International Journal of High-Rise Buildings
March 2018, Vol 7, No 1, 1-16
https://doi.org/10.21022/IJHRB.2018.7.1.1

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

Dynamic Interrelationship between the Evolution of Structural Systems and Façade Design in Tall Buildings: From the Home Insurance Building in Chicago to the Present

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Abstract

The emergence of tall buildings in the late 19th century was possible by using new materials and separating the role of structures and that of non-structural walls from the traditional load-bearing walls that acted as both. The role of structures is more important in tall buildings than in any other building type due to the "premium for height". Among the walls freed from their structural roles, façades are of conspicuous importance as building identifiers, significant definers of building aesthetics, and environmental mediators. This paper studies dynamic interrelationship between the evolution of tall building structural systems and façade design, beginning from the early tall buildings of skeletal structures with primitive curtainwalls to the recent supertall buildings of various tubular and outrigger structures with more advanced contemporary curtainwalls.

Keywords: Tall buildings, Skeletal structures, Tubular structures, Diagrids, Outrigger structures, Curtainwall façades

1. Introduction

Tall Buildings emerged in the late 19th century in the US. The Home Insurance Building of 1885 in Chicago designed by William Le Baron Jenny is generally considered as the first skyscraper by many because it was the first multistory office building structured mostly with iron/steel frames. Prior to the Home Insurance Building, typical multistory office buildings were built primarily with masonry structures in which masonry walls performed not only as structures but also as façades on the building perimeter. As buildings of masonry structures become taller, masonry walls become very thick toward the base. These thick masonry walls reduced the rentable area and limited the amount of natural light introduced to the interior space through the narrow and deep openings on the perimeter. With only incandescent lamps which produced intense heat and no HVAC systems at that time, the interior work environment of the early tall masonry office buildings was uncomfortable, especially at lower levels. In order to overcome this undesirable condition and maximize rental incomes, skeletal structures were invented using iron/steel.

With skeletal structures constructed with iron/steel, the strength of which is far higher than that of masonry units, much smaller areas were taken up by building structures. Consequently, abundant natural lights could be introduced through the wide openings between the perimeter columns. While traditional masonry structures on the building perimeter did the dual roles as both structures and façades, the skeletal structures performed only as structures. Therefore, façades in skeletal structures were supported by the structural frames, and this newly developed façade concept began to be called curtainwalls. With these new concepts of skeletal structures and curtainwall façades, which overcome the limitation of the traditional masonry structures for tall buildings, the new building type has continuously evolved rapidly.

As a building becomes taller, the impact of lateral loads becomes significantly larger. Eventually, for very tall buildings, lateral loads, especially wind loads, generally govern their structural design. Therefore, it is essential to design tall building structural systems to resist not only gravity but also lateral loads efficiently. In many early multistory steel framed buildings, the columns and girders were rigidly connected to resist lateral loads. Alternatively, or in addition to the rigid connections, diagonal bracings were employed typically for interior frames around the building core to make the otherwise orthogonal frames to perform like triangulated vertical trusses to resist lateral loads more efficiently.

As a building becomes very tall and slender, resisting lateral loads by rigid frames or braced frames around the building core becomes inefficient structural solutions. More efficient lateral load resisting systems were developed as the heights of tall buildings became greater and structural efficiency began to be considered more seriously for their economic developments. In various tubular

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structures developed in the 1960s and 70s, the concept of early skeletal structures is still used. However, major components of lateral load resisting systems are located over the building perimeter in order to maximize their structural depth against lateral loads. In outrigger structures, also initially employed for tall buildings in the 1960s, the lateral load resisting system relies on the building core designed to resist lateral loads. However, in order to increase the structural depth of the building, outrigger trusses are extended out from the core and connected to the perimeter columns.

Today, while applications of some of the traditional tubular structures, such as framed and bundled tubes, are rare, diagrid structures have emerged as another prevalently used new tubular structural system composed of perimeter diagonal members. Braced tubes are still widely used often in modified forms. In terms of outrigger structures, the system is also very widely used for today's tall buildings throughout the world.

The evolution of structural systems for tall buildings has primarily been based on the concept of providing more efficient lateral load resisting systems. Therefore, developing rational structural design ideas is of significant importance to produce structural configurations which can carry lateral loads with maximized structural depths and more efficient mechanisms. Unlike the structural design, however, building façades, in addition to their environmental performances, have been designed to a large degree based on more subjectively judged architectural aesthetics, which has often been associated with many differentisms or styles,.

The new building type, tall buildings, in the late 19th century was possible by the technological breakthrough of dividing the functions of structures and nonstructural walls including façades on the building perimeter. Since then, the structural systems for tall buildings have continued to evolve. Nonetheless, they have mostly been some forms of skeletal structures especially on the building perimeters. With the new façade concept of curtainwalls resulting from the invention of skeletal structures, tall building façades have been designed with greater flexibility and represented an extremely broad range of architectural design concepts from classical to medieval to modern. Based on these two paths of technological evolution and architectural design transitions of different nature, structural and façade systems of tall buildings have been designed with numerous different design ideas. This paper investigates the dynamic interrelationship between the evolution of tall building structural systems and façade design. The study is performed with some of the most representative tall buildings of certain periods beginning from the early tall buildings of skeletal structures with primitive curtainwalls to the recent supertall buildings of tubular or outrigger structures with more advanced contemporary curtainwalls.

2. Early Tall Buildings of Skeletal Structures

The Home Insurance Building of 1885 was the first 10-story office building constructed with skeletal structures for its significant portion including its street front perimeter walls. While the original height was 138 ft (42.1 m), two more stories were added in 1891 and its height was increased to 180 ft (54.9 m). When it was demolished in 1931, the building's iron/steel frames were clearly revealed. However, it was also found that the columns and girders were not rigidly connected to resist lateral loads. Masonry walls on the lot lines at the back of the building carried most of the lateral loads instead. In addition, bricks surrounding the street front columns were not purely constructed as curtain walls, and granite stone masonry was employed for the street front exterior walls of the first two stories. Therefore, there has been some skepticism about accepting this building as the first skyscraper of a skeletal structure. However, as with most breakthrough technologies, the importance of them lies in their potential. The invention of skeletal structures and consequently developed curtainwall concept for multistory office buildings have led to the present state of the new building type, tall buildings, which was impossible with traditional masonry structures.

The column spacing along the long street front of the Home Insurance Building was about 11 ft (3.4 m). These perimeter columns encased by brick layers were clearly expressed on the façade. Since the column spacings were almost identical, it could be reasonably assumed that their sizes were also almost identical for the same floors. However, their architectural expressions were different on the building façade. The building's corner columns and the columns on the column lines along the both side piers of the entrances were more boldly expressed. In fact, corner columns take less loads than the other columns due to their smaller tributary area. Along the long street front, the bold expression of the granite masonry piers at the entrance was not only architectural but also structural because of the wide opening between them to produce the large entrance. The loads applied to the entrance piers were larger than those applied to the other piers.

The building façade design also shows vertically grouped tiers of two or three stories using expressive bands of cornices. Tall office buildings were a new building type developed in the late 19th century. Architectural design of this unprecedented building type was very challenging to architects at that time. Among various façade design strategies developed, the approach of grouping multiple stories was a widely used trend in early tall buildings including the Home Insurance Building.

The breakthrough technology of skeletal structures was able to make the early tall buildings much lighter and transparent, and these two important themes of modern architecture began to be captured by some of the late 19th century Chicago architects. However, early tall buildings

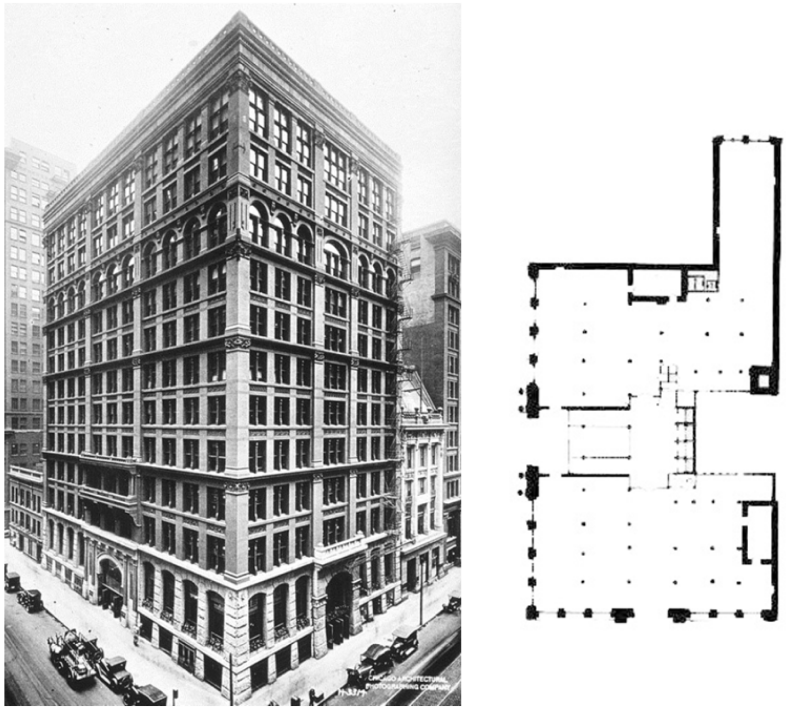


Figure 1. Home Insurance Building and its ground floor plan (photograph in public domain).

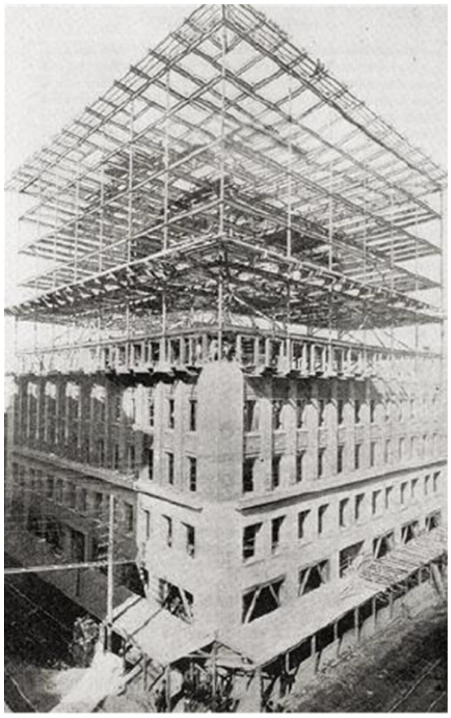


Figure 2. Construction of Wainwright Building in Saint Louis (photograph in public domain).

even including those designed by these Chicago architects still employed some of the traditional building type's architectural languages and technologies. Masonry arches were still employed in the Home Insurance Building as both a structural component and a façade design element.

The Wainwright Building in St. Louis is another 10-story early tall building designed by Louis Sullivan. Completed in 1891, the Wainwright Building was built six years after



Figure 3. Wainwright Building [left], Bayard Building [middle] and Carson Pirie Scott Department Store Building [right] (photographs in public domain).

the Home Insurance Building. During the years between the constructions of the two buildings, the breakthrough concept of skeletal structures and curtainwalls was substantially refined. While the Home Insurance Building used skeletal structures, the masonry walls encasing the street front iron/steel columns also contributed partially to carrying the gravity loads. In the Wainwright Building, however, the steel frames carry the entire loads and the masonry walls around the columns are truly curtainwalls supported by the frames. This could be well observed during its construction.

The construction photo of the Wainwright Building shows a typical construction process of steel famed structures with curtainwalls even from today's standard. The construction of the structural steel frames begins first independently from the façade construction. As the steel frame construction progresses, the curtainwall construction is followed. In Fig. 2, the 10-story steel frames of the Wainwright Building were already completed, while the construction of the curtainwalls was still in progress at around the mid-height of the building.

The self-weight of the masonry curtainwalls is typically transferred to the structural frames at each floor through shelf angles. In addition, the lateral loads applied to the masonry curtainwalls should also be transferred to the structural frames behind. For this purpose, back-up structures, such as the steel studs behind the masonry curtainwalls shown in Figure 2, are placed vertically between the perimeter floor beams, through which the lateral loads can be transferred to the structural frames.

In the Wainwright Building, Sullivan employed his tripartite design concept for tall buildings. The first two floors, which were functionally more public than the other floors, were designed as the base, the third through ninth floor office spaces, as the shaft, and the 10th floor, as the attic. The column spacing is typically about 17 ft (5.2 m), while it is about 22 ft (6.7 m) around the corner. On the ground floor, these columns are expressed without any substantial nonstructural elements between them to make large entrances and show-windows there. From the third to the ninth floor, however, additional non-structural vertical bands of masonry curtainwalls are placed between the perimeter columns which are also enclosed by the identical looking masonry curtainwalls. Using masonry on building façades in early tall buildings was related to protecting perimeter steel columns from fire and typical interior space layout at that time with small offices divided by demising walls. However, these non-structural masonry curtainwalls were not related to these issues. A similar design approach was introduced for the second floor, but the width of the masonry curtainwalls around the structural columns is wider. Based on these configurations, it is difficult to identify which vertical bands of masonry curtainwalls express structural columns behind them without the clues subtly expressed on the second floor and more directly expressed on the ground. This façade design could also cause misunderstanding of the perimeter structure as very narrowly spaced columns from the second floor to the top and widely spaced columns on the ground floor with transfer girders between them. As in the Home Insurance Building, the corner columns are also more boldly expressed in the Wainwright Building. Though the column spacing becomes somewhat wider than typical at the corners, the tributary area of the corner columns is still smaller in this building and they carry less loads.

The newly developed breakthrough technology initially



Figure 4. Reliance Building and its typical floor plan (photograph by author, plan drawing in public domain).

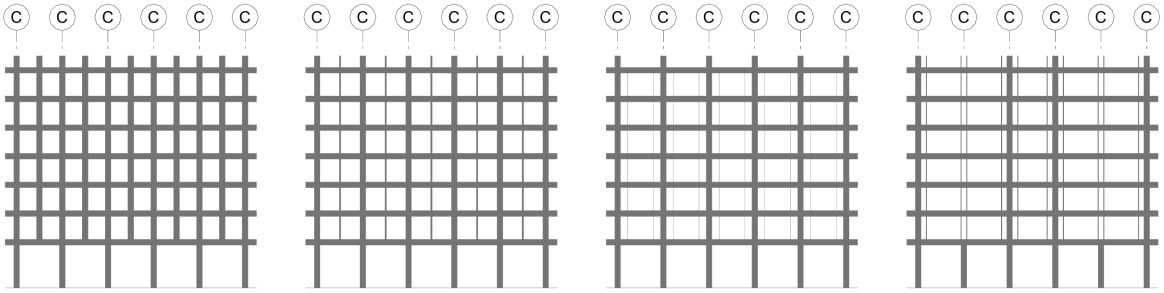


Figure 5. Simplified comparative diagrams of Wainwright Building [first], Bayard Building [second], Carson Pirie Scott Department Store [third] and Reliance Building [fourth], showing the relationship between the perimeter structural members and façade design.

employed in the Home Insurance Building was better understood and much more refined in the Wainwright Building. However, the desired architectural design at the time did not fully explore the potential of the refined new technology. Instead, a hybrid-integrated design between the structural frames and curtainwall façades was pursued. A similar design approach was also employed in Sullivan's *Guaranty Building* of 1896 in Buffalo. However, in his *Bayard Building* of 1889 in New York, the expression of the structural steel columns and nonstructural vertical elements between them are significantly different on the façade. While the structural columns are much more boldly expressed with white terracotta, the nonstructural bands between them are far thinner. With this hierarchical expression, structural and nonstructural expressions are clearly distinguished. Though the nonstructural vertical bands are omitted from the second floor to the ground in the Bayard Building, it no longer produces the illusion of load transfer at the third floor perimeter girder. Finally, in his *Carson Pirie Scott Department Store Building* of 1904 in Chicago, Sullivan completely omitted the nonstructural vertical elements between the columns, and, consequently, the façades truly expressed the structural frames of the building. The large openings between the vertical and horizontal terracotta enclosing the structural frames are filled with Chicago Windows.

Oriel windows were employed in many early tall buildings in Chicago. Floors are cantilevered typically in trapezoidal forms beyond the main façade planes defined by the perimeter columns. While most of the oriel windows

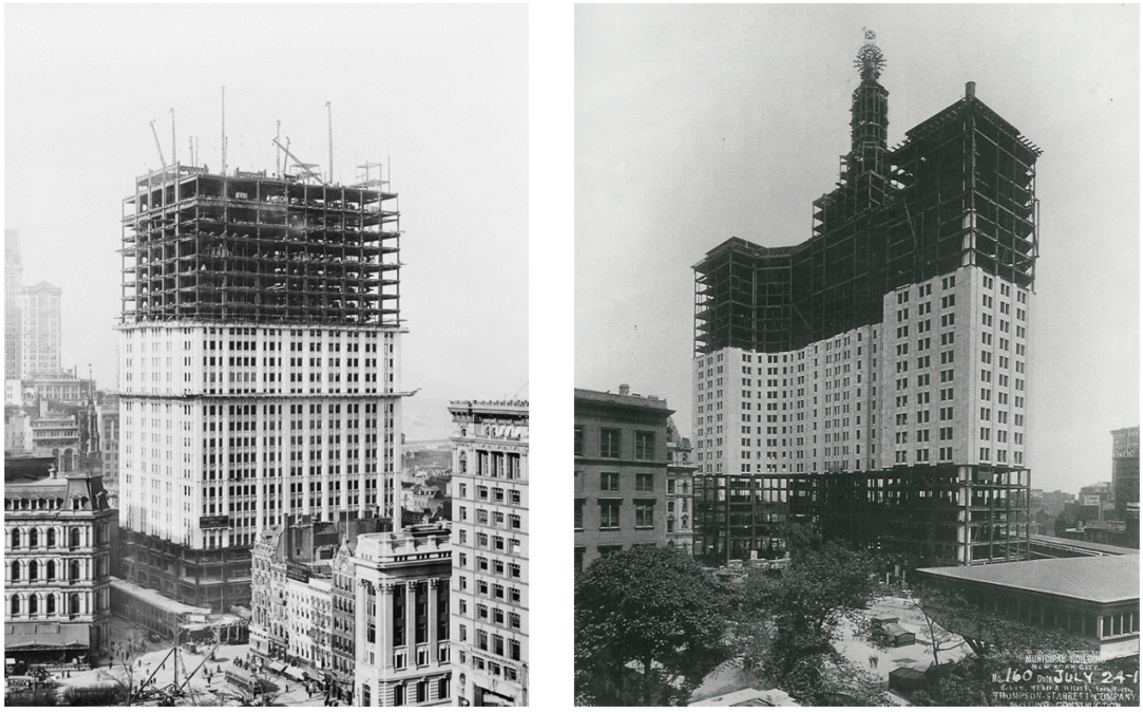


Figure 6. Construction of Woolworth Building [left] and Municipal Building [right] (photographs in public domain).

are single bay windows, some exceptions existed. *The Pontiac Building* of 1891 and *Reliance Building* of 1895 were designed with double bay oriel windows. Therefore, the middle columns between the two bays are substantially behind the projected façade planes of the oriel windows. This configuration allowed even greater transparency on the building façades and maximized the amount of natural light introduced to the interior.

With the double bay oriel windows from the second floor to the top in the Reliance Building, the structural columns are accurately expressed only on the ground floor, while many of those on the second through 14th floors are hidden behind the curtainwall façades of glass windows and terracotta. In all of the buildings presented so far, perimeter structural columns were truly expressed on the ground floor. However, the expressions of the columns on the floors above are widely different. The design approach of the Reliance Building is in a sense an embryo of the prototype of typical Miesian tall buildings with exposed columns on the ground floor and those behind the glass façades above.

3. Early 20th Century Tall Buildings

Despite the early Chicago spirit pursuing the aesthetic potential of the newly developed technology, this design approach was not appreciated in many tall buildings in the early 20th century. While the newly developed technologies of skeletal structures and corresponding curtainwall concept were the standard methods of construction, many architects still relied on the traditional architectural languages for the façade design. Various hybrid integrations between the structural systems and façade design for tall buildings prevailed for decades in association with many eclectic styles at that time.

Construction photos of the early 20th century tall buildings clearly reveal that they used new technologies already mature by then. However, the buildings' form and façade design returned to the design ideas of old days. The breakthrough technology was developed to minimize structural member sizes especially on the building perimeters and maximize natural lights introduced to the interior spaces. However, this motivation was intentionally compromised and the potential of maximum transparency for enhanced daylighting was not fully pursued. In fact, there were some opposing trends with regard to transparency. For instance, a renowned Art Deco skyscraper architect Ralf Walker's concept of architectural space was opposed to that of transparent volumes. He noted that "to merely build a shed with one or two walls of glass does not create space …… it merely interrupts it".

While American eclectic architects in the early 20th century were going in a direction somewhat opposed to transparency, their European counterparts pursued it more rigorously. Notable examples among them were Glass Chain's pursuit for transparency through glass in architecture, Bauhaus design in Dessau by Walter Gropius and the unbuilt glass skyscraper projects by Ludwig Mies van der Rohe who eventually moved to the U.S. in the late 1930s.



Figure 7. 860-880 Lake Shore Drive Apartment [left], Seagram Building [middle] and IBM Building [right] (first and therd photographs by author, second photograph in public domain).

4. Mid-20th Century Tall Buildings

In tall buildings of Ludwig Mies van der Rohe in the mid-20th century, the architectural potential of the skeletal structure and curtainwall concept was finally more deeply explored. In Mies's *Lake Shore Drive Apartments* of 1951 in Chicago, structural steel frames on the building perimeter are clearly expressed as integral part of the façade design. The openings surrounded by the perimeter structural frames are filled with glass windows to complete the façade. Steel was predominantly used as structural materials for the skeletons of tall buildings at that time beginning from the emergence of tall buildings in the late 19th century. However, steel was rarely used as material for façades. In the 860-880 Lake Shore Drive, steel columns were encased by concrete for fire safety and its surfaces were finished again with steel plates which were directly expressed on the building façade. The direct expression of the steel frames from the second floor to the top is as two dimensional façade elements, while the steel columns on the ground floor are fully exposed as pilotis. Steel in Mies's signature I beam shaped section was also used for the mullions of the glass windows between the columns.

After the Lake Shore Drive Apartments, the relationship between the structural frames and façades in most Mies's buildings changed due to functional performance issues. When the structural frames are exposed on the façades, they are directly subject to outdoor temperature changes of a wide range. Furthermore, these exposed structural members act as systematic thermal bridges between the exterior and interior. In the *Seagram Building* of 1958, the structural frames from the second floor to the top are hidden behind the metal and glass curtainwalls and protected from the fluctuating outdoor temperature except for the corner columns which are still partially exposed. Mies used bronze for his signature I beam shaped mullions in the Seagram Building. All of the ground floor perimeter columns of the main tower are still fully exposed as pilotis. Therefore, different from the Lake Shore Drive Apartments, the façades of which are composed of structural frames and infill metal/glass windows, Seagram Building's metal/glass curtainwalls are actually hung from the structural frames inside. The louvers at the top for the ventilation of the mechanical room there complete the façades as a tripartite configuration.

The revised configuration used in the Seagram Building acted as a new prototype for Mies's tall office buildings. Compared with the earlier tall office buildings, each floor of which was typically composed of many small offices, large open floor plans were desired in the mid-20th century, and Mies's new prototype suited this new need well. From the environmental performance viewpoint, however, thermal bridges between the exterior and interior were still everywhere on the façades through the metal mullions and single pane glasses. The façade technology of Mies's buildings continuously evolved to resolve this issue. In the *IBM Building* of 1970 in Chicago, thermal breaks were inserted into the mullions as integral part and double plane insulated glasses were used to better protect the building thermally. These technologies are predominantly on the functional domain and do not impact the architectural aesthetics much.

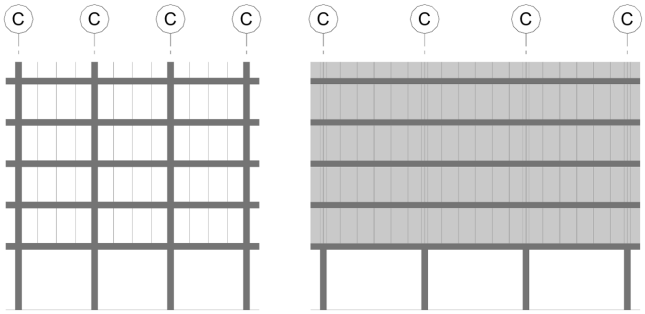


Figure 8. Simplified comparative diagrams of 860-880 Lake Shore Drive Apartment [left] and Seagram Building [right], showing the relationship between the perimeter structural members and façade design.



Figure 9. 860-880 Lake Shore Drive Apartment, DeWitt-Chestnut Apartment and John Hancock Center in Chicago (photograph by author).

5. Framed Tube Tall Buildings

Next to Mies's 270 ft (82.3 m) tall 26-story Lake Shore Drive Apartment Buildings stands 395 ft (120.4 m) tall 43-story *DeWitt-Chestnut Apartment Building* of 1966 that was designed and constructed with a significantly different structural concept. The early steel moment resisting frames and braced frames were developed as two dimensional structural systems. In moment resisting frames, multiple layers of two dimensional moment resisting fames typically configured in two orthogonal directions carry lateral loads. When braced frames were used, the bracings were generally confined within the narrow interior core structures. For very tall and slender buildings, these configurations provide inefficient lateral load resisting systems.

In order to carry lateral loads more efficiently, moment resisting frames composed of very narrowly spaced columns and deep beams are placed on the entire building perimeter to produce framed tubes of a three dimensional configuration with maximized structural depths against lateral loads. In the DeWitt-Chestnut Apartment Building, the perimeter columns are placed at 5 ft 6 in. (1.7 m) on center, which is similar to the spacing between the mullions in the Lake Shore Drive Apartment Building. On the ground floor, the column spacing is doubled to create reasonably wide entrances. These structural configurations are directly expressed on the building façades. Due to the inherent compositional characteristics of the tubular system, structures and façades are integrated to a great degree.

As the very first building of the framed tube system in reinforced concrete, the DeWitt-Chestnut Apartment Building was not significantly tall. Supertall examples of the



Figure 10. Aon Center and its ground floor entrances (photographs by author).



Figure 11. Demolished World Trade Center and its ground floor entrances (source: Wikipedia).

framed tube system in steel can be found several years later in the *Aon Center* of 1973 in Chicago and the demolished *World Trade Center Twin Towers* of 1971 in New York. In the Aon Center, at its height of 1123 ft (342.3m), V shaped perimeter columns are spaced at 10 ft (3 m) on center throughout the height of the building in association with very large L shape corner columns which significantly contribute to the lateral stiffness of the tower. These ver-

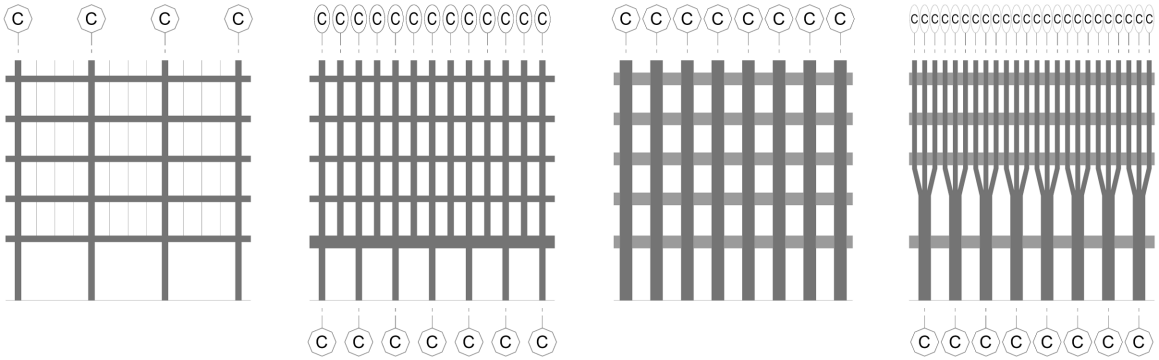


Figure 12. Simplified comparative diagrams of 860-880 Lake Shore Drive Apartment [first], DeWitt-Chestnut Apartment [second], Aon Center [third] and World Trade Center [fourth], showing the relationship between the perimeter structural members and façade design.



Figure 13. 432 Park Avenue (photograph by author).

tical structural components on the perimeter are currently clad with white granite (originally clad with marble) and boldly expressed as major façade design elements. Expressions of the deep perimeter beams are much diminished behind the V shaped columns to emphasize the verticality of the building.

In the 110-story tall World Trade Center Twin Towers in New York demolished by terrorist attack, an extremely narrow column spacing of 3 ft 4 in. (1m) on center was used. Considering the width of the perimeter columns, the width of the openings between the columns was only about 2 ft 2in. (66cm). With these extremely narrow openings, it was impossible even to produce reasonably spaced entrances on the ground. Therefore, every three perimeter columns were merged into one large columns toward the ground to create wider spacing between them. As in the Aon Center, these vertical structural components on the perimeter were boldly expressed as major façade design elements. Due to their very dense structural configurations on the building perimeter, the framed tube structures are almost always integrated with façade design.

Though framed tubes were developed as a very efficient structural system for tall buildings of the 1970s and 1980s, they were not widely used during the following decades because of their geometric configurations involving very narrowly spaced perimeter columns which obstruct views and govern the façade design significantly. However, framed tubes are employed again for some of the recent residential towers, such as the 1396 ft (425.5m) tall *432 Park Avenue* in New York and 445 m tall *Marina 106* in Dubai. While tall buildings were predominantly commercial towers until even the late 20th century, beginning from the 21st century the number of residential towers is greatly increasing. And for residential tall buildings whose floors are typically composed of many separate rooms, smaller perimeter openings of the framed tube system could be well integrated with the floor plans and corresponding façade design.

6. Tall Buildings with Large Perimeter Diagonals

Adding large perimeter diagonals to the framed tube structure results in the braced tube. Once diagonals are added, the performance of the system is substantially improved and the column spacing can be significantly wider. In the *John Hancock Center* of 1969 in Chicago, with large perimeter diagonals, the perimeter columns are spaced at 40 ft (12.2 m) on the wide façade planes and 25 ft (7.6 m)



Figure 14. John Hancock Center in Chicago [left] and Hearst Tower in New York [right] (first photograph by author, second photograph by Adam Gimpert).

on the narrow façade planes. All of these perimeter columns and large diagonals are expressed and become important façade design elements.

Diagonal bracings were added to numerous early tall buildings of skeletal structures beginning from the late 1880s. However, they were always employed for interior frames to perform only as a structural component. It took about eight decades for these significant structural components for tall buildings to be used on the building perimeter not only structurally but also architecturally. Braced tube structural systems are still one of the most efficient structural systems for tall buildings though they are now about 50 years old. Despite their significant structural performances, however, large perimeter diagonals are not always welcomed architecturally. Therefore, when large perimeter diagonals are used, they are often hidden behind the façades in today's tall buildings such as the 528 m tall *China Zun Tower* in Beijing and 596.6 m tall *Goldin Finance 117 Tower* in Tianjin.

Another system using large perimeter diagonals is diagrid structures which can be obtained by eliminating all the perimeter vertical columns from the braced tube structures and increasing the density and adjusting the angles of the perimeter diagonals. The structural efficiency of braced tube systems, composed of vertical perimeter columns and perimeter diagonals, is not substantially affected by the angles of diagonals. However, the performance of diagrids, primarily composed of perimeter diagonals without verticals, is significantly influenced by the angles of the diagonal grids. For tall and slender buildings, diagrids placed at relatively steep angles perform better structurally. As the building height is decreased, the structurally optimal angle of the diagrids is decreased. When properly configured, the structural efficiency of diagrids for tall buildings is very similar to that of braced tube systems.

Diagrid structures are not a new structural concept. However, they began to be used for major tall buildings in the 21st century after the history of tall buildings over 100 years with either orthogonal frame type or braced frame type structural configurations. As a structural system composed primarily with diagonal members without verticals, the diagrid system provides a distinguished unique aesthetics. Therefore, diagrid structures are usually expressed as an important façade design element as are the cases with the *Hearst Tower* in New York, *D2 Tower* in Paris, *Tornado Tower* in Doha, and unbuilt *Lotter Super Tower* project in Seoul by SOM.

The Hearst Tower of 2006 is the first major diagrid tall building. The 46-story building rises from the landmark façade of the old Hearst Building of 1926. Vertical megacolumns and super-diagonals are used as the structural system of the new building up to the ninth floor. This portion of the new building is mostly hidden behind the preserved façade of the old building. The structural system of the new building changes to the diagrids from the 10th floor to the top. Considering the building's plan dimen-

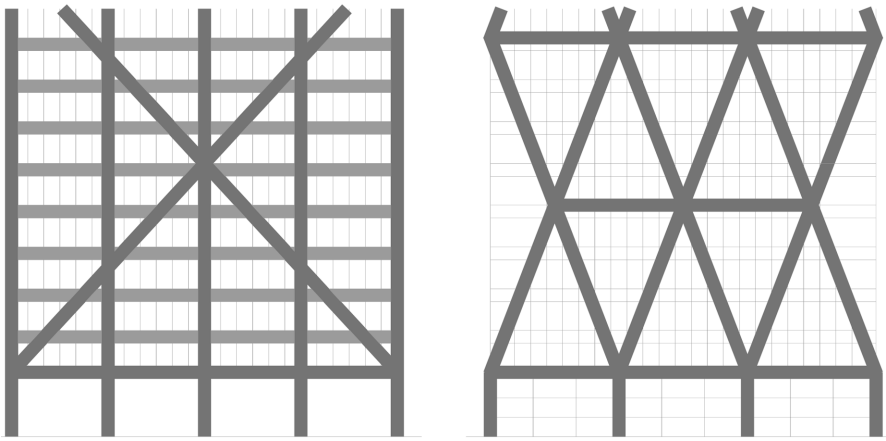


Figure 15. Simplified comparative diagrams of the braced tube in John Hancock Center and diagrids in Hearst Tower, showing the relationship between the perimeter structural members and façade design.

sions of 120 ft × 160 ft (36.6 m × 48.8 m) and its height of 600 ft (182.9 m), its height-to-width aspect ratio is 5. A diagrid angle of about 70 degrees is consistently used throughout the diagrid portion of the structure, and these uniform angle diagrids are boldly expressed on the building façade. This diagrid angle is close to the optimal for diagrid tall buildings of this height and height-to-width aspect ratio range. Conventionally configured orthogonal glass curtainwalls are employed in combination with the triangulated perimeter diagrid structure.

The unbuilt 110-story Lotte Super Tower project by SOM is a much taller and slenderer diagrid building than the



Figure 16. Three different expressions of diagrid structures in Doha and Tornado Towers in Doha [left] and Gunagzhou International Finance Center in Guangzhou [right] (first photograph: courtesy of Terry Meyer Boake, second photograph source: Wikipedia).



Figure 17. CCTV Headquarters Building in Beijing during construction (source: Wikipedia, photograph by Jakob Montrasio).

Hearst Tower. The height-to-width aspect ratio of this building is about 8. If a constant diagrid angle is desired, a uniform angle a little steeper than 70 degrees should be used. Instead of using a uniform angle, however, varying angle diagrids were proposed in order to maximize the structural efficiency of the system. In fact, varying angle diagrids with steeper angles toward the ground and shallower angles toward the top could enhance structural efficiency of the system for very tall and slender buildings. Based on this structural logic, an angle of about 78 degrees was used in the lowest diagrid modules and that of about 60 degrees was used in the highest diagrid modules. These varying angle diagrids which directly reflect structural logic of the system was expressed as an important façade design concept for this unbuilt design project by SOM.

Certainly, diagrid structures are not always expressed on the façades of tall buildings. In the 103-story tall *Guangzhou International Finance Center*, diagrid structures are placed behind the glass façades. However, the diagrids were designed to be still visible through the glass façades in daytime, and they are accentuated by lighting at nighttime. In the *Doha Tower*, the diagrids are placed behind the two layers of façades composed of normal glass curtain wall inner layer and metal sun screen outer layer. The diagrids hidden behind these two layers are hardly visible because the mashrabiya-motivated metal screens are very dense. Only at nighttime with a certain lighting condition, the diagrids of the Doha Tower temporarily perform as an important façade design element. The Doha Tower and the Tornado Tower nearby make an interesting contrast in terms of building forms and expressions of diagrids on the façades. Both towers have circular floor plans. However, the Doha Tower tapers toward the top while the Tornado Tower tapers toward the mid-height. Both towers employ diagrids as their primary lateral load resisting systems. While the diagrids in the Doha Tower are hidden most of the time behind the façades, those in the Tornado Tower are boldly expressed on the façades.

The CCTV Headquarters Building in Beijing is a unique case in terms of its building form and architectural expression of the structure with large diagonals on the perimeter. The building was designed in a continuous loop form to better fulfill the project specific functional requirement. This loop form involves conjoined two slanted towers connected at lower and higher levels. The connections are made in L shapes, which result in a large merged cantilever at higher levels. In this uniquely formed tall building, a braced tube type structural concept was employed with perimeter columns and varying density diagonals depending on the regional structural requirement on the perimeter. On the building façades, however, only diagonals are expressed as an important façade design element and consequently this building reads as a diagrid structure without vertical columns.



Figure 18. Jin Mao Building's exterior, typical floor plan and ground floor lobby (photographs by author).

7. Tall Buildings with Outrigger System

Tubular systems provide very efficient structural solutions for tall buildings. However, the system inevitably affects architectural design of tall buildings to a great degree. The framed tube system requires very narrowly spaced perimeter columns. In the bundled tube system, the perimeter column spacing can be wider than that in the framed tube. However, the bundled tube system results in interior columns which can be avoided in other tube type structures. In the braced tube system, the perimeter column spacing can be as wide as non-tubular structures. However, the system requires large perimeter diagonals, which may not always be welcomed architecturally.

The outrigger system is another tall building structural system which uses the full width of the building as the structural depth against lateral loads. Different from the tubular structures, however, the outrigger system does not solely rely on the perimeter structural members to resist lateral loads. Typically perimeter mega-columns of limited number (most commonly eight) are connected to the interior core structure through outrigger trusses. In many cases, gravity columns are also placed between the mega-columns. Since these perimeter column spacing is not narrow as in the framed tube structures and no large perimeter diagonals are required as in the braced tubes or diagrids, façade design is not significantly governed by the lateral load resisting structural components in the outrigger systems.

The *Jin Mao Building* is an 88-story tall mixed-use building in Shanghai structured with the outrigger system. Four pairs of composite mega-columns are placed on the building perimeter. The cross-sectional dimensions of the mega-columns are 1.5 m × 5 m approximately for the lower third, 1.5 m × 4.5 m for the middle third, and 1.5 m × 3.5 m for the upper third of the building. As the building approaches the top, the floor plates become smaller, but the exterior surface of the mega-columns still remain vertical to maintain the maximum structural depth provided by the outrigger system. The tapered form of the tower is obtained by reducing the floor plates around the four corners only.

Though the structural logic of the outrigger system influences the overall form of the building as described above,



Figure 19. Hong Kong International Commerce Center (photographs by author).

the mega-columns, outrigger trusses and the structural core composed of shear walls are all hidden behind the reflective glass façades which enclose the traditional Chinese pagoda-motivated building form. Inside the building, the very large mega-columns take up significant floor area, but their spacing is not as narrow as that in the framed tubes. The spacing between the mega-columns in the Jin Mao Building is about 9 m on center. The outrigger system also does not require perimeter diagonals or interior columns which are required in the braced tubes and bundled tubes respectively. Instead, the outrigger system requires interior outrigger trusses of typically one or two stories tall. However, these outrigger trusses are placed only on a very limited number of floors, which are typically integrated with mechanical rooms or refuge areas. Therefore, the outrigger structure eliminates major architectural challenges of the various tubular structures. This has made the outrigger system as one of the most prevalently used structural systems for today's tall buildings even though its structural efficiency is not as high as that of the tubular structures with large perimeter diagonals, such as braced tubes and diagrids.

There are many other supertall buildings structured with the outrigger system, including the 632 m tall *Shanghai Tower* in Shanghai, 555 m tall *Lotte World Tower* in Seoul, 508 m tall *Taipei 101* in Taipei, 484 m tall *International Commerce Center* and 412 m tall *Two International Finance Center* both in Hong Kong. In all of these buildings, the outrigger structural systems are not directly expressed on the façades unlike the tubular structures discussed earlier. Fig. 19 shows the International Commerce Center at daytime and nighttime. During the daytime, the perimeter mega-columns of the outrigger system are hidden behind the reflective glass façade. Only at nighttime, the mega-columns are expressed due to the interior lighting, and give some hint of the outrigger system to those who have some knowledge about tall building structural systems.

While perimeter mega-columns are typically not directly expressed on the building façades, those in the 205.6 m tall Pabellon M in Monterrey, Mexico, are an exception. Unlike typical mega-columns placed behind the curtainwalls, the reinforced concrete mega-columns in the Pabellon M are placed in such a way that about 50% of each mega-column is inside the glass curtainwall façade planes and another 50%, outside. Therefore, the structural depth of the building against lateral loads becomes even greater and at the same time the mega-columns perform as an important façade design component.

8. Conclusion

In the history of architecture of thousands of years, tall buildings are still a relatively new building type with its history of only over a hundred years. However, during that time period, tall buildings have grown from about 40 m tall office buildings to mixed-use mega-tall buildings including the tallest Burj Khalifa of 828 m. A kilometer tall tower is under construction at the time of this writing, and it is expected that a mile high tower (about 1.6 km) envisioned by Frank Lloyd Wright in the mid-20th century will no longer be only a vison in the near future.

Without the technological breakthrough of skeletal structures and curtainwall concept, the emergence and continuous evolution of tall buildings would not have been possible. Many different types of very efficient structural systems for tall buildings have been developed since the invention of the early skeletal structures in conjunction with the advancements of structural materials and other related technologies. Façade systems for tall buildings have evolved from the early primitive curtainwalls to today's dramatically advanced systems including double skin façades of various configurations. While these two key technologies have continuously been evolving, architectural design of different nature than technologies has played crucial roles in how to integrate these two.

Today's tall buildings are still designed and constructed based on the original concept of skeletal structures and curtainwalls. This paper studied their dynamic interactions beginning from the late 19th century when tall buildings emerged to the present. As a quintessential building type of today and for the future, the importance of understanding various aspects of tall buildings cannot be overemphasized to create higher quality built environments.

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