

Structural Innovation

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INTRODUCTION

The very existence of skyscrapers is a testament to innovation.

Mankind had always lived close to the ground. During the thousands of years that preceded the birth of the skyscraper, life was limited by a reality of stairs and ladders. It was only after Elisha Otis invented a safer elevator that architects and engineers started a race to the sky with the 12 story Home Insurance Building – taking office buildings from the historical range of 5 or 6 stories to the 102-story Empire State Building in merely 40 years.

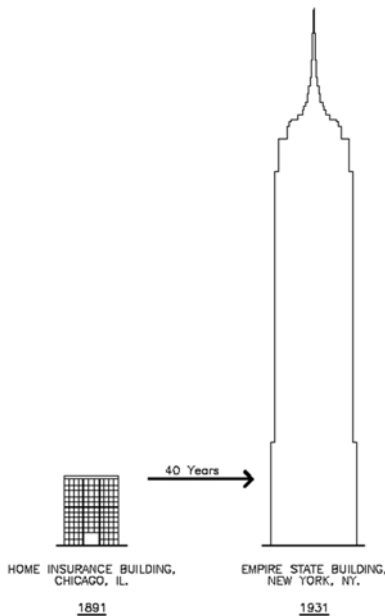


Figure 1 Skyscraper Development.

The invention of the skyscraper came shortly after major breakthroughs in railroads, bridge building, shipbuilding, and manufacturing. While these nascent technologies created the economic foundations for modern cities, the skyscraper created an entirely new kind of city. The skylines of Chicago and Manhattan were unlike anything the world had ever seen.

Technical innovations in systems and materials for these first towers are now subjects for historians. Although innovations that have followed the first skyscrapers have not been as sociologically profound, they represent levels of creativity and inventiveness that equal and, perhaps, exceed the original breakthroughs.

REBIRTH

The rebirth of skyscrapers in the 1960s, after a hiatus of over thirty years, came with structural innovations that transformed the industry. Gone were the interiors filled with columns and frames resisting the wind (with substantial help from the “non-structural” cladding and interior partitions). Instead there was a whole new structural vocabulary of framed tubes, braced tubes, tube-in-tube, bundled tubes, frame-shearwall interaction, outrigger systems, etc.

This cloudburst of new systems was made possible by the advent of computers and engineering pioneers such as Fazlur Khan, Hal Iyengar, William LeMessurier, Leslie Robertson and others. Although the conceptual foundations of these systems were straightforward, earlier computational methods were not adequate for use in design. At last, the viability of these systems could be demonstrated by utilizing the mainframe computer. In addition to validating the systems, important parametric studies were done to establish the applicable height range for the various systems.

A seminal building from this period is the Chestnut-Dewitt apartment building (arguably the first tubular building) designed by Fazlur Khan and architect Myron Goldsmith. This simple, elegant tower – now dwarfed by its neighbors – was a major development in modern architecture. The integration of the tubular structural system and Miesian architecture was complete and seamless. Architecture and structure were one and the same, inseparable. The computer was able to verify that this concrete building could be viewed as one complete continuous structure rather than merely a collection of columns and beams. Designers could now verify that the building behaved as a three-dimensional system much like a solid tube, only partially softened by the openings for windows.



Figure 2 Chestnut-Dewitt Apartment Building, Chicago IL.

If concrete was the material of choice for moderate height residential buildings, steel dominated the construction of super tall buildings – so much so that if construction of skyscrapers had stopped in 1974, the tallest buildings would have all been made of steel. The Sears Tower was a steel bundled tube; the World Trade Center and the Standard Oil towers were steel framed tubes, the much earlier Empire State Building was a steel frame and the John Hancock Center was a braced steel tube. All of the newer towers had long, column free, lease spans and, interestingly, were of similar slenderness ranging from a height to width ratio of 6.0 to 1 for the Standard Oil Tower to 6.6 to 1 for the John Hancock Center.

The first practical use of boundary layer wind tunnels for buildings occurred during this time. These tests often utilized expensive aeroelastic testing to measure building motions. Criteria were needed for these motions, so moving room tests were done for the John Hancock Center and the World Trade Center projects.

Speed of construction is critical in the economics of a skyscraper. Therefore, innovations in construction technologies were essential. Structural steel could be fabricated off site in ways that minimized field connections and thus speed the construction. Welding and high-strength bolts replaced the rivets of an earlier age. Although none of the newer buildings could match the incredible 18-month construction schedule of the Empire State Building (built during the Great Depression), these new buildings were efficiently assembled like great machines.

Profiled metal deck was a major addition to the industry. It increased the speed of construction by providing economical permanent formwork for the floors that could be used as a working surface for the ironworkers and could later function as reinforcement for the concrete slab. The flutes of the metal deck could also be configured to accommodate electrical and communication wiring for the tenants' workstations.

As essential as speed was to skyscraper construction, equally paramount was cost. The generally accepted measure of a structure's cost was the total steel tonnage divided by the total framed area. Expressed in pounds per square foot of floor area (psf), the economy of these buildings was made evident by the substantial reduction in the steel used. While the Empire State Building weighed in at 42.2 psf the substantially taller Sears Tower was only 33.0 psf.

RECENT TIMES

Unlike the generation-long interruption of projects between the time of the Empire State Building and the John Hancock Center, the construction of very tall buildings has not stopped for the last forty years (although there have been periods of slowing down).

In the era from the mid-1980s until today, there have been a series of innovations that have once again changed the vocabulary of tall building design.

One such innovation was a major shift from all steel construction to systems that utilize the benefits of both steel and concrete in the primary structural systems. The industry has weighed the strengths and weaknesses of these two primary structural materials and now uses each to its advantage.

Steel is excellent for framing long span office floors; it is lightweight, can be easily modified by tenants and can be quickly erected. Concrete, on the other hand, is very cost effective in carrying the weight of the tower, and the mass is beneficial in reducing building motions. New formwork systems and the ability to pump concrete to great heights have also greatly increased the speed of concrete construction. In addition, the inherent damping of a concrete lateral system is generally higher than a steel system.

The resulting merger of steel and concrete into composite buildings has resulted in seemingly endless combinations of the two systems. Perhaps the most common composite systems use reinforced concrete cores and steel floor framing. The perimeter framing varies from reinforced concrete frames or tubes to reinforced concrete mega-columns or even to perimeter steel frames. This results in an extremely large variation in the manner that the cores can be

arranged or how the building might be expressed architecturally. The Jin Mao Tower in Shanghai is an example of a highly integrated super-core.



Figure 3 Jin Mao Tower, Shanghai, China.

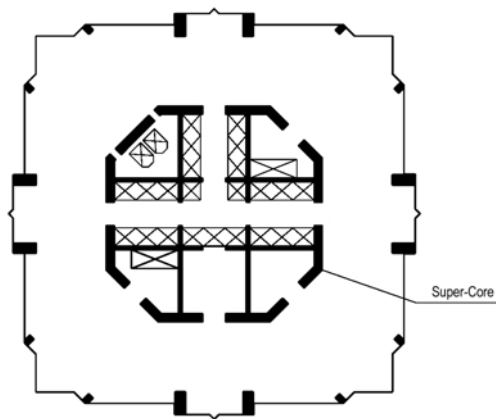


Figure 4 Super-Core, Jin Mao Tower, Shanghai, China.

Recent years have seen a major increase in computer power, with mixed results. The benefits of this enhanced computational power include the ability to perform more extensive behavioral studies to better understand the nuances of a given structural system. It is also much easier to accurately compare alternative structural solutions for a particular building.

Recent advancement in the application of optimization techniques to tall buildings has also resulted in more efficient buildings that use less of our limited resources. It is now possible to use optimization techniques to “tune” a building to achieve a better behavior under wind loading.

The “downside” of such advanced computational horsepower, however, is that it allows the engineer to make a building “stand up” without having a rational structural system. Although super-tall buildings still tend to have rational systems, many of the mid-rise towers often employ a complicated set of ad-hoc structural systems. It could be argued that architecture and the efficiency of many buildings, particularly in the late 1980s and early 1990s suffered from the undirected freedom permitted by the computer. In an earlier time, the computational limitations on the structural engineer necessitated straightforward structural systems that could be calculated with the available tools. The resulting architecture often benefited from this discipline.

In addition, optimized structural systems favor more efficient load paths and tend to eliminate less efficient ones. While this can greatly reduce the quantities of steel and concrete, it often results in a building with less redundancy. It

is very important to study the robustness of an optimized structure and give special consideration to fracture critical members and similar issues.

Major advancements have occurred in wind engineering and motion control. Tall buildings are generally not controlled by the strength of the lateral load resisting system but by limiting the motion to within acceptable limits. The wind related dynamics of a tall building have three components: background static, background dynamic and resonant dynamic. The background static and background dynamic wind forces are independent of the building behavior and are a function of the surrounding environment and wind climate. Although these components are important, it is the resonant dynamic behavior that is critical to the structural design of a tall tower. The resonant dynamic forces and motions, particularly in the dominant across-wind direction, are related to vortex shedding and the accompanying pulsating forces.

The design team has several approaches available for controlling the resonant dynamic behavior. The natural dynamic behavior of the tower can be modified to optimize the response. This refers to modifying any or all of the basic structural properties of the building: mass, period, mode-shape and inherent damping. The design team may choose to add artificial damping to the tower through special devices and machines. Most importantly, the design team can actually decrease the dynamic forces imposed on the building by judiciously shaping the building in plan and profile.

Examples

The successful design of very tall buildings requires extremely close cooperation between the architect, structural engineer, building services engineer, specialty consultants and contractors. In order to demonstrate how this cooperation and interplay can be manifested in a skyscraper, two recent projects will be briefly reviewed.

The Samsung Togok project is a very tall residential tower in Seoul, Korea. Because it is a residential building, the motion criteria are the most restrictive. The span from the core to the perimeter is very short because of the natural lighting requirements of a residential building. It will be the tallest all-residential building in the world when it is completed. The integrated architectural and structural solution is a floor plate of three leaves that brace each other against the lateral forces of nature. The shape of the building greatly reduces the resonant dynamic forces on the building to such an extent that the motion criteria are easily met using a conventional structural system.



Figure 5 Samsung Togok Project, Seoul, Korea.

The important components of the building shape are the heights of each of the wings and the shape of the floor plans. The different height wings create different floor plans that have different vortex shedding behavior. This prevents the wind forces from becoming organized in a manner that can lead to large dynamic building responses. The elongated shape of the floor plate at the top of the structure also prevents well-defined vortices from forming, while the sawtoothed edge avoids creating an airfoil that would have created “lift” forces for certain wind directions.

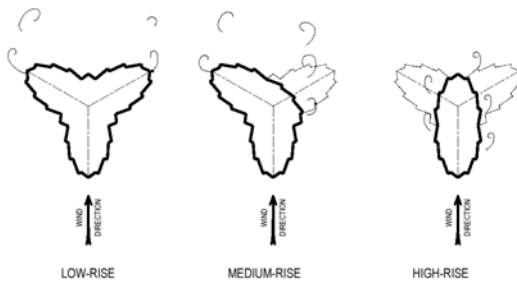


Figure 6 Samsung Togok Project: Vortex Shedding Behavior.

Another proposed building that incorporates many of the latest innovations in structural systems and wind engineering is 7 South Dearborn in Chicago. The design uses the latest innovations in materials, systems and wind engineering to create a tall, slender and economical tower. The proposed tower is very slender, with a height to width ratio of 8.5 to 1. It avoids the overly deep lease spans of earlier towers to create conventional office floor plates and uses a relatively small site of less than one acre for a building that would be the world's tallest.

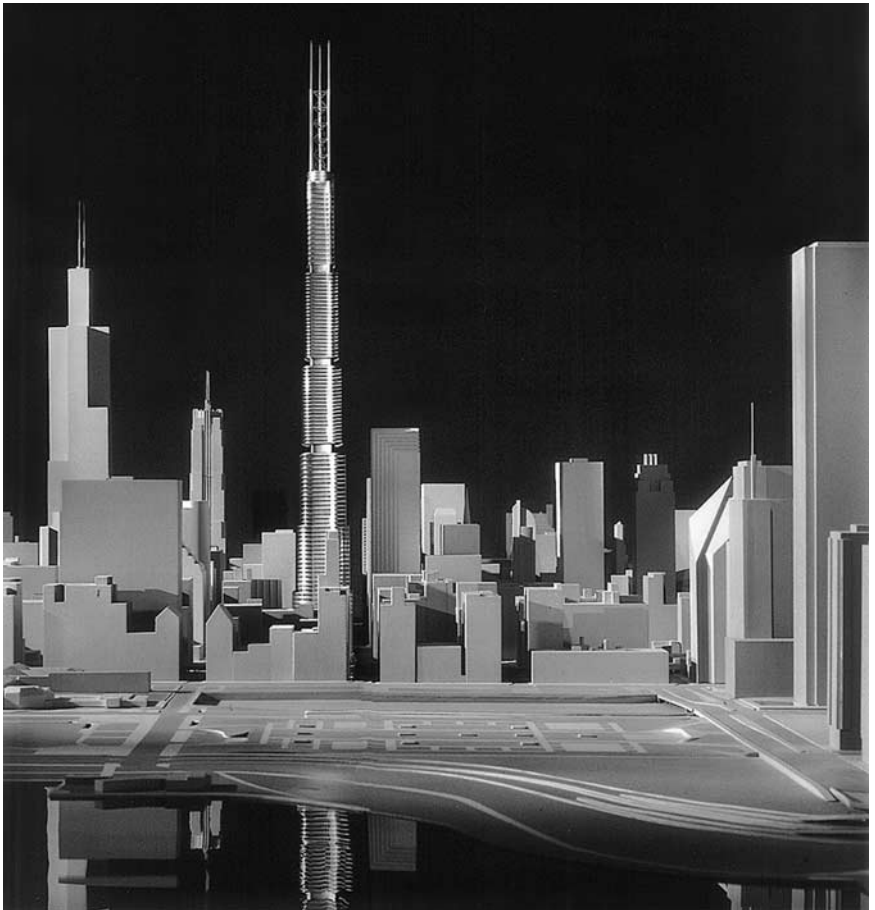


Figure 7 7 South Dearborn, Chicago, IL.

The lateral load resisting system is termed a “stayed mast” that uses an outrigger system at the mid-height to brace the high strength concrete core that extends from the foundation to 1550 feet (472 meters) above grade. A “virtual” outrigger on the parking stories above the ground floor lobby augments this straightforward system. This system is the latest development in super-core systems.

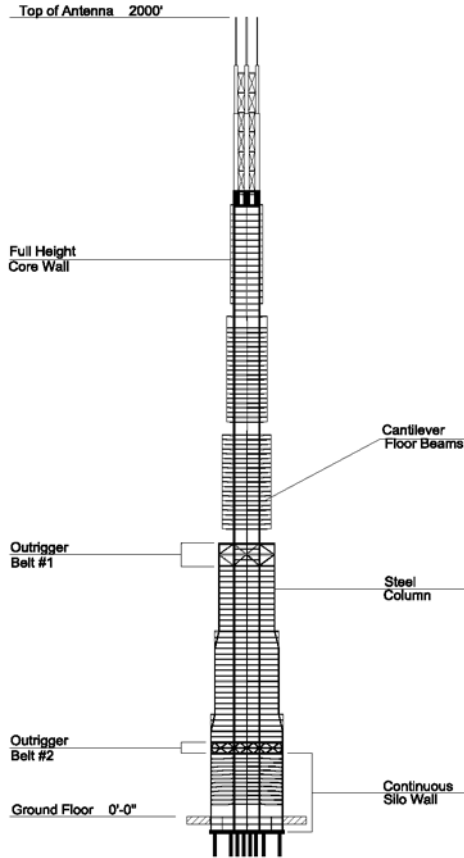


Figure 8 Structural System for 7 South Dearborn, Chicago, IL.

Structural steel is utilized for the floor framing and perimeter columns in the office floors due to advantages in tenant use and speed of construction.

Cantilever floor construction is used in the residential floors for reasons of construction, core strength, and improved serviceability. This cantilever construction takes full advantage of the speed that concrete core wall construction permits by allowing for multiple floors to be constructed simultaneously without needing to proceed in the one-floor-at-a-time method normally required. It also maximizes the gravity loads on the core, thus increasing the strength of the concrete core. In addition, this type of construction also eliminates problems of differential creep, shrinkage and elastic shortening movements between the core and the perimeter for these upper floors. Finally, this system eliminates the racking that often contributes to motion perception in tall buildings. It also creates a column free perimeter and spectacular views.

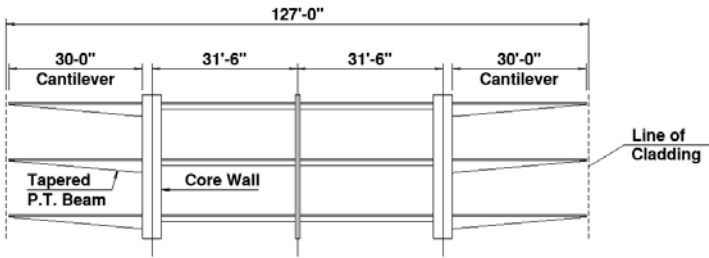


Figure 9 7 South Dearborn Cantilever Floor System.

Wind engineering and motion control have been addressed by the proper shaping of the building and by controlling the period, mass and mode shape of the tower. The tower was tested in the wind tunnel several times during the conceptual design phase in order to assess the wind behavior and to evaluate refinements in the building shape. The “wind signature” of the building was studied by analyzing the autospectra curves. This permitted judicious modifications of the building’s dynamic properties. It also gave insight into the effects of various shapes. One series of tests was done to evaluate the effect of the distinctive notches on the building behavior. The effect was dramatic: the notches reduced the wind forces in critical wind directions by up to 20%.

The resulting building is new, exciting and unique. One of the wonderful results of new technology is the opportunity for new architectural interpretations of the skyscraper.

Damping devices

Although the 7 South Dearborn design met the strict residential motion criteria with only inherent structural damping, studies were done on the use of supplemental damping systems. Several innovative systems for motion control currently exist. These include mechanical or liquid tuned mass dampers, piston dampers, and visco-elastic dampers. An interesting system that was reviewed for the 7 South Dearborn project was a tuned liquid column damper, a type of tuned mass damper that uses the water in a tank as the mass, a water column at each end as the spring and an orifice to dissipate energy. This type of damper will undoubtedly be used more on buildings with less optimal architectural massing and structural systems.

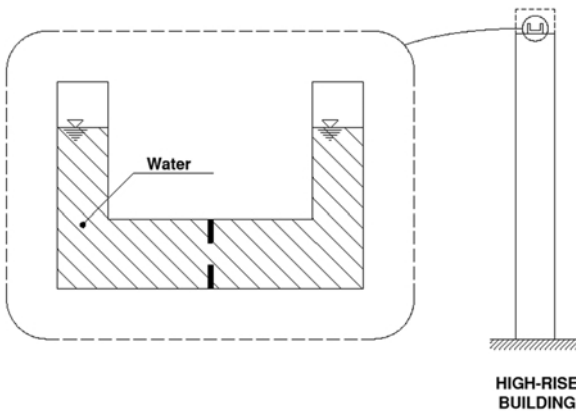


Figure 10 Tuned Liquid Column Damper.

Artificial damping devices should be used with caution. The reliance on these systems for issues of strength should be carefully considered and generally avoided. The actual track record for these systems is very limited, and long-term maintenance is a serious issue. It is not unusual for even famous buildings to undergo periods of neglect, as they become older.

There are times where the use of damping systems for improved serviceability would be appropriate. Even then, it is important to evaluate the total cost of these items, including the cost of occupying space that is very expensive to build and the cost and practical concerns of maintenance.

CONCLUSION

Structural engineering innovations and their influences on skyscrapers continue to be significant in changing the nature of tall buildings. It is important to note, however, that the most profound structural advancements occur through the collaboration of architects, structural engineers, building services engineers, specialty consultants and contractors. The time and money that it takes to construct a tall building require an efficiency and optimization that exceeds any other type of building.

The current level of innovation is quite high and is focused on composite systems, materials, wind engineering/motion control and optimization approaches. The future of tall buildings looks bright, as each of these fields is just beginning to be mined for their full potential. As in the past, skyscrapers of the future will change in response to these influences: contractors will find new ways to construct, engineers will continue to invent new systems, and architects will continue to create new buildings that embrace and benefit from these technical influences.