

Evolution of Concrete Skyscrapers: from Ingalls to Jinmao

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ABSTRACT

This paper has provided a broad overview of different historic developments for concrete high-rise buildings. The evolution of concrete skyscrapers from the first reinforced concrete high-rise, the Ingalls Building, which was 15 stories high to modern skyscrapers Petronas and the Jin Mao is discussed. How new innovations in construction technology such as the advances in formwork, mixing of concrete, techniques for pumping, and types of admixtures to improve quality have all contributed to the ease of working with concrete in high-rise construction is also briefly discussed in the paper.

KEYWORDS

Tall buildings, Reinforced concrete, High-strength concrete, Construction Technology

1. Introduction

Concrete, unlike any other structural building material, allows the architects and engineers to choose not only its mode of production, but its material properties as well. When architects and engineers call for a concrete structural system, they must also specify a multitude of variables, such as its strength, durability, forming techniques, hardening characteristics, nature and extent of reinforcement, aesthetics and much more. As a result, the field of concrete tall building construction is rapidly changing and its limits are constantly being tested and stretched. The introduction of composite construction to tall tubular buildings, first conceived and used by Fazlur Khan of Skidmore, Owings & Merrill (SOM) in the 1960s, has paved the way for supertall composite buildings like the Petronas Towers and the Jin Mao building in the present era.

Travelling through time, one learns that the art of proportioning of concrete was known to the Roman builders and the Pharaohs of Egypt in a primitive way. Most current research and development occurred in the mid- to late-nineteenth and early-twentieth centuries with men like Monier, Hennebique, Ransome and Talbot. Techniques of concrete for the design and construction of buildings have been used by architects and engineers like Frank Lloyd Wright, Pier Luigi Nervi, Robert Maillart and, more recently, Fazlur Khan. Of course, application with regard to high-rise structures is the most recent, and each of these people had a hand in the development and use of concrete as it exists today in various forms.

2. Early history

Supertall buildings are a relatively recent addition to the history of the cities around the world. Technology of the nineteenth century made their development possible. Steel, concrete and masonry materials have existed for a long time in the history of civilization but not in such a configuration. Masonry is the oldest material. Concrete in its present form is the youngest of these three basic structural materials of construction. Research shows that early societies used

lime as a binding element in mortar. These included the Phoenicians and their colonies, Cyprus in Mycaenae, Minoan Crete, Egypt and Mesopotamia. Structures from as early as 1200 BC have been found with polished, lime-concrete floors and surfaces of hard, colored plaster. Even earlier during the Neolithic period, builders knew "burning of limestone, slaking the lime, mixing the mortar, spreading the concrete, and finishing the surface" [1]. Current frame of reference tends toward a comparison between the history of concrete and its use in tall buildings and that of the Roman's of primitive concrete buildings. In the early centuries as now, time, money and human ability were important factors in choosing building materials [2]. Skill was required for building formwork--skill that may have been difficult to identify within large groups of slave laborers. Projects involving elaborate arches and utilitarian structures were supplemented in their strength by bricks and left-in-place forms as they attempted to economize and conserve skilled labor [3]. With the decline of the Roman Empire, society lost the ability to mold the ingredients into cementitious materials. Only ruins exist as a testament to Roman ingenuity and the history of concrete. The use of concrete was lost for centuries until discovered again in the nineteenth century and put to work as a workhorse for large warehouses, apartment buildings and factories.

The baseline from which to measure the history and development of the skyscraper is the 1876 Centennial Exposition in Philadelphia. While there were no skyscrapers or even structures that resembled them at the exposition, there were in the construction of the buildings and in the exhibitions many of the seeds that germinated and took roots under the quickening impulse that the exposition furnished. Portland cement, while known for some time and used in concrete and in mortar for brickwork below grade, was imported from England, but was hardly employed in the masonry walls of the superstructure. Specimens of reinforced concrete were exhibited at the Centennial as a usual curiosity in the field of specific possibilities, but as yet unrecognized for any general use, although a few obscure but adventurous leaders had begun to catch the vision. This was, however, the era of bridge building, not high-rises. Steel rolling mills were then establishing their standard shapes, which were later to become the foundation of the skeleton steel design for skyscrapers.

Discovery in a modern sense of reinforced concrete actually occurred during the eighteenth and nineteenth centuries. Wilkinson of New Castle, England, François Hennebique of France, and Thaddeus Hyatt of America are some who greatly contributed to its development in the 19th century. In 1884, E. L. Ransome's patented twisted bars for greater bond is the precursor for our current deformed bars.

In 1904, the first technical bulletin, "Tests of Reinforced Concrete Beams," was published by Robert Talbot of the University of Illinois at Urbana-Champaign following his testing of concrete in its civil engineering laboratories.

As materials testing continued to improve, built forms of reinforced concrete systems were witnessed both in Europe and the United States. Factories, warehouses, residential houses and low-rise apartment buildings were considered appropriate uses of concrete. At first, exterior walls were load bearing with beams, columns and floor systems built to imitate those of steel and wood, two popular systems of the time. These applications did not, however, utilize concrete to its fullest potential. Between 1901 and 1902, Ransome first patented a system with an exterior belt course to hold up walls from stories above. He also developed the first precast wall units that were placed integrally with cast-in-place floors and columns. Precast systems were initially popular making erection quicker and more efficient as well as avoiding cold weather problems. These two innovations changed the exterior walls from ones that carried their own loads to ones that bore integrally with the rest of the system. This created an ability

to use concrete as the framing with a curtain wall sealing the building from external forces [3]. Another innovation, which led the construction industry away from its traditional construction techniques of imitating steel and wood, was Robert Maillart's use of the floor slab instead of beams and girders to carry loads. These breakthroughs, along with concrete's ability to resist fire, carry heavy loads, and dampen noise, made it a good choice for factory and apartment buildings at the turn of the century. The difficulty for inventors was then to convince the public that its uses went beyond low-rise apartment buildings. Like steel, it could also soar toward the sky.

3. First Concrete Skyscraper

The history of concrete high-rise truly belongs to the realm of the twentieth century. E. L. Ransome's system of casting square, twisted, steel bars with concrete as a frame with slabs and concrete exterior walls was used in the Ingalls Building in Cincinnati, Ohio, the first 15-story concrete "skyscraper" built in 1903 by A. O. Elzner. Initial speculation by the news media and many skeptics in the construction profession predicted that once shoring was removed, the building would crack and crumble under its own weight or through shrinkage during curing. One news reporter stayed awake all night waiting for the event in order to be the first to provide news coverage of such a catastrophe. Fortunately, they were proven wrong for the building remained standing. When first designed, tremendous city fires around the world had destroyed numerous steel tall buildings. The steel literally became ribbons when subjected to high heat, which concerned many at the time. Concrete was proving itself to be an excellent fire-resistant material through its use in factories and providing sustenance during fires in those facilities. A. O. Elzner, in a 1904 article, mentioned the additional benefits of concrete over steel: concrete "is considerably cheaper. Steel requires a great amount of capital and equipment and money to operate a steel plant. Long hauls and heavy freight bills are also involved" [4]. In addition, the schedule for completion was tight and concrete construction could begin well in advance of delivery of steel to the site. Elzner [4] further wrote about the building:

"The structure is a concrete box of 8" walls, with concrete floors and roof, concrete beams, concrete columns, concrete stairs--no steel. It consists merely of bars embedded in concrete, with the ends interlaced, making actually a complete concrete monolith of the entire building, covered on the exterior with a veneer from four to six inches thick of white marble for the lower three stories, glazed gray brick for the next eleven, and glazed white terra cotta for the top story and cornice . . . There are no shrinkage cracks and the building (has sustained) the highest winds, there is not even a perceptible tremor, and that too with concrete walls only eight inches thick in unbroken slabs sixteen feet square, a portion of which on the second floor carries a bank vault weighing nearly a hundred tons."

4. Innovation in Construction Technology

Much of the technological change in concrete construction was in the first half of the 20th century. Advances in formwork, mixing of concrete, techniques for pumping, and types of admixtures to improve quality have all contributed to the ease of working with concrete in high-rise construction.

Formwork: The most efficient construction coordination plan for a tall building is one that allows formwork to be reused multiple times. Traditionally, formwork was made of wood but as technology has advanced, the forms have become a combination of wood, steel, aluminium, fiberglass and plastic, to name only a few materials. Each set may be self-supporting with trusses attached to the exterior or may need additional shoring to support it in appropriate locations. New additions to the family of forms include flying-forms, slip forms, and jump forms.

Flying forms or table forms are rental items. They are built in "typical" span lengths in order to provide continual reuse in a variety of jobs. The assemblage is made of fiberglass pan forms, steel trusses and purlins, and plywood, which are moved as a unit providing the base for a floor slab. After concrete placement and when it is determined that the strength of concrete has reached an appropriate maturity, the forms are removed, cleaned and "flown" with a crane to the next level of a building for reuse.

Slip forms are another type of early removal system using materials, which are continuously re-employed. Three types of jacks--hollow screw jack, hydraulic jack and pneumatic jack--are used worldwide to "slip" formwork for a wall section to higher levels as the concrete cures. The screw jack is manually operated and used in areas of the world where mechanization is limited. The hydraulic and pneumatic jacks are fully automated moving continuously as concrete is pumped into place.

Jump forms are another type of concrete formwork, which moves as concrete cures to create a reusable, economic system. Jump forms also have a lifting mechanism but it is used differently from that of the continuous pours made with slip-forming. These are designed to swing away from the structure (like a door opening) for cleaning and oiling with subsequent reattaching to the wall as it increases in height.

Delivery Systems: While the history of concrete as a material is long, its use in tall buildings was partially curtailed because of difficult delivery systems. For the construction of the Ingalls Building, the ingredients of concrete were brought to the site and stored on the basement floor. Blending of materials was accomplished mechanically by power-driven, on-site mixers, which had been developed in the 1880s. When transport began in 1913, it was executed using open trucks. Since segregation occurred on the way to the site, remixing was always necessary. Actual means of transporting the quantities needed for such an enormous job as a high-rise project entails by a transit-mix vehicle was not available until after 1920. In 1947, the first "hydraulically driven truck-mixers" were introduced in the scene.

Delivery of concrete had been an issue for tall buildings and other large projects. Hand-in-hand with this concern came the challenge of material placement in large quantities. Technology remained primitive and stagnant in this area until the 1960s when hydraulically powered and controlled pumps were first developed and mounted on a truck for mobile service. From here, techniques improved continually till now when pumping of concrete is considered even for small jobs. In recent years, concrete pumping has reached new heights. The builders for the Jin Mao Building in Shanghai, China, boast of pumping high strength concrete as high as 1200 ft (366 m). Pumping is limited by the plastic qualities of concrete, the type of pump available and the piping needed to carry the product up to the desired level. For such great heights, a high-pressure unit is needed. Great thought must be given to the properties of concrete and how it will react when pressure is applied in a pipe. All these factors demanded innovations in concrete technology.

5. Improvements in Concrete Technology

Along with advances in the ways that concrete is brought to the site, the types of formwork in which it is cured, and how it is placed at high elevations, its mechanical and chemical properties have made great advances in the past century. Again, many of these were developed and used in the first half of the twentieth century, but are valid for today's applications and further improvements.

Lightweight Concrete: It can be made from a variety of aggregate types. A few of these are scoria, pumice, vermiculite, perlite, herculite and polystyrene beads. Extra-lightweight aggregates, such as: polystyrene beads, perlite and vermiculite are considered low density and can produce concrete weights as low as 50 pounds per cubic foot (800 kg/m^3). Their compressive strength is between 100 and 1,000 psi (0.69-6.90 MPa)--not one that will hold a structural load; however, they have high insulative qualities. Intermediate range structural lightweights include pumice, scoria and herculite. With compressive strengths from 1,000 to 2,500 psi (6.9 to 17.2 MPa), they are considered topping. Structural lightweight concrete has the highest compressive strength of the three categories with a minimum of 2,500 psi (17.2 MPa) up to and sometimes exceeding 6,000 psi (41.4 MPa). Its weight can range from 90 to 120 pounds per cubic foot (1441 to 1922 kg/m^3). Absorption, particle size, shape, and the surface texture of the aggregate affect the properties of lightweight concrete.

Lightweight concrete as a structural material has many uses. This includes multistory building frames, curtain walls, shell roofs, folded plates, precast elements, pipes and tubes, and ocean-going ships, to name only a few. Lightweight concrete is especially appropriate for tall buildings having many floors. The additional cost of this material is often recovered from the reduction in the building's weight and consequent saving in the cost of columns and foundations. The 52-story One Shell Plaza of 1971 in Houston, Texas, is a lightweight structure from top to bottom and is still the tallest lightweight building in the world.

High Strength Concrete (HSC): HSC is also known as micro silica concrete or condensed silica fume concrete (CSF). Silica fume is a byproduct of the electric arc furnace production of silicon and ferro-silicon alloys. Its first structural use was in Norway in 1971. In addition to CSF, this material also contains Portland cement, water, crushed gravel of granite or limestone, fine sand and superplasticizers. All of these are combined to create a product that has strength greater than 5,000 psi (34.5 MPa) and even up to 20,000 psi (138 MPa). When CSF is mixed with water, a chemical reaction occurs creating crystals which physically fill any voids in the concrete containing pore water; thus, creating both a water-resistant and a high-strength material. HSC is much more brittle than the ordinary concrete and must be mixed and placed with care.

Even with the precautions for handling, this type of material is finding more and more uses in the construction industry. The current trend for HSC is to pump it to soaring heights. New equipment has been developed to keep the materials from segregating thus retaining its strength. HSC is used for high-rise apartments and skyscrapers like those already built or being built in Malaysia, China and the United States. Its appeal for this type of building is that with higher strengths, members can be made smaller. The sizes of columns using HSC and reinforcing steel in tall buildings are greatly reduced and consequently the usable floor space is increased yielding higher revenues.

High Performance Concrete (HPC): Use of HPC truly began in 1927 when engineers building a tunnel through the Rocky Mountains near Denver needed a quick way of supporting the loads on the tunnel. At that time HPC was in the research stages and was not yet ready to enter the market. The engineers prevailed upon scientists to allow its use. Eventually, the tunnel was built using this material. Why were the builders so interested in HPC? The answer lies in its ability to reach an adequate maturity in 24 hours rather than 7 days for regular concrete. In this way and others to be described in the following, HPC is very different from conventional reinforced concrete, even that which contains admixtures.

The definition of HPC encompasses more than just high-early performance. It is a mixture whose properties include increased strength and better performances in the areas of durability, ductility, density, mixture stability and chemical resistance, to name only a few. These will change depending on the type of admixture combined with cement, aggregates and water for the final product. Building industry professionals are interested in increasing productivity by decreasing the amount of time for concrete to reach its strength and the amount of material required to carry the loads of a structure as well as have improved stability and toughness.

From the evidence presented in the literature, HPC is very flexible with applications to many classifications of construction. It is well known that time, money and labor costs together is a matter of great concern in the building industry. HPC, with its low water/cement ratio, can develop strength of 3,500 to 6,000 psi (24.1 to 41.4 MPa) within 24 hours of placing. This performance speeds the time for project completion and may reduce cost with the reduction of waiting time and more reuse periods for formwork. Higher strengths that can be achieved by HPC also add a few other beneficial effects to the structure. These features of HPC make it appropriate for applications to high-rise buildings.

6. Advances in Structural Systems

The issues involved with structural design and technology are ones of both natural and human implications. A structure must be designed to carry gravity, wind, equipment and snow; resist high or low temperatures and vibrations; protect against explosions; and absorb noises. Adding to this the human factor means considering rentable spaces, owner needs, aesthetics, cost, safety and comfort. Although one set is not mutually exclusive of the other, careful planning and consideration are essential in an attempt to satisfy and integrate both.

Over the history of tall building structures, the changes in technology have been tremendous. Part of this comes from the daily strategies of human living. In the early years of skyscrapers, urban centers included mostly structures with a storefront next to the street, offices in the stories immediately above, and, finally in the upper levels, apartments for city dwellers. These types of buildings were difficult to arrange to take total advantage of structural and mechanical systems. Offices needed large open spaces with large loads from mechanical and electrical systems. The living quarters, with their more intimate spaces, needed closer column spacing, and had fewer vents and wires required to meet needs of comfort. Shallow floor-to-floor heights in the apartment areas were possible since they could be accommodated by a flat plate design. Offices needed grid or pan systems covered by drop ceilings to allow HVAC and electrical systems to be delivered to desired locations within each square. As the automobile became a transportation reality, people moved to the suburban areas and commuted to the city for work. This eliminated most mixed-use issues and allowed new forms of tall buildings, which could accommodate wider column spacing desired by businessmen [5]. In recent years, the trend is returning to mixed-uses as limited natural resources, the expense, time and stresses of commuting draw people back into the city center. Hence, architects and engineers are returning to the challenges of structural design to accommodate people's total daily life. In addition to the past needs of storefronts, offices and apartments, parking is a major consideration in any new structure within the city.

Considering structure alone, there are two main categories for high-rise buildings--structures that resist gravity and lateral loads and those that carry primarily gravity loads. Since skyscrapers have the largest needs for resisting high magnitudes of wind, the lateral load resisting system becomes the most important.

When reinforced concrete was first introduced as a building material, there were limitations on the heights that those buildings could reach. Structural engineers have gradually learned more about the properties of concrete and the structural systems. Fazlur Khan revolutionized the design of tall buildings in both steel and concrete when he proposed his well-known system charts for tall buildings [6,7]. The concrete systems that are suitable for different ranges of number of stories are shown in Fig.1. Shear walls, first used in 1940, may be described as vertical, cantilevered beams, which resist lateral wind and seismic loads acting on a building transmitted to them by the floor diaphragms. Reinforced concrete's ability to dampen vibration and provide mass to a building makes it a good choice of materials. These elements are a variety of shapes such as, circular, curvilinear, oval, box-like, triangular or rectilinear. Many times, a shear wall exists as a core-wall holding internal services like elevators, janitor's closets, stairwells and storage areas. Sometimes they serve external functions as a diagonal bracing system. When carefully planned, these walls may be used as partitions in a structure serving as both a gravity- and a lateral-load bearing system. Concrete's quality of sound absorption makes it suitable for use in hotels and apartment buildings to reduce the transfer of noises from unit to unit.

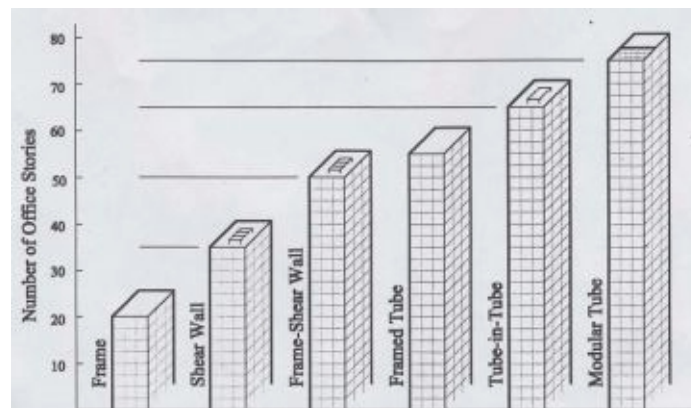


Fig. 1 - Concrete systems that are suitable for different ranges of number of stories

Moment-resisting frames are structures having the traditional beam-column framing. They carry the gravity loads that are imposed on the floor system. The floors also function as horizontal diaphragm elements that transfer lateral forces to the girders and columns. In addition, the girders resist high moments and shears at the ends of their lengths, which are, in turn, transferred to the column system. As a result, columns and beams can become quite large.

A combined system called shear wall-frame interaction system first seriously studied by Fazlur Khan [8] was a milestone in the development of taller concrete buildings. In this system, a central core or dispersed shear walls interact with the remaining beam-column or slab-column framing in the building via rigid floor diaphragms.

A framed tube structure is a new addition to the structural systems. Khan is generally credited with its invention in the 1960s. It is defined as [9]:

"a three dimensional space structure composed of three, four, or possibly more frames, braced frames, or shear walls, joined at or near their edges to form a vertical tube-like structural system capable of resisting lateral forces in any direction by cantilevering from the foundation."

The tubular structure operates as an inherently stiffened three-dimensional framework where the entire building works to resist overturning moments. Tubes can encompass shear walls, columns and beams attempting to make them act as one unit. The main feature of a tube is closely spaced exterior columns connected by deep spandrels that form a spatial skeleton and

are advantageous for resisting lateral loads in a three-dimensional structural space. Window openings usually cover about 50% of exterior wall surface. Larger openings such as retail store and garage entries are accommodated by large transfer girders, albeit disrupting the tubular behavior of the structure locally at that location. The tubular concept is both structurally and architecturally applicable to concrete buildings as is evident from the DeWitt-Chestnut Apartment building (Fig. 2) in Chicago completed in 1965, the first known building engineered as a tube by Khan.



Fig. 2 - DeWitt-Chestnut Apartment building in Chicago



Fig. 3 - The Ontrie Center in Chicago

Several configurations of tubes exist: framed, braced, solid core-wall tubes, tube-in-tube and bundled tubes. The framed or boxed tube is the one most likely associated with the initial definition given above. The DeWitt-Chestnut Apartment building in Chicago is a framed tube. A braced tube is three dimensionally braced or a trussed system. Its unique feature is that members have axial but little or no flexural deformation. The Ontrie Center (Fig.3) in Chicago is an example of such a system in concrete. The John Hancock Center in Chicago, on the other hand, is a remarkable example of this system in steel. Tubular core walls could either carry full lateral load or they may interact with frames. The Brunswick Building (Fig. 4) in Chicago is an example where the core walls interact with the exterior frame comprising closely spaced columns. This gives the building a tube-in-tube appearance although it was designed using the shear wall-frame interaction principle. Tube-in-tube is a system with framed tube, an external and internal shear wall core, which act together in resisting the lateral resisting loads. One Shell Plaza (Fig. 5) in Houston is a tube-in-tube building. Bundled tubes are used in very large structures as a way of decreasing the surface area for wind resistance and creating intimate spaces for apartment rentals. Multiple tubes share internal and adjoining columns depending on their adjacencies. One Peachtree Center in Atlanta is an example of a concrete bundled tube design. Similarly, the One Magnificent Mile building (Fig. 6) in Chicago is another example. The Sears Tower is one of steel but probably the most well known in this category of tubular configuration. Details of these and other concrete tall buildings designed by Khan can be seen in Ali [10].



Fig. 4 - The Brunswick Building in Chicago



Fig. 5 - One Shell Plaza in Houston



Fig. 6 - One Magnificent Mile building in Chicago

Choosing a structural system is very complex in today's market. In the years of the Ingalls Building, one system of post-and-beam construction existed. Concrete's formwork was complex but putting the building together was not as complex as today's systems. Developments in the world of concrete since 1960 have been mostly in new systems such as the tubes and composite construction. The challenge for engineers and architects today is to make all the systems work together to their maximum capacity and create a habitable environment for the people within the built structure.

7. Trends in Tall buildings

The first reinforced concrete high-rise, the Ingalls Building, was discussed early in this paper. It was a post-and-beam system standing 15 stories. In the design of the Ingalls Building, standing at 210 ft. (64 m), every major development that had been made by then was taken into consideration. The building utilized a heavy monolithic beam-column framing system. The floor slabs contained two-way reinforcing systems. The beams were reinforced with bent bars near the supports. Hoops and continuous helixes were employed in the columns to tie the vertical reinforcement together. Ransome's square, cold-twisted reinforcing bar was used for the steel throughout the entire building for horizontal as well as vertical reinforcement. Since the construction of the Ingalls Building, rarely has any concrete building has exceeded the 20-story high mark until about 1960. Many tall concrete buildings have been built all over the world since then. Only a few such representative buildings are discussed below.

The Marina City Twin Towers were built in 1962 in the center of an industrial park. Architect Bertrand Goldberg knew that whoever lived there would need 24-hour services, entertainment, parking and offices all in one structure. Marina City contains a movie theater, bowling alley, shops, offices, restaurants, meeting rooms, gym, skating rink, parking for cars and boats and, finally, apartments. Originally marketed to single adults and couples without children, the apartment complex was a success. The Towers were two of the first new mixed-use structures in downtown Chicago and were the tallest reinforced concrete buildings in the world for that year at 588 feet (179 m). Goldberg's plan in building a circular structure, which was very innovative at the time, was based on efficiency of HVAC systems and to reduce the service core of the structure. Another innovation was the 20-story parking garage directly below the 900 units of apartments. He introduced a circular core wall in hopes that it would take the entire

lateral load from cantilevering floors. This was actually modified with two rows of columns so that the depth of the cantilever and beams between "petals" could be reduced. Even with these modifications, the circular core area carries 70% of the total lateral loads. The core, which acts as a circular concrete shear wall, was carefully designed with staggered openings and by minimizing their size in an effort to maintain enough stiffness.

The Water Tower Place (Fig.7) became yet another high-rise structure of concrete located in the downtown area of Chicago. Designed in 1975 by Loeb, Schlossman, Dart & Hackl, it stands 859 ft.(262 m) in height and serves as another mixed-use building with a mall on the interior, offices and apartments above. The strength of concrete used in this building took a dramatic jump to as high as 9,000 psi (62.1 MPa). This was, however, only one of eleven mixes placed by six cranes. Mix strengths could vary from 3,000 psi (20.7 MPa) for slabs to 9,000 psi (62.1 MPa) for columns. This building demonstrates concrete technology's ability to rival that of steel for tall buildings as it was 2/3 the height of the tallest steel building of the time. The structural system for Water Tower combines "reinforced concrete peripheral framed tube, interior steel columns, and a steel slab system with a composite concrete topping."



Fig. 7 - The Water Tower Place

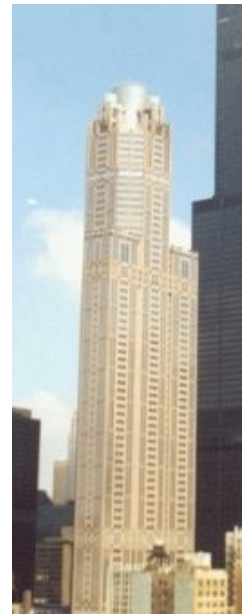


Fig. 8 - 311 South Wacker Drive

One Magnificent Mile building in Chicago completed in 1983 was designed by SOM and is one of the last buildings engineered by Khan. One Magnificent Mile was designed with the same concepts that made the Sears Tower possible. The bundled tube system had already proven to be successful when executed in steel, as in the Sears Tower. The designers at Skidmore, Owings and Merrill decided to translate the bundled tube system into reinforced concrete. The structural system of One Magnificent Mile consists of three hexagonal tubes bundled together (Fig.6). The tied tubes give the building added stiffness. As in the Sears Tower, the tubes terminate at different heights, as the gravity loads decrease.

The Onterie Center of 1985 in Chicago, another SOM building, is generally considered as the "final work" of Fazlur Khan. The structural system for Onterie Center utilizes a trussed tube system in concrete. Once again, SOM successfully translated a structural system originally intended for Hancock, a steel tower, into reinforced concrete. The result is a concrete tube structure that has visible diagonal stiffening braces on the exterior (Fig.3). Although the diagonal bracing of the John Hancock Center was comprised of continuous diagonal steel

members, that approach was not strictly possible in concrete. Instead, the diagonal bracing is achieved by blocking out the windows along the facades by filling them in with concrete.

311 South Wacker Drive of 1990 is a supertall reinforced concrete building in Chicago (Fig. 8). It stands at 969 feet (295 m) with 12,000 psi (82.7 MPa) as its highest concrete strength. The structural system is a modified tube with a reinforced concrete peripheral frame, interior steel columns, and a composite steel and concrete slab. 311 is known to be a good example of shear wall-frame interaction systems. The building is engineered in such a way that the relative stiffnesses of both internal and external elements remain the same for the entire height of the building. Two strengths of concrete were used, 10,000 and 12,000 psi (68.9 and 82.7 MPa). A self-climbing pump with a separate, mounted, placing boom pumped concrete to the top of the structure. Post-tensioned floor slabs reduced the amount of steel consumption while that for concrete was reduced with thinner elements due to the material's high strength. Two sets of flying forms were cycled every five days through the structure.

One Peachtree Center, built in 1991 in Atlanta, Georgia, is a 62-story, 842 ft.(257 m) tall, bundled-tube design with three strengths of concrete used in its columns and shear walls-- 8,500, 10,000 and 12,000 psi (58.6, 68.9 and 82.7 MPa). Designers used technology developed in the 1960s and 1970s by Material Service Corporation in Chicago. Architectural requirements dictated a column-free interior and thus a 50-ft (15.2 m) floor span was accomplished with HSC and post-tensioned steel bars. Silica fume and granite aggregates were used to achieve the necessary strengths. Of special note for the owner of the building, each floor has about 36 rentable corner offices. This building is remarkable because of its design allowing multiple desired spaces for renters, the structural design and its desired use of Chicago style high-strength concrete.



Fig. 9 - Petronas Towers



Fig. 10 - The Jin Mao building

Two more recent buildings constructed around the turn of the 20th century where concrete has been primarily used as the structural material in conjunction with steel are the Petronas Towers (Fig. 9) in Kuala Lumpur, Malaysia (currently the tallest building in the world) and the Jin Mao building (Fig.10) in Shanghai, China. These are good examples to show that concrete has greatly advanced as a material in a century since the days of Ingalls Building construction. The

structural frames for the 1,483-ft.(452 m) tall Petronas Towers use columns, core and ring beams of HSC, and floor beams and decking of steel to provide cost-effectiveness, fast construction and future adaptation to the internal and external environment. The core and frame together provides adequate lateral stiffness for such a tall building. The recently built 1,380-ft. (421 m) high Jin Mao building of 1999 is a mixed system that has a number of steel outrigger trusses tying the building's concrete core to its exterior composite mega-columns.

8. Summary and Conclusions

The research and knowledge in concrete gained in the first half of the twentieth century benefit technologies today. This paper has provided a broad overview of different historic developments for concrete high-rise buildings. To summarize, the first users of concrete date before 1200 BC and include societies like the Phoenicians, Minoans, and Egyptians, to name only a few. The late 1700s and early 1800s found a renewed discovery of and interest in reinforced concrete as a building structure. Americans and Europeans used it in large warehouses, factory buildings, apartment buildings and homes. In 1898, François Hennebique was credited as the "father of reinforced concrete" with his first system of using straight round bars with heavy metal stirrups clipped to each. In 1884, E. L. Ransome patented the system of twisting square steel bars to increase strength and adhesion to concrete. In 1903, A. O. Elzner completed the first reinforced concrete skyscraper using Ransome's twisted steel bars. Throughout the first fifty years of the 20th century, research and development grew at a heightened pace. New delivery systems, changes in formwork, high-strength concrete and other admixtures were invented which improved concrete's strength and workability. Structural systems which go beyond the traditional post-and-beam construction of the Ingalls Building and the introduction of high-strength concrete mixes have together allowed reinforced concrete skyscrapers to grow to heights of the Petronas Towers and the Jin Mao Building never dreamed of in Elzner's and Ransome's day.

Little more than a century ago, reinforced concrete was invented. In that short period of time, reinforced concrete has gone from being a very limited material to one of the most versatile building materials available today. The first reinforced concrete buildings were heavy and massive. Valuable floor space was taken up by the massive concrete structural systems. Today, due to our increased knowledge and improved technology, reinforced concrete buildings can be tall, graceful and elegant. Due, in part, to the use of shear walls, innovative structural systems and ultimate strength design, very little usable floor space is occupied by the structure. HSC and lightweight structural concrete allow us to use smaller member sizes and less steel reinforcement.

Because of the rapid developments of concrete construction and technology, with every passing year the use of concrete for tall buildings is becoming a constant reality. The moldability of concrete is a major factor in creating exciting building forms with elegant aesthetic expression. Khan [11] predicted in as early as 1972 that concrete is the material of the future for tall buildings. A recently completed 66-story Plaza 66 office tower in Shanghai is an all-concrete building. The building was designed for typhoon winds. Joseph Colaco had conducted a study showing the structural feasibility of a mile-high skyscraper – one proposed by Frank Lloyd Wright for Chicago in the 1950s -- with currently available technology [12]. He selected concrete as its structural material because it is a naturally fireproof material and monolithic concrete can absorb thermal movements, shrinkage and creep, and foundation movements. Also, the structure is inherently stiff and has a great deal of redundancy. Compared to steel, concrete tall buildings have larger masses and damping ratios that help in minimizing motion perception. A heavier concrete structure also provides better stability against overturning caused by lateral loads. Colaco further demonstrated that either an all-concrete or a composite

structural system for skyscrapers is also cost-effective. New structural systems including the composite ones that are popular now have allowed concrete high-rises to reach new heights during the last four decades. The floor erection cycle time for concrete high-rises is now almost comparable with that of steel buildings. Although steel will continue to be the structural material of choice for many tall buildings for its strength and ductility, we may expect to see more and more concrete and composite high-rise structures shaping the skylines of major cities of the world in the forthcoming years.

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