the case with the Ping An Financial Center. This approach particularly in this building was driven by the relatively recent seismic design requirements of the local building code regarding perimeter structures introduced in 2010 (Poon and Gottlebe, 2017), which did not exist at the time of the design and construction of the previously discussed Shanghai World Financial Center.

Alternatively, the mixed system of this combination could also be designed to have a much stiffer braced megatube. As the stiffness of the exterior tube is increased, the effectiveness of the outrigger trusses will be decreased compared to the core-outrigger-system-dominant mixed structure. When the stiffness of the exterior tube is configured to exceed that of the core eventually, the efficiency of adding the outrigger trusses will be minimal. Then, the system could be reconfigured to the conventional tube-in-tube system instead without outrigger trusses as are the cases with the previously presented Goldin Finance 117 and Citic Tower. They could also remain to provide greater level of redundancy for enhanced safety and still add some limited stiffness.

This type of mixed system is still relatively new and other types of new mixed systems are also in use for some other supertall buildings. In the Signature Tower in Jakarta and Suzhou Zhongnan Center in Suzhou, core-outrigger structural systems are used as the primary lateral load resisting system. In the core-outrigger system, the belt trusses are typically placed at the outrigger levels. In these buildings, however, additional belt trusses are placed mostly between the outrigger levels. Consequently, the megacolumns in combination with the belt trusses placed more densly than usual form so-called megaframes (Wijanto et al., 2012). Therefore, the megacolumns are also shared in these cases between the core-outrigger and perimeter megaframe systems. Without perimeter diagonals, however, the stiffness of the orthogonal perimeter megaframe is comparatively limited, and consequently it is almost always a secondary system.

Indeed, these as well as more mixed systems are possible and different stiffness distributions between the component systems may result in different structural performance characteristics even though they will still look very similar. The decision making regarding these issues is dependent on the various project-specific design requirements. Deriving an optimal structural solution based on not only structural but also all the other related aspects for each project is up to the collaborative efforts of the architects and engineers.

## 4. Structural Systems for Tall Buildings over 1 km

For extremely tall buildings, structural systems cannot be configured independently without considering building forms. In order to maintain structural efficiency, it is important to keep reasonable height-to-width aspect ratios for extremely tall buildings such as those whose heights are close to or even over 1 km. In order to maintain reasonable height-to-width aspect ratios, the width of the building has to become larger as a building becomes taller, and this condition makes very deep interior space uncomfortable for users, especially due to the lack of natural daylight, when typical squarish plans are used. In order to resolve this issue, two different design strategies can be considered.

First, building plans can be configured to have multiple wing spaces of reasonable spatial depths branched from the central area. Building cores are also configured to have a central structural core and its extensions as shear walls into the wing spaces to better structure this type of overall plan configuration. Then, by extending the length of the wings and shear walls into them, desired structural depths against wind loads can also be obtained. This design strategy results in the buttressed core system shown in Fig. 14.

Second, multiple extremely tall and slender buildings of reasonable spatial depths can be structurally conjoined at multiple locations over the building height. In this way, the structural depth of the tower complex can significantly be increased to the depth of the group of the conjoined towers. This scheme results in superframed conjoined towers shown also in Fig. 14. While the buttressed core system involves a significant limitation in architectural plan forms to perform structurally as intended. Plan forms of the individual tall buildings of the superframed conjoined towers are less limited. Instead, the distances and structural connections between the towers substantially influence the architectural design of the superframed conjoined towers.

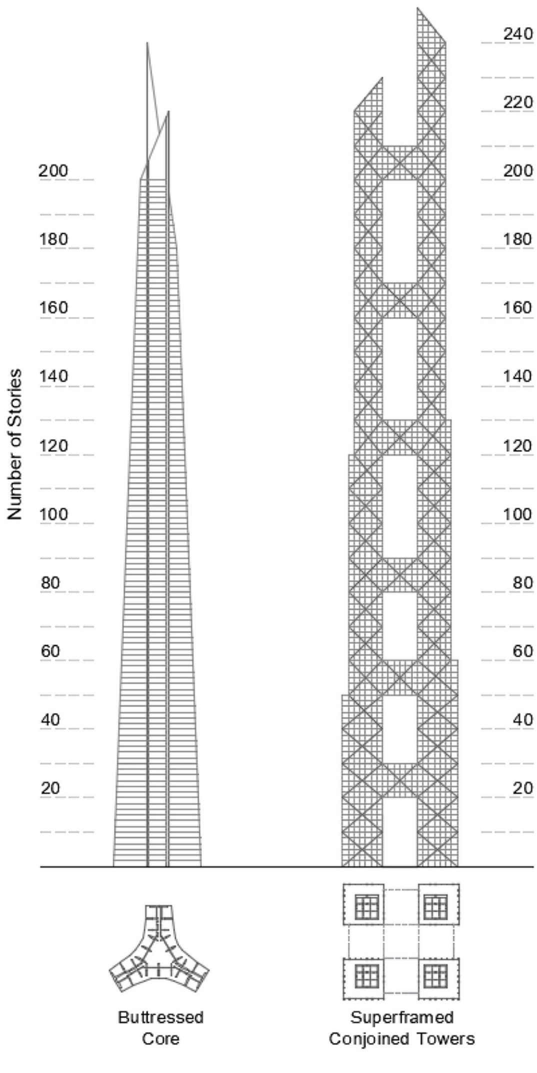


**Figure 14.** Buttressed core and superframed conjoined towers with simplified plans showing their structural and architectural design concepts.

### 4.1. Buttressed Core Systems

Both the tallest at present and soon-to-be tallest buildings employ the buttressed core structures. These extremely tall buildings have three wings in combination with tapered forms for better architectural and structural performances. Three winged Y-shaped tall buildings are not new though they are more common recently. The 197-m tall Lake Point Tower of 1968 in Chicago with its central triangular concrete core is one of the early examples. The 264-m tall Tower Palace Three of 2004 in Seoul is another example of more recent Y-shaped tall buildings also with its triangular concrete core engaging virtual outrigger system to increase its structural depth against lateral loads. As the height of the Y-shaped tall buildings becomes extreme in the 828 m tall Burj Khalifa of 2010 and the 1000+ m tall Jeddah Tower currently under construction, the central core itself is further extended as shears walls into the architectural spaces of the three wings.

The extended shear walls from the central core to form the buttressed core structures are terminated with thickened flange walls perpendicular to the extended shear walls around or at the end of the wings as can be seen in Fig. 15. These thickened end flange walls are comparable to the flanges of a vertical cantilever beam with Y-shaped cross section, while the extended shear walls are like their webs (Tamboli, 2014). Therefore, the buttressed core system could be understood as extended core shear walls with thickened end flange walls to efficiently structure the Y-shaped plan form buildings. The extended shear walls to the wing spaces are further stiffened by additional shear walls called "fin walls" perpendicular to them with outriggers or through deep coupling walls as in the Burj Khalifa and Jeddah Tower respectively for necessary openings in the fin walls, which often also act architecturally as interior demising walls.

Though the architecture-integrated buttressed core system provides efficient structures with increased structural depths, flexibility in interior space use is limited to a large degree due to the specific forms required. However, within the overall mass of vertically extruded Y-shape, creating varied exterior building forms can be done without much difficulty as the extended shear walls can be terminated in various different ways without transfer structures. They are terminated to create spirally stepping or smoothly tapering forms in the Burj Khalifa and Jeddah Tower respectively. These tapered forms provide superior structural performances in terms of not only static but also dynamic wind responses by disturbing organized vortex shedding over the building height. In tall buildings, vortex shedding-induced lock-in phenomena causing resonances often create the most critical structural design conditions. Vortex-shedding frequency is directly related to wind velocity, Strouhal number, and plan dimensions of the building. Thus, tapered forms with continuously changing plan dimensions help tall buildings prevent shedding organized alternating vortices over the building height. Therefore, the benefit of flexibility in easily creating varied tapered building forms could be significant.

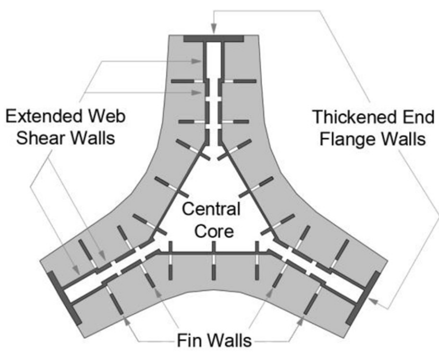


**Figure 15.** Jeddah Tower under construction (photograph in public domain) and its simplified structural plan showing central core, extended shear walls, thickened end flange walls, and fin walls.

### 4.2. Superframed Conjoined Towers toward Mile-High Cities

Fazlur Khan renowned for his tube structures also developed his idea of superframe for the unbuilt 168-story tall Chicago World Trade Center (Ali, 2001). In Khan's superframe with a square plan form, four trussed L-shape corner megacolumns are interconnected by multistory trusses at every about 20 stories over the building height. By conceptually expanding and modifying Khan's idea of superframe for a multiple tower complex, superframed conjoined towers can be developed. Conjoined supertall towers are a relatively new architectural phenomenon. When the superframe idea is applied to interconnected three or more conjoined towers, their heights can be increased very efficiently by structurally connecting the towers. In superframed conjoined towers, braced tube buildings are located at each corner of the conjoined tower complex and interconnected by multistory horizontal braced tube structures. These horizontal braced tubes are what create the superframed conjoined tower structure which uses the entire width of the conjoined tower complex as the structural depth instead of the width of the individual towers. Therefore, the stiffness of the horizontal connection braced tube structures, which in a sense perform like link beams in much smaller scale coupled shear wall structures, is a very important structural design consideration.

The left image of Fig. 16 shows lateral displacement profile of the 100-story braced tube structure studied in section 3-1 in comparison with the outrigger structure. A displacement scale factor of 50 is used in this figure. In the right image, two of the braced tube structures are conjoined with horizontal braced tube structures. Though the actual wind loads these towers are subjected to in the direction of the connections will be complicated, the two towers are loaded with code-defined winds in this simpli-

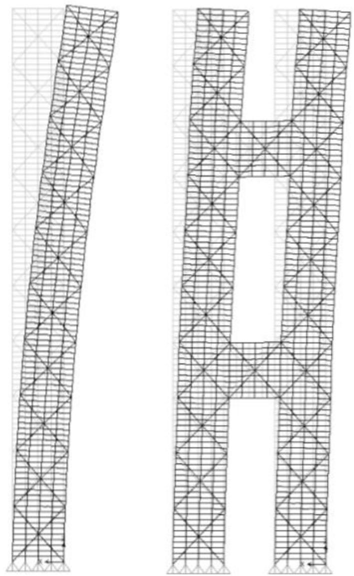

**Figure 16.** Lateral displacement profiles of 100-story braced tubes stand-alone and structurally conjoined (elevation view of SAP2000 3D models).

**Figure 17.** Mile-high superframed conjoined tower design project.

fied and conservative comparison study. It is clear that the lateral stiffness of the conjoined towers in the direction of the connections is much greater than that of the individual tower due to the structurally linking horizontal braced tubes.

Fig. 17 shows a mile-high superframed conjoined tower design project by Chris Hyun at Yale School of Architecture under the guidance of the author. The project was proposed for the empty site in Chicago partly including the area once used for the never-completed Chicago Spire project by Santiago Calatrava. In this design project, four exceedingly tall buildings are interconnected with the structural concept of superframe to create mile-high conjoined towers.

Four braced tube towers are placed in the corners of the enormous superframe allowing it to reach the height of one mile (1.6 km). The braced tube towers are interconnected by horizontally linking braced tube structures of multiple story height, which become the structural and architectural connections between the towers housing potentially sky lobbies and other public spaces of truly city-like conjoined mega-towers. By structurally interconnecting multiple towers, greater structural depths as a group against lateral loads for an enormous height and desired lease depths for individual towers for better functional performances can be achieved simultaneously. The individual towers are tapered through multiple setbacks toward the top creating varying lease depths for different functions placed at different heights. At the same time, the stepped tapering helps reduce both static and dynamic wind responses of the towers as discussed earlier. The placements of the structurally linking horizontal braced tubes are denser toward the base where the maximum overturning moments are applied.

Despite its characteristics much appropriate for extremely tall buildings, the architecture-integrated structural concept of superframed conjoined towers may not be easily employed for existing dense urban land because very large building sites are required for them. However, where appropriate, these towers may be a viable solution for the problem of dense urban environments, by way of creating mile-high vertical cities toward the sky.

## 5. Conclusions

This paper has reviewed structural systems for the tallest buildings of different periods as well as for today's most tall buildings over 500 m either completed or under construction. Performances of some of the major structural systems for these extremely tall buildings, such as core-outrigger, braced megatube, mixed, and buttressed core structures have also been studied. Further, the potential of superframed conjoined towers has been investigated as a viable solution where appropriate for future mega-towers creating mile-high cities.

The 42 m tall 10-story Home Insurance Building of 1885 in Chicago is considered by many as the origin of tall buildings of skeletal structures. It took only about 45 years for this new building type to grow into a ten times taller building of the 381 m tall 102-story Empire State Building of 1931 in New York. About 25 years later, Frank Lloyd Wright proposed his mile-high ILLINOIS in 1957, a visionary tower about four times taller than the Empire State Building. In his mile-high ILLINOIS, Wright even envisioned to provide rentable space in the final tier of the building up to 528th floor. Considering these extremely rapid developments of tall buildings including the visionary one in the past, their current status is, in fact, not comparable.

The exceedingly tall buildings presented in this paper are certainly astonishing achievements. Despite that it has been almost 90 years since the construction of the Empire State Building and 60 years since the proposal of the mile-High ILLINOIS, however, even the tallest Burj Khalifa reached only about a half mile. The height of the soon-to-be tallest Jeddah Tower of about 1 km is also still quite below one mile. These gaps are even severer when the occupied height is considered. Therefore, though it is said by many that we are now very close to reaching mile-high towers, we have reached only a fraction toward it yet especially in terms of the occupied height. For comfortable and sustainable mile-high occupancies, developing technologies and designs further beyond what we have reached so far is essential.

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