



# TRUTH IN TALL BUILDINGS

A Tour Guide of Select Buildings in  
New York City  
Chicago  
Houston

CEE463: A Social and Multi-dimensional Exploration of Structures

Fall 2010

Cover image from [http://www.som.com/content.cfm/john\\_hancock\\_center](http://www.som.com/content.cfm/john_hancock_center)



a “clear understanding of structural behavior and the resulting forms... [helps] architects and engineers to design buildings in which the aesthetic quality of structure and technology can merge with the social and architectural values to create buildings that will eloquently speak of our time.”

Fazlur Khan

“Structural Aesthetics in Architecture and Its Social and Technological Relevance.”, In Eleventh Congress, Final Report (Vienna 1980), by IABSE. Zurich: IABSE, 1980.

photograph: Fazlur Khan(left) and Bruce Graham (right), *Princeton University Maillart Archive*



Yasmin Sabina Khan Byron (Fazlur Khan's daughter), center, with our class – September 2010

# CEE 463: A Social and Multi-dimensional Exploration of Structures

Princeton University  
Department of Civil and Environmental Engineering  
Fall 2010

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## TABLE OF CONTENTS

	Preface .....	8
<b>PART 1 – NEW YORK CITY</b>	780 Third Avenue .....	12
	Citicorp .....	18
	Hearst Tower .....	26
	World Trade Center .....	32
	Times Square Tower .....	38
	New York Times Tower .....	44
	Bank of America Tower .....	50
<b>PART 2 – CHICAGO</b>	Marina City .....	56
	Inland Steel .....	60
	Brunswick Building .....	64
	Sears (Willis) Tower .....	70
	John Hancock Center .....	76
	Chestnut-DeWitt Apartments .....	82
	One Magnificent Mile .....	86
	Onterie .....	90
<b>PART 3 – HOUSTON</b>	One Shell Plaza .....	96
	Two Shell Plaza (Walker Building) .....	102

## Preface

The best structures of our society (e.g bridges, buildings, towers, vaults) come to existence not only by selecting proper forms and making engineering calculations, but also by (1) knowing and working with the related economic and political circumstances, (2) developing an appropriate and economical construction process, which is intimately connected to the design, and (3) considering the environmental impacts of such a construction (i.e., durability and other sustainability measures). Our class, CEE463 “A Social and Multi-dimensional Exploration of Structures” examines these aspects of structural engineering design and it teaches a sense of scale, to consider constructability aspects of design, to reflect on aesthetics, and to learn to communicate ideas to the general public.

This booklet summarizes some social and engineering facts about the structures to be visited by the class. These visits provide the student with a full scale three-dimensional experience, which give one a sense of scale that is not possible to fully experience through photographs. One also becomes intimately connected with the construction process. The connections are observed up close and the details of bolts and welds that comprise the simple or sometimes complex part of the steel design is seen. For a concrete structure the imprint of the form boards that reminds one that formwork (what molds the concrete) needs to be built before the concrete can be poured. During a site visit one can also observe the durability of the structure over time, which is a measure of sustainability.

Before the visit, the students had begun their study of an assigned structure through structural analysis, a study of the social context, and the making of a model of the structure. During these visits,



the students will study carefully the structure, its details, and its surroundings. In some cases there will be an opportunity to talk to the engineers and owners involved with the project. By observing these structures 'in action', they can measure the success or failure to meet the structure's functionality and one understands the structure's relationship to the community.

For the Fall 2010 academic semester, the theme of the class is based on the tall building designs of Fazlur Khan while working at Skidmore Owings and Merrill (SOM), Chicago. Most of the structures that we will visit are Khan's designs, although we will also visit some other tall buildings in the cities where the "structure" is expressed, thus revealing "Truth in Structure". The idea of expressing structure in architecture is very old. The medieval Gothic light cathedrals (like Chartres 12th century AD, France) seemed to be pulled out of stone -a rather heavy material- and expressed only what was structurally needed. Similarly in Japanese temples Kyoto (like Kiyomizu-dera 10th century AD, Japan) most sublime emotions are expressed through the use of structure. This idea of structural architecture appealed to the Chicago School at the end of the 19th century. The Monadnock Building (Burnham and Root, 1889) is an impressive load bearing brick structure and the Carson, Pirie, Scott and Company Building (Sullivan,1899) uses a steel frame to articulate its architectural intention.

These successful historic tall buildings show that for their design the line between the architect and the engineer becomes blurred and results in a relationship between equal designers. The Chicago based SOM team Khan and Bruce Graham, an exemplary engineer – architect tandem first known for the Inland Steel Building (Chicago 1958), revolutionized the approach to tall building design in the 1960's and 1970's and moved away from the traditional rigid frame systems. The shear wall/frame

interaction system largely increased the stiffness of tall buildings against lateral (wind) loads. This system performed efficiently in the new tubular concrete structures such as De Witt-Chestnut (1965 Chicago), Brunswick (1965, Chicago), and One and Two Shell Plaza (1971, 1972, Houston). The tubular configurations, highly effective in carrying lateral loads, also became the natural structural form of much taller systems such as the bundled tube Sears (Willis) Tower (1973, Chicago), the steel trussed tube of the John Hancock Center (1970, Chicago), and the concrete trussed tubes of Onterie (1985, Chicago) and 780 3rd Avenue (1983, NYC). Structural expression as a basis for architecture has not always been desired and is clothed over with some tall buildings (e.g., Citicorp, 1977, NYC).

David Billington, Professor Emeritus of Princeton University, has taught us that structure can be art when it is efficient, economical, and elegant; but to make this latter assessment in tall buildings, the *structure* must be expressed. That is not to say that if the structure is concealed behind façade, the tall building cannot be a work of art; but in this case it would be considered architectural art, not structural art. We are grateful to Professor Billington for his consultation and participation in this class as well as Yasmin Khan (Fazlur Khan's daughter), Bill Baker (partner SOM), Leslie Robertson (founder Leslie E. Robertson Associates), Guy Nordenson (founder Guy Nordenson Associates), and Esther da Costa Meyer (Professor of Art and Archaeology, Princeton University). Finally, we are thankful to Princeton University for recognizing the value of such a course as part of the structural engineering education and thus funding the travel expenses related to our structures tour as well as other financial support for the course development.

Maria E. Moreyra Garlock & Sigrid Adriaenssens



## ***PART 1***

### ***NEW YORK CITY***

780 Third Avenue .....	12
Citicorp .....	18
Hearst Tower .....	26
World Trade Center.....	32
Times Square Tower.....	38
New York Times Tower.....	44
Bank of America Tower .....	50

Image left: 780 3<sup>rd</sup> Ave, photo from  
<http://www.780third.com/AboutJRTRealty/tabid/94/Default.aspx>



**Figure 1.a.** The completed 780 3<sup>rd</sup> Avenue, NY building showing its 8:1:1 slenderness ratio

**Figure 1.b.** 780 3<sup>rd</sup> Avenue, NY under construction with its concrete structure exposed

780 3<sup>rd</sup> Ave.

## 780 3<sup>rd</sup> Avenue

### Quick Facts

**Alt Name:** 780 3<sup>rd</sup> Avenue

**Location:** New York, 780 3rd Avenue

**Engineer:** Rosenwasser-Grossman  
consulting engineers

**Architect:** SOM New York

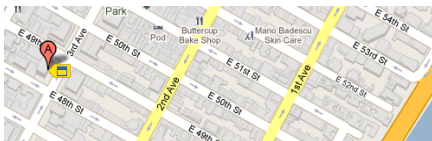
**Start of Construction:** -

**Completion:** 1983

**Height:** 570 ft (174 m)

**Number of Floors:** 50

**Material:** Concrete



### *SOCIAL, POLITICAL and ECONOMIC CONTEXT*

Most office space in the City (Manhattan, New York) is very old. Approximately 45 percent of office space was built before World War II, and only 15 percent of office space was built after 1979. This fact is surprising as the City experienced a huge office space development burst in the 1980s. The construction of the 780 3<sup>rd</sup> Avenue building, shown in Figure 1, is set in this context. In the early 1980s, the US economy started to feel the effect of the 1973 oil crisis and the 1979 energy crisis. Socially, the City was at the heart of the AIDS crisis in the 1980s (Manhattan 2010). A brief, severe recession that started in 1980 and ended in 1982 affected many industries, including steel manufacturing (Early 80's recession 2010). This fact played to the advantage of the development of concrete structural systems for tall buildings in the mid 1980s. One year into the recession, Ronald Reagan, the new President, stated that the economy was in a "slight recession". These political and economic factors created a challenging construction environment: high demand for office space in the City, high financing and construction cost and interrupted economic expansion (Khan 2004). Following this early recession, the City saw a rebirth of Wall Street which greatly improved not only the City's economic health but also its role at the center of the worldwide financial

industry (Manhattan 2010). Besides this financial boost, an expiring zoning bonus in the 1980s prompted developers to finance office space in West Midtown, despite traditional corporate preference for buildings east of Fifth Avenue. The 780 3<sup>rd</sup> Avenue building is one such development.

### **STRUCTURAL SIGNIFICANCE**

After having successfully introduced the steel trussed tube system in the Hancock Center, Kahn was keen on experimenting with this economic and efficient system in concrete. However, in the 1960s and early 1970s developers did not want to accept a concrete version of this highly efficient system for aesthetic and economic reasons. (Khan 2004). The presence of external diagonal members blocking desirable window office space deterred many developers (Bauer 2006). In 1972, in an article in *Progressive Architecture*, Khan writes “Given the right circumstances, this type of system will find its way in the near future” (Khan 1972). The 780 3<sup>rd</sup> Avenue building is the first completed concrete trussed tube.

### **STRUCTURAL SYSTEM**

While Khan was designing the Onterie Tower, the SOM New York Office teamed up with the structural engineer Robert Rosenwasser Associates (now Rosenwasser /

Grossman consulting engineers) for an office development in midtown NY, the 780 3<sup>rd</sup> Avenue building. This team investigated several proposals (including framed tube with shear wall system) for the slender 1:8 width to height ratio tower. The SOM NY architects talked with Khan about the team’s ideas. Khan proposed a concrete trussed tube for the structural system. This system integrates multistory diagonals with columns and spandrels in the exterior frame. The diagonals are more than merely lateral load bracing elements, for they also support gravity loads and distribute them to the vertical columns of each frame. The X-form diagonals bring together the four frames into one tube through their connection at the corners. This arrangement minimises shear lag and results in an economic system. This system had been pioneered in steel in the John Hancock Center (Chicago) and was, at the time of preliminary design, also being studied as a concrete option for the Onterie Centre, Chicago, which has coincidentally similar proportions. Casting concrete diagonals in situ seemed an inappropriate solution. Instead of slender diagonals cast throughout the window apertures, the openings were filled in with infill panels in a stepped pattern as shown in figure 2. The Rosenwasser engineers were convinced of this new system’s efficiency.

## 780 3<sup>rd</sup> Ave.



**Figure 2.** The X form diagonals are formed by infill panels in a stepped pattern. The Plaza with its 22 trees is both elegant and simple in design.

Figure 3 shows that the concrete structure is (unlike the Onterie Center in Chicago) clad in a rose Finnish Balmoral Granite . The 780 3<sup>rd</sup> Avenue building was completed before the Onterie Building in Chicago. Only two decades later, the next major trussed tube tall building, the Times Square Tower, appeared in New York.



**Figure 3.** The concrete structure is – unlike the Onterie Centre - clad in rose Granite.

### **SPECIAL NOTES**

This tall building is set back from 3rd Avenue, 48th Street and 49th Street to accommodate a large urban plaza with twenty-two trees, shown in Figure 2. The entire plaza is constructed with red Hastings brick and rose Granite. The plaza appears simple and elegant in design. The building offers an inviting entrance to the user (see Figure 4).



**Figure 4.** The Plaza in front of the 780 3<sup>rd</sup> Avenue focuses the attention of the pedestrian to the entrance of the building.

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780 3<sup>rd</sup> Ave.

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**Figure 3:**

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9/](http://www.flickr.com/photos/leokoolhoven/400128419/)(accessed 10/19/2010)

**Figure 4:**

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9/](http://www.flickr.com/photos/leokoolhoven/400128419/)(accessed 10/19/2010)

## Citicorp Center



**Figure 2 a.** *The Citicorp building sits 130 feet in the air and is supported by a central concrete core and four perimeter columns, which are positioned at the center of each building face.*

**Figure 1.b.** *The Citicorp building with its 45-degree slanted roof, as seen from Queens*

## Citicorp Center

### Quick Facts

**Alt Name:** Citigroup Center, 601

Lexington Avenue

**Location:** New York, Lexington Avenue  
between 53rd and 54th Streets

**Engineer:** Le Messurier Consultants

**Architect:** Stubbins Associates, Emery  
Roth & Sons

**Start of Construction:** 1974

**Completion:** 1977

**Height:** 915 ft (279m)

**Number of Floors:** 59

**Material:** Steel



### *SOCIAL, POLITICAL and ECONOMIC CONTEXT*

**THE CITY:** In 1970, New York's population was at almost 7.9 million, which was the same as 20 years earlier. The City had also gained a reputation as a crime city. 1977, the year of the Citicorp Center completion, is remembered for two catastrophes: the blackout, resulting in city-wide looting, and the Son of Sam serial murders. The construction of the World Trade Center, in the beginning of the 1970s initiated further office space development in Lower Manhattan. The oil crisis prompted developers and designers to construct energy efficient buildings.

**THE CONGREGATION:** In 1862, a group of German immigrants founded the Lutheran congregation of St-Peters, based in Manhattan. At the turn of the century, the congregation moved into a new gothic church at the corner of 54<sup>th</sup> and Lexington Avenue. In the 1960s, congregations were fleeing from the city to the suburbs. The people of St-Peters decided "to affirm human life amidst the skyscrapers and develop a ministry that would serve more than just a Sunday congregation." They wanted to use their valuable real estate as a resource for their Ministry (New York Architecture Images 2010). In 1970, they sold their building and

## *Citicorp Center*

formed a condominium with Citicorp. "One of the most successful urban schemes in New York in the 1970s, 'Citicorp' brought new life to a downtown Manhattan city block that had been largely filled by a popular but far too big Lutheran Church." (Sharp D. 2006).

### **STRUCTURAL SIGNIFICANCE**

The trussed tube concept arrived first in New York with the Citicorp Center in 1977. This building is the first tall building in the US to have a tuned mass damper to counteract swaying motions due to the wind and reduce the building's motion by as much as 50% (Greer 1982). The damper is located in the mechanical space at the top of the building.

### **STRUCTURAL SYSTEM**

From day one, the Citicorp Center was an engineering challenge: the northwest corner of the proposed building site was occupied by St. Peter's Lutheran Church. The church allowed Citicorp to construct a 59-story tall building on their site under one condition: a new church should be built on the same corner, with no connection to the Citicorp building and no structure passing through it. As a result, the Citicorp building sits

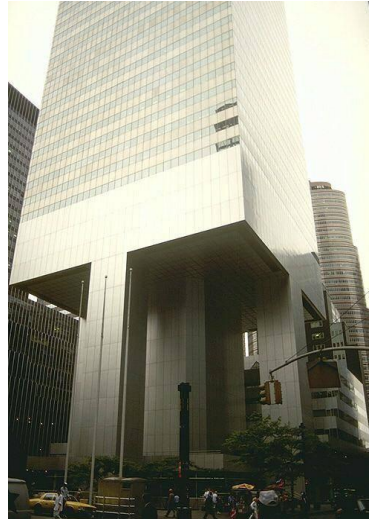
130 feet in the air and is supported on a central concrete core and four perimeter columns, which are positioned at the center of each building face (see Figure 1a and Figure 2). This design allows the Citicorp Center to cantilever 72 feet over the new church, shown in Figure 2. To resist wind loads, the engineer, LeMessurier, designed 8-story tall chevron braces on the exterior facades (see Figure 3). These braces also collect gravity loads and guide them towards a stiffer central column, which extends over the entire height on each face of the building. This system reduces the gravity loads that need to be transferred at the bottom of the perimeter columns. In the John Hancock Center, (Chicago) Khan used the diagonals to take lateral loads but also to distribute the gravity loads equally over the perimeter columns (Bauer 2006). LeMessurier uses the chevron bracing to concentrate the gravity loads towards single points of support, the central columns in the building faces. The expression of this innovative structural system was not on the agenda of the architect Hugh Stibbins. A curtain wall that articulates horizontal bands obscures the braces. About this disguise of the structure, Le Mesurrier said: "I would have liked my stuff to be expressed on the outside of the building, but Stibbins wouldn't have it. In the end I told myself I didn't give a damn –the structure was there, it'd be seen by God." The towering office building stands out

## *Citicorp Center*

because of its diagonal roofline, (shown in figure 1b) slanted for a solar collector but not bearing one. (The orientation of the slant is such that the solar panels would not directly face the sun.)



**Figure 3.** *The new Lutheran St-Peters church sits untouched underneath the Citicorp Building.*



**Figure 2.** *The Citicorp building sits on a central core and four columns in the center of the building faces. The structure is hidden behind horizontal bands of cladding.*

## SPECIAL NOTES

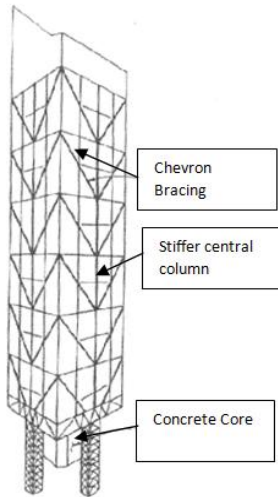


Figure 4. Chevron Bracing in the Citicorp Center

In 1978, prompted by a Princeton engineering student, Le Messurier discovered a crucial flaw in the building's design: the bolted joints were too weak to withstand 70 mph cross winds. With hurricane season coming closer, Le Messurier convinced the client to hire a crew of welders to repair the weak bolted connections. For the next three months, a construction crew working at night, out of sight and out of knowledge of the public, welded steel plates over each of the 200 bolted connections. This engineering crisis was kept hidden from the public for almost 20 years. In 1995, the *New Yorker* (Morgenstern 1995) published an article that criticized Le Messurier for insufficient oversights, for misleading the public about the extent of the danger during the rectification procedure, and for keeping the engineering insights from his peers for two decades. (see Figure 4) Engineering textbooks however have praised Le Messurier's undertaking of alerting Citicorp to the problem in his own design as an example of ethical behavior. The 30-page document outlining the structural mistakes in the Citicorp building was called "Project SERENE." The acronym stands for "Special Engineering Review of Events Nobody Envisioned."

## Citicorp Center

As a result of the events of 9/11 in 2002, one of the columns, the one facing 53<sup>rd</sup> Street, was clad with blast resistant sheets of steel and copper and steel bracing to protect the building from possible terrorist attacks. O'Driscoll 2002).

**Figure 5.** *The article in the New Yorker discussing the Citicorp crisis read "To avert disaster, Le Messurier knew that he would have to blow the whistle quickly---on himself." Notice the bolt, the chevron bracing, the Lutheran church, the approaching hurricane Ella.*



Adriaenssens

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**Figure 3:** New York Architecture Images (2010)

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Figure 3. Original Hearst Building (1928)

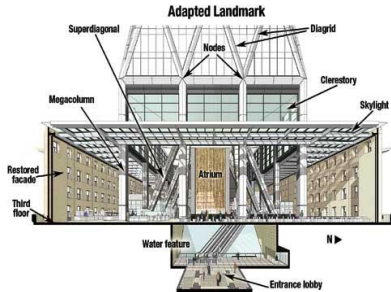


Figure 2. Hearst Tower cross-section



Figure 3. Hearst Tower

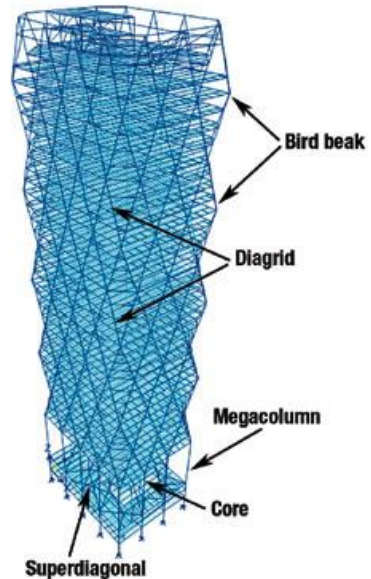


**STRUCTURAL SYSTEM**

The structural system is called a “diagrid”, where diagonals on the perimeter of the building act as a “tube” to carry the wind and gravity loads (Fig. 3, 4). The wide flange diagonal columns and 10-in. plate connection nodes are field assembled in 4-story A-frames, with the intermediate beams preinstalled to the columns (Fig 5). The “legs” of the A’s are 57-ft-long and the nodes are 40 ft. apart.

The diagrid transfers loads at the tenth floor into 12, perimeter megacolumns that are unbraced for 85 ft and continue to foundations. Eight, 90-ft-long superdiagonals slope in from third-floor megacolumn nodes to column lines at the tenth floor. Superdiagonals carry load and also stabilize the core wall (Fig. 2). This mega-column/mega-brace system consists of 44-in. square plate box weldments.

Only the framing at the perimeter of the old building remained to stabilize the existing landmark façade, and that was upgraded to meet current wind and seismic criteria. The new building has its own foundation and new columns.



**Figure 4.** Hearst Tower structural parts.

## Hearst Tower



**Figure 5.** Hearst Tower diagrid under construction.

Compared to conventional steel construction (steel beam-column framing) the diagrid structure uses reportedly about 20% less structural steel (9,500 metric tons ,10,480 tons). However, the idea that the diagrid is an optimum system has not gone unchallenged.

Fazlur Khan wrote about this system [Khan, “The John Hancock Center”, *Civil Engineering Magazine*, ASCE,

1967] calling it a “diagonal tube” indicating that the system is “probably the closest to a rigid tube with the characteristics of a true cantilever.” But the disadvantage to the system is that “Since the optimum system would be one in which the design for vertical loads is at the same time adequate for lateral loads, this system of closely spaced diagonals is questionable because all vertical loads must be increased by a certain factor [owing to the inclination of members].”

### **SPECIAL NOTES**

“Hearst Tower is the first “green” high rise office building completed in New York City, with a number of environmental considerations built into the plan. The floor of the atrium is paved with heat conductive limestone. Polyethylene tubing is embedded under the floor and filled with circulating water for cooling in the summer and heating in the winter. Rain collected on the roof is stored in a tank in the basement for use in the cooling system, to irrigate plants and for the water sculpture in the main lobby. 85% of the building’s structural steel contains recycled material. Overall, the building has been designed to use 26% less energy than the minimum requirements for the city of New York, and earned a gold designation from the United States Green Building Council’s LEED certification program,

becoming New York City's first LEED Gold skyscraper.”  
[wikipedia]

**Figure 5:** Post, Nadine, “Manhattan High-Rise Is Chock Full Of Jarring Juxtapositions”, ENR, October 31, 2005

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**Figure 3:** <http://adaptivereuse.net/page/2/>

**Figure 4:** Post, Nadine, “Manhattan High-Rise Is Chock Full Of Jarring Juxtapositions”, ENR, October 31, 2005



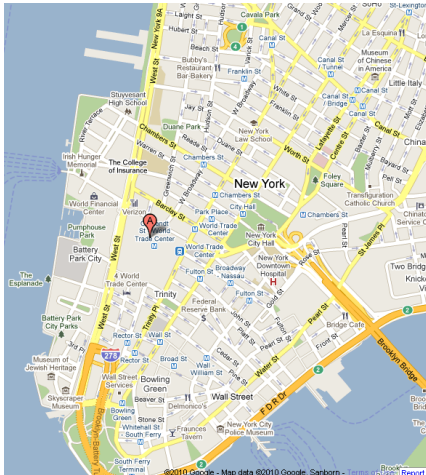


**Figure 4.** *New World Trade Center*



## New World Trade Center

# WORLD TRADE CENTER



## *SOCIAL, POLITICAL and ECONOMIC CONTEXT*

During the late 1940s and 1950s, economic growth in New York City was concentrated in Midtown Manhattan, but not Lower Manhattan. To help stimulate urban renewal, a “World Trade Center” (WTC) in Lower Manhattan was proposed to be established by the Port Authority. The initial suggested site was along the East River. In gaining approval for the project, the Port Authority agreed to take over the Hudson & Manhattan Railroad which became the Port Authority Trans-Hudson (PATH). The Port Authority also decided to move the World Trade Center project to the Hudson Terminal building site on the west side of Lower Manhattan, a more convenient location for New Jersey commuters arriving via PATH.

Following the attacks on September 11, 2001, several years of contract negotiations resulted in the PANYNJ developing 1WTC and Silverstein Properties developing 2WTC, 3WTC, and 4WTC.

## *New World Trade Center*

### Quick Facts: One WTC

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**Alternate Name:** Freedom Tower  
**Location:** New York City  
**Engineer:** WSP Cantor Seinuk  
**Architect:** David Childs, SOM  
**Start of Construction:** 2006  
**Estimated Projected Completion:** 2013  
**Height:** 1776 ft (541 m) (with Antennae)  
**Number of Floors:** 105  
**Material:** Steel



**Fig. 2: 1 WTC**

### Quick Facts: Two WTC

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**Location:** New York City, 200 Greenwich Street  
**Engineer:** WSP Cantor Seinuk  
**Architect:** Foster and Partners  
**Start of Construction:** June 2010  
**Estimated Projected Completion:**  
**Height:** 1270 ft (387 m)  
**Number of Floors:** 79  
**Structure & Material:** central concrete core, steel encased in reinforced concrete, and an external structural steel frame.



**Fig. 3: 2 WTC**

## *New World Trade Center*

### Quick Facts: Three WTC

**Location:** New York City, 175 Greenwich Street

**Engineer:** WSP Cantor Seinuk

**Architect:** Rogers Stirk Harbour + Partners (RSHP),  
formerly Richard Rogers Partnership

**Start of Construction:** July 2010

**Estimated Projected Completion:**

**Height:** 1140 ft (348 m)

**Number of Floors:** 71

**Structure & Material:** central concrete core, steel  
encased in reinforced concrete, and clad in an external  
structural steel frame.



**Fig. 4. 3 WTC**

### Quick Facts: Four WTC

**Location:** New York City, 150 Greenwich Street

**Engineer:** Leslie E. Robertson Associates (LERA)

**Architect:** Maki and Associates

**Start of Construction:** 2008

**Estimated Projected Completion:** 2013

**Height:** 975 ft (297 m)

**Number of Floors:** 64

**Structure & Material:** a reinforced concrete core,  
composite structural steel and reinforced concrete  
columns, and floor system with steel girders and beams.



**Fig. 5. 4 WTC**

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**Figure 5:**

[http://www.wtc.com/media/images/d/34\\_02\\_Tower4\\_Rendering.jpg](http://www.wtc.com/media/images/d/34_02_Tower4_Rendering.jpg)



*Times Square Tower*



**Figure 5.** *Times Square Tower – day and evening view – looking southeast*

## Times Square Tower

# TIMES SQUARE TOWER

### Quick Facts

**Location:** New York City, West 41st St.

**Engineer:** Thornton-Tomasetti

**Architect:** David Childs, SOM

**Start of Construction:** 2002

**Completion:** 2004

**Height:** 724 ft (221 m)

**Number of Floors:** 47

**Material:** Steel



### *SOCIAL, POLITICAL and ECONOMIC CONTEXT*

The Times Square Tower was constructed as part of the 42 St. Development Project, whose goal was to revitalize the 42<sup>nd</sup> St – Times Square neighborhood that, by the late 1970s, had significantly deteriorated both physically and morally (it was “given over to burlesque and prostitution”). In 1992, in order to jump start the street's revitalization, the City and State agencies working together as the 42nd Street Development Corporation Inc., invited a team of architects and designers to provide an interim plan for the theater block of 42nd Street, tied to the development of office buildings at the Times Square end of the block. But plans for the revitalization were stalled by lawsuits and by the deep economic recession of the early 1990s.

In November of 2000 Boston Properties acquired the leasehold to the 7 Times Square Site. Originally, it was planned to be Arthur Andersen's headquarters. The firm signed a lease in October 2000, but then backed out in 2002 after the Enron scandal, which led to the dissolution of Arthur Anderson, one of the largest audit and accountancy companies at the time.

## Times Square Tower

### STRUCTURAL SYSTEM

As part of the 42nd Street Development Project (42 DP), NYC zoning did not control the site; therefore, unlike other tall buildings in New York City, the Tower did not require setbacks, which meant that the entire size of the lot could be used for the whole building height. A floor plan is shown in Fig. 2.

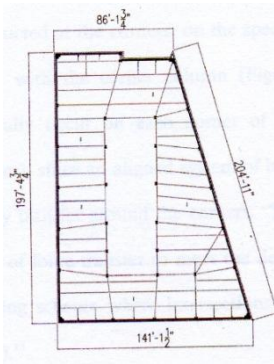


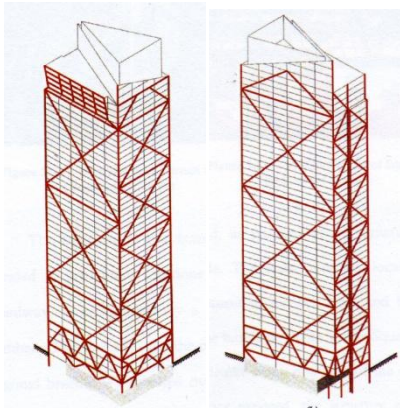
Figure 2. Floor Plan

Other zoning issues meant that the only mechanical floor was placed at the roof, which eliminated an outrigger structural system (that relies on large trusses crossing the space from the core to the perimeter). In order to maximize rentable space on each floor, the core was to be as small as possible, which meant that the perimeter would be mostly relied on for a structural system. “The need to engage the perimeter to create an efficient structural system, the lack of outrigger locations, the need for a minimal core and the elevator core ending at the 5th floor Sky Lobby meant that a braced core was not a viable solution. The only practical solution is an exterior structural system.” [Gottlieb, 2005]

The building was designed to resist lateral loads using a trussed tube. The John Hancock Center also uses a trussed tube, but there is a subtle difference between these two towers. In the John Hancock Center, the diagonals on perpendicular faces intersect at the same location. In the Times Square Tower, the diagonals on perpendicular faces do not intersect. This was done to minimize the obstructed views in the corner offices. While the force transfer is more continuous if the diagonals on the corners meet, a study [Bauer, 2006] has shown that had the diagonals on the two faces met at the corner, the structural effects would not have been too much different.



## Times Square Tower



**Figure 3.** Trussed tube structural system: (left) south-west view, and (right) north-east view.

“The signage zone between the 2nd floor and underside of the 5th floor is used to hide a belt truss. The truss accommodates the removal of every other perimeter

column for a typical column spacing of 60ft (18.3m) at the ground floor. In addition the NE corner column at Broadway and 42nd is removed on the ground floor. This is done by splitting the column at the 5th floor into 2 columns each setting back from the corner along the North and East sides of the building.” [Gottleib, 2005]

“The average steel weight of the building is around 24 pounds per square foot (1.17 kN per square meter). Due to the perimeter lateral system much of this steel is in the outside columns particularly the corner columns which reach a maximum size of 2tons per foot (58.4 kN per meter).” [Gottleib, 2005]

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415495

**Figure 2:** Bauer, 2006

**Figure 3:** Bauer, 2006





**Figure 6 a.** *The newly completed NYT “green” building has a cruciform plan with exposed steel work.*  
**Figure 1 b.** *A ceramic rod screen, extending far above the roof, blocks out direct sunlight and reduces cooling loads*

## New York Times Building

### Quick Facts

**Location:** New York, 620 Eighth Avenue, between 40<sup>th</sup> and 41<sup>st</sup> Street

**Engineer:** Thornton Tomasetti Inc.

**Architect:** Renzo Piano Building Workshop, FXFowle Architects

**Start of Construction:** 2003

**Completion:** 2007

**Height:** roof 748 ft (228m) antenna 1046 ft (319m)

**Number of Floors:** 52

**Material:** Steel



### *SOCIAL, POLITICAL and ECONOMIC CONTEXT*

*The New York Times (NYT)* is a daily newspaper founded and continuously published in New York City since 1851. The NYT is nicknamed "The Gray Lady" and long regarded within the industry as a national "newspaper of record". (New York Times 2010) The Times is owned by The New York Times Company. In 1904, the NYT moved to 42<sup>nd</sup> Street in the Times Square Area, which subsequently was named after the paper. More recently the Times Company had been housed at 229 West 43<sup>rd</sup> Street. The Empire State Development Corporation (ESDC) had obtained the building site through eminent domain (action of the state to seize a citizen's property with monetary compensation but without the owner's consent). The ESDC purchased ten blighted existing buildings in Times Square. Once the new 7400m<sup>2</sup> site was assembled from the different properties, ESDC leased it to the New York Times Company and Forest City Ratner (the developer) for 85.6 million USD for 99 years. This lease is considered to be considerably below the market value. On top of that, the New York Times Company received 26.1 million USD in tax breaks.

## *New York Times Building*

### **STRUCTURAL SIGNIFICANCE**

The expression of the exterior steel work involved a compromise between aesthetics, structural efficiency, fabrication and ease of construction.

### **STRUCTURAL SYSTEM**

The architect Renzo Piano says about this building “Each architecture tells a story, and the story this new building proposes is one of lightness and transparency. The building is about defying gravity. A building that will disappear in the air, that will bring the same magic to the skyline that the neo-Gothic brings.” (New York Times Building 2010) Contributing to this vision is the structural steel exoskeleton that is integrated into the architectural design and a glass and ceramic curtain wall design that admits natural light to the building on all floors. The exposed steel-framed building has a cruciform plan with its structural system as an outrigger. The cantilevered bays have three framing lines: one on each side of the cantilevered bay and one down its centre. The two side framing lines have multiple load paths to allow exposed steel on the exterior (Scarangelo 2008). Load path one: a diagonal rod at each floor ‘hangs’ the outer end of the floor beam from the supporting column (see Figure 2). Second load path:

a continuous vertical member connects the ends of multiple beams together. This vertical member is available in case of fire when one or more diagonal rods go, for the vertical hanger can redistribute the load. Load path 3: the tapered floor beams are moment-connected to the supporting column with sufficient capacity to cantilever, though with excessive deflection. The central framing line uses a Vierendeel system with floor beams moment-connected to both the supporting column and the cantilever tip vertical post.



**Figure 2:** By introducing several load paths in the cantilevered framing lines, the exterior steel can be exposed.

## *New York Times Building*

In order to achieve perimeter transparency, a braced core lateral load resisting system was selected to resist horizontal loads. To further improve the lateral stiffness of the building, this core reaches out to the perimeter columns through outrigger trusses positioned at the mechanical floors.

The east-west direction of the building has a broader wind face and a narrower core dimension: X-braced bays in the perimeters notches (shown in Figure 3) work together with the core to provide lateral stiffness. These external slender X-braces brought their own challenges in terms of fire resistance and pre-tensioning.

Fire resistance: Conventional spray-on and mineral wool fire protection creates unacceptable bulky elements. Fire protection on the rods is avoided through the following approach. Under wind and seismic loads, the perimeter bracing is ignored in the safety and stability analysis. The second check on occupant wind comfort does include the X-bracing in the building stiffness. The X-bracing reduces the building's sway from height/350 to height/450.

Pre-tensioning: the brace should be designed so that no half of the brace ever buckles. However, as the columns of the building shorten, the X-braces experience compression. Pre-tensioning of the X-braces through locknuts during construction specifically compensated for this phenomenon.



**Figure 3.** *The slender X-bracing in the perimeter notches, orientated in the east-west direction, work in tandem with the braced core to resist lateral loads.*

## *New York Times Building*

### **SPECIAL NOTES**

The tower is portrayed as a green building but is not LEED certified. Increased energy efficiency is achieved in the façade through maximizing natural light within the building through a fully glazed curtain wall with low-e glass and blocking out the direct sunlight and reducing cooling loads through a ceramic 5/8 inch rod screen. This screen extends up around the rooftop mechanical zone, with the rods gradually increasing in spacing to make a smooth transition between building and sky. More than 95% of the structural steel was recycled.

In the summer of 2008, three climbers illegally and independently of each other climbed the façade of the NYT building (see Figure 4).



**Figure 4:** Alain Robert illegally climbed the ceramic rod screen intended to increase the energy efficiency of the building. Piano states the building is all about defying gravity.

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*Bank of America Tower*



**Figure 7a.** Bank of America Tower rendering  
**Figure 1b.** Bank of America Tower

## Bank of America Tower

### Quick Facts

**Alt Name:** One Bryant Park

**Location:** New York, 113 West 42<sup>nd</sup> St.

**Engineer:** Severud Associates

**Architect:** Cook + Fox Architects

**Start of Construction:** 2004

**Completion:** 2009

**Height:** 1200 ft (366 m)

**Number of Floors:** 55

**Material:** Composite



### *SOCIAL, POLITICAL and ECONOMIC CONTEXT*

Reigning as one of the largest financial institutions in the United States, Bank of America has played an integral role in the nation's economy for nearly a century. Despite such historic stature, Bank of America has never had a signature headquarters in New York—ironically, the financial hub for national and global markets. The Bank of America Tower, also known as One Bryant Park, now serves as this signature headquarters and houses Bank of America's consumer and commercial banking, investment banking, and investment management for its New York operations.

The vision for One Bryant Park was inspired from New York City's 1853 Crystal Palace (Fig 2). This was the first glass and iron building in the U.S. It was the intent of Cook + Fox Architects to modernize the Crystal Palace into a landmark that was distinguished by its crystalline form, record height, and nationally acclaimed sustainability features. Michael J. Crosbie described in an article of ArchitectureWeek Magazine, "...the building appears like a slender piece of ice, jutting up with an elegantly fractured surface that suggests a crystal emerging from the depths of New York's glacial past."

## *Bank of America Tower*

### **STRUCTURAL SYSTEM**

One Bryant Park is composed of steel frames with a core surrounded by reinforced concrete shear walls. To accommodate the building's unique form, the exterior columns are spaced at 20ft-on-center and begin to slope after the 18<sup>th</sup> floor. These slopes offset the columns which in turn generate additional lateral loading on the structure. To account for this additional load, horizontal trusses were added to the floor framing system in order to properly transfer these loads to the core. This type of bracing is shown in Figure 3.



**Figure 2.** *The Crystal Palace, New York 1853*

### **STRUCTURAL SIGNIFICANCE**

Measured to its pinnacle, One Bryant Park is the second tallest building in New York after the Empire State Building. It is the first building ever to strive for the United States Green Building Council's highest rating of Platinum LEED designation and was the world's first office tower to actually reach this certification. In 2008, it was named the "Best Green Project" by New York Construction Magazine.



**Figure 3.** *Horizontal truss system employed to transfer additional lateral loads to core*

## *Bank of America Tower*

At the owner's request, the elevator shafts and stairways were made more robust by means of encasing a steel frame within the original shear wall core. While design alterations needed to be made based on the sloping façade, this form exposed more of the building to sunlight, reduced the mass, and gave the structure a more slender appeal.

One of the challenges that came about in designing One Bryant Park was accounting for the various live load conditions. These values ranged from office space requirements of 50psf to staging areas of up to 600psf. To account for these considerable differences, the exterior columns vary from typical wide-flange sections at the top to built-up box sections at the base.

### **SPECIAL NOTES**

In order to achieve Platinum LEED certification, there were several sustainability features that were incorporated into the building. To name a few, this structure uses onsite power generated from a 4.6 MW cogeneration plant that produces electricity, incorporates an under floor air system to enhance the quality of the indoor environment, and utilizes a greywater system that captures and reuses rainwater.

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## ***PART 2***

### ***CHICAGO***

Marina City .....	56
Inland Steel.....	60
Brunswick Building .....	64
Sears (Willis) Tower.....	70
John Hancock Center.....	76
Chestnut-DeWitt Apartments .....	82
One Magnificent Mile.....	86
Onterie Center.....	90

Image left: Willis Tower, photo from  
<http://apronthriftgirl.typepad.com/.a/6a00d8341c969953ef01156eba1f3b970c-popup>



**Figure 1.** *Marina City Towers*



## Marina City

### Quick Facts

**Location:** Chicago 300 North State St

**Engineer:** Severud Associates

**Architect:** Bertrand Goldberg

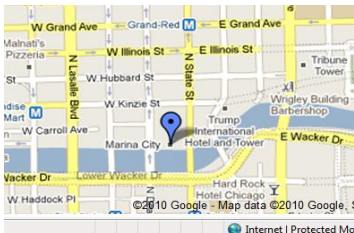
**Start of Construction:** 1959

**Completion:** 1964

**Height:** 562 ft (171 m)

**Number of Floors:** 61

**Material:** Concrete



### ***SOCIAL, POLITICAL and ECONOMIC CONTEXT***

Following World War II, downtown Chicago began to experience a gradual migration of people from the city to the suburbs. Approximately 77% of all residential developments were taking place outside the downtown area. This evident withdrawal created a sense of fear for many union workers that this flow would trigger a mass decrease in city jobs. In response, a campaign was commissioned to revitalize the downtown Chicago area. What was birthed from this movement was Marina City, a 'city within a city'. Financed primarily through the Building Service Employees International Union, this project was intended to be a model of how to maintain and sustain the central business district.

Marina City was originally marketed to single adults and couples without children. The 3.1 acre complex consists of five structures, two twin residential towers, a hotel, a theater, and a marina. With additional amenities like a movie theater, bowling alley, restaurants, and shops, the complex is truly a 'city within a city'. As shown in Figure 1, the 'corn-cob shaped' Marina Towers are undoubtedly the most notable features of the complex. Art historian David Jameson described the towers as 'looking at pure truth', he states, "You're not really looking *at* the building, you're looking *into* the building."

### STRUCTURAL SIGNIFICANCE

The Marina Towers are credited as being two of the first new urban, mixed-use, residential high rise structures in downtown Chicago. Additionally, it has been argued that the towers started the residential renaissance of the inner cities not just in Chicago, but also nationwide.

Another unique feature of the Marina Towers is its lower 19 floors of exposed spiral parking. As shown in Figure 2, this type of integrated space of parking and living was a novel and distinct component not typically explored in the design of high-rise buildings at that time.



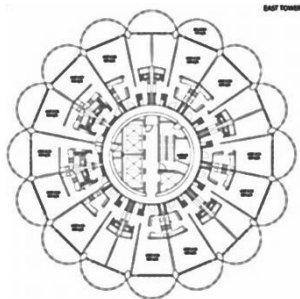
Figure 2. Marina Towers Parking

### STRUCTURAL SYSTEM

When describing his vision for the Marina Towers, architect Bertrand Goldberg stated, “The towers will be like two trees, the central columns will house the elevators, stairways, and utility lines. They will be the trunks in the tree design.” And indeed, this concrete shear wall core structural system is just that. This integrated circular core is intended to take the entire lateral load from the cantilevered floors. It has been estimated that the core in fact absorbs 70% of the total lateral load. The core’s shear wall was designed with staggered openings that were optimized during the design process to minimize the size of the openings and maximize the amount of stiffness.

The diameter of each tower and core is 105ft and 35ft, respectively. The core wall varies from 30” at the base to 12” at the top. As shown in Figure 3, there are 16 reinforced concrete beams that radiate from the core, acting as branches of Goldberg’s “tree” design. Additionally, beyond the perimeter columns are 10ft balconies in a fan-like formation that can be considered the leaves of the structural tree. There are three concentric rings of piles on which the towers are supported, the inner ring supporting the core, and the two outer rings supporting the perimeter columns.

## Marina City



**Figure 3.** Schematic Floor Plan of East Tower

Normal-weight concrete was employed for the vertical load carrying system. Alternatively, lightweight concrete was chosen for the floor slabs and framing beams.

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**Figure 8.** *Inland Steel Building*

## Inland Steel

### Quick Facts

**Location:** Chicago

**Architect:** SOM

**Engineer:** SOM

**Start of Construction:** 1954

**Completion:** 1958

**Height:** 332ft

**Number of Floors:** 19; 25

**Height:** 332 ft (101.3 m)

**Material:** Steel



### ***SOCIAL, POLITICAL and ECONOMIC CONTEXT***

The Inland Steel Company was an independent firm that operated in the Illinois and Indiana area from 1893-1998. At the time of World War II, there were many opportunities for the company to grow. Using this as leverage for their reputation, the Inland Steel Company also started specializing in cold-rolled sheet and strip steel for vehicles. As a result, the company's business soared and quickly garnered honors as one of the top ten largest steel companies in the U.S.

After deciding to build its headquarters in Chicago, the company was determined to use its new home to represent the future of development. Leigh Block, former Vice President of the company at the time commented on the main objective for the design of the new headquarters, "We are the only major steel company with headquarters in Chicago. We wanted a building we'd be proud of, one that spelled steel." Not only did Inland Steel 'spell' steel with its elegantly exposed perimeter columns and flat stainless steel curtain wall, but it also was a catalyst for a new wave of high-rise office structures within the urban community.

**STRUCTURAL SIGNIFICANCE**

Inland Steel was the first time Fazlur Khan and architect Bruce Graham met. Khan was brought onto the project to assist specifically in the design of the perimeter column-beam connection. Up until this point no building had ever been designed with columns exposed on the perimeter. Khan discovered a new way to detail the connection between the beams and columns. The success of this project started a partnership between Khan and Graham whose work would forever influence tall building design.

One of the first skyscrapers to be built in the Chicago Loop post-Great Depression, this building has also achieved many other accolades, including the following:

- *First major structure to be built on steel pilings instead of concrete*
- *First building with an attached structure for service and mechanical systems*
- *First major building with underground parking*
- *First building using a combination of steel beam bracing and soldier beam piling*
- *First building in the Loop with built-in 100% air conditioning*
- *First large building with a flat stainless steel curtain wall free of fluting or embossing*

**STRUCTURAL SYSTEM**

The entire structure is supported by seven perimeter columns on the front and back faces of the building. There are no structural columns on the sides of the building. This is clear in Figure 2a where no columns on the side reach the street level. This type of structural system allows for a completely column-free interior space. This concept was ideal for the owners giving them flexibility in how to utilize and vary the interior space. Figure 2b is a typical floor plan of the Inland Steel Building.



**Figure 2(a).** *Inland Steel Building and (b),right, floor plan*

## *Inland Steel*

Notice also in Figure 2 that the core is attached to the rear of the building, which differs from the conventional center core. This service tower is 25 floors whereas the actual building is only 19 floors.

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**Figure 2b:** <http://www.inlandsteelbuilding.com/>

*Brunswick Building*



**Figure 1.** *Brunswick Building*



**Figure 2.** *Brunswick Building - at street level*



## Brunswick Building

# Brunswick Building

### Quick Facts

**Alt Name:** Cook County Administration Bldg

**Location:** Chicago, 69 W. Washington St

**Engineer:** Fazlur Khan

**Architect:** Bruce Graham, Myron Goldsmith

**Start of Construction:** 1961

**Completion:** 1965

Number of Floors:

Material:



### *SOCIAL, POLITICAL and ECONOMIC CONTEXT*

The Brunswick Building (Figure 9) was built in the post-Depression era, a time in which city overcrowding and unemployment emerged in the aftermath of a fragile economy. (Khan, 2004) Newly elected Chicago Mayor Richard J. Daley commissioned a Loop revitalization project to cure inner city stagnation and substandard housing. This involved constructing new roads, parking garages, and the state-of-the-art O'Hare Airport, incentives that brought people back into the city for work. (Pacyga, 2009)

Demand for new office space was also catalyzed by newly instituted height and zoning restrictions gave rise to the need for innovative, efficiently designed high-rise buildings. (Khan, 2004)

The Brunswick Building represented the beginning of a building boom driven forward by the demand for high-rise office space and supported by Daley's tenure.

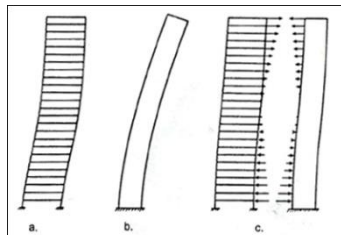
**STRUCTURAL SIGNIFICANCE**

The structure of the Brunswick Building employs a framed tube system. Exterior columns form the outer frame, with a central shear wall 'tube'. The columns were closely spaced and connected by relatively deep spandrels, which simulated a concrete bearing wall (Khan, 1968). This system was a significant step forward, due to the demand for high-rise buildings as population and prosperity was increasing in the limited urban areas (Coull, et al., 1967).

Before Khan introduced this system, there were several predecessors in structural systems. The traditional vertical shear truss and the beam-column type rigid frame construction were combined into the shear truss frame interaction system. This significantly reduced lateral drift, compared to a standard shear truss. Improvements to this design were developed by the addition of belt trusses. This increased the lateral strength and stiffness by connecting all exterior columns to the interior shear truss through horizontal belt trusses. This was followed by the development of the framed tube. (Khan, 1972)

**STRUCTURAL SYSTEM**

The Brunswick Building is the first building where Khan used the system where the horizontal forces are resisted by both the outer frame and the interior shear walls. The rigid outer frame resists most of the wind loading at the top of the building, while bearing little of the wind load near the base. The shear walls, made of monolithic reinforced concrete, have high rigidity, and resist most of the wind loading, particularly in the lower floors (Khan, 1979). They act as a huge vertical cantilever fixed at the foundation level. (Khan, 1966)

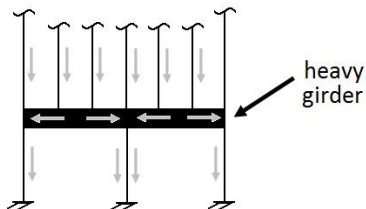


**Figure 10.** *Moment interaction of (a) beam-column frame & (b) shear wall vertical cantilever resulting in (c) mutual restraining system*

## Brunswick Building

With a shear wall and a frame existing in the same building, each one will try to obstruct the other from taking its natural free deflected shape, and as a result a redistribution of forces between the two occurs (Khan, et al., 1964). The frame tends to push (horizontally) the shear wall at the top, and pull it towards the bottom, as shown by the arrows in Figure 10. The resulting deflections are significantly smaller than the deflections which would have resulted from each component acting on its own. (Khan, 1966)

Another issue in tall building design is how to carry the vertical loads. A load applied to the top of a column would simply travel down that column through the entire building until it hits the girder. The load is not distributed into the other columns (Khan, 1966). At the girder, load transfer needs to be achieved between the smaller, closely spaced columns, to the large supporting columns. This is done by the loads transferring sideways through the large transfer girder and concentrating at the supporting columns (see Figure 11).



**Figure 11.** Transfer of gravity loads from the smaller columns at the top to the large supporting columns

### SPECIAL NOTES

A prominent feature of the Brunswick Building is the exposed columns and spandrels that make up the exterior frame. All typical exterior columns were exposed about 70% of their area, which meant that in an extreme case the top floor could move 1.25 inches. To relieve the high bending stresses which would occur, the floors are hinged around the shear wall by resting on neoprene pads. (Findel, et al., 1968)

The massive transfer girder of the Brunswick Building corresponds with a recessed architectural plane on the Civic Center's lobby glass wall (Khan, 2004). In fact, the

## Brunswick Building

building was designed such that it created a large open space (see Figure 9) in relationship to the Civic Center (Graham, 1984).

The building was also the tallest concrete structure of its time. (Khan, 2004)

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- Figure 4:** Courtesy of Morgan Neal





***Figure 1. Willis Tower***

## Willis Tower

### Quick Facts

**Alt Name:** Sears Tower

**Location:** Chicago, 233 S. Wacker Dr.

**Engineer:** Fazlur Khan

**Architect:** Bruce Graham

**Start of Construction:** 1970

**Completion:** 1973

**Height:** 1450 ft (442 m)

**Number of Floors:** 110

**Material:** Steel



### **SOCIAL, POLITICAL and ECONOMIC CONTEXT**

Started in 1893, Sears, Roebuck & Co. had grown to the largest retailer in the world by 1969. (Langmead 2009) This growth meant the company needed new, modern headquarters. Sears favored Chicago due to the economic boom locally and nationally, as well as a sense of loyalty to the city where it was founded.

Sears located a site at S. Wacker Drive and purchased it with the endorsement of Chicago's Mayor Richard Daley. (Khan, Y. 209) The mayor's support also allowed the building to achieve its final height, as he lifted building height restrictions to support downtown growth. (Pridmore 2002)

The building's original design included fewer, larger stories to meet Sears' requirements of 110,000 square feet per floor. The design firm, Skidmore, Owings and Merrill LLP (SOM), completed a study showing increased employee efficiency through smaller stacked floors. ([Anonymous] 1973) This improved marketability and rentability pushed the building's height to increase to its final position in the Chicago skyline (Iyengar p 71). The height of the building also allowed the Sears Tower to surpass the World Trade Center in NYC. The two cities had competed with each other for the most dominant

skyline. At 1450 feet, the Sears Tower set the record for height for almost thirty years (Khan, Y. p 218).

### STRUCTURAL SIGNIFICANCE

The Willis Tower is a bundled tube structure composed of 9 tubes each 75 feet by 75 feet. At the 50<sup>th</sup>, 66<sup>th</sup>, and 90<sup>th</sup> floors, two or more of the tubes terminate, gradually decreasing the area of the floor plans (see Figure 1). The tubes are tied together at various levels by truss belts. This not only improves lateral stiffness, but prevents differential gravity settlement from the various tower heights (Iyengar p 72)

The braced tube system used for the John Hancock Center in Chicago preceded the bundled tube system, but was inadequate for the height of the Willis Tower. The system's reduction of shear lag allowed for a lighter structure, utilizing only 33 pounds of structural steel per square foot (see Figures 2 & 3). This made the bundled tube system incredibly efficient (Khan, FR p 8).

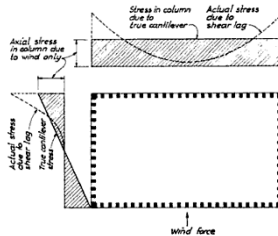


Figure 2. Shear lag of typical building

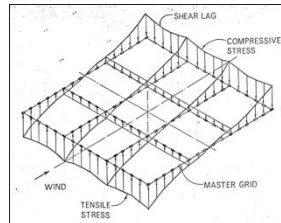


Figure 3. Reduced shear lag of Sears Tower



## Willis Tower

### STRUCTURAL SYSTEM

The structural system of the Willis Tower consists of a system of columns spaced at 15' on center with each of the nine tubes sharing at least two faces of columns with the other tubes. Due to the asymmetry of the building, the gravity loads vary by each tube. However, the belt trusses that precede the set backs help equally distribute the gravity loads to the columns (see Figure 4) (Khan, FR p 6).

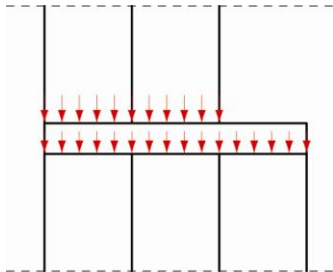


Figure 4. Gravity load transfer through belt truss

For the lateral wind loads, the Willis Tower acts as a cantilevered tube with differing moments of inertia due to the different column layouts from the set backs. The lower floors have a larger moment of inertia. (see Figure 5). The wind pressures on the building depend on the area exposed as well as a variety of environmental factors.



Figure 5. Cantilever Beam Model for Wind

Due to the extreme height of the building, traditional building codes were not sufficient to determine required strengths. The building was designed using a combination of Chicago Building code and wind tunnel testing, also utilizing computer aided design and statistical analyses (see Figure 6) (Khan, FR p 10-11).

## Willis Tower

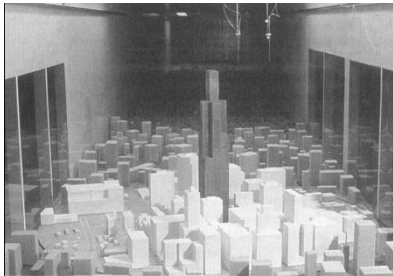


Figure 6. Wind Tunnel Model

### SPECIAL NOTES

- The construction of the Sears Tower was quick and economical thanks to prefabricated two store column and beam sections nicknamed “Christmas trees” (Khan 1980).
- After Sears' relocation in 1988, the building's lobby was remodeled to suit its new multi-tenant occupation. (Jaquet 1992)
- The building was renamed the Willis Tower in 2009 after insurance broker Willis Group Holdings Ltd., after the company leased 125,000 square feet. (Dow Jones Newswire 2009)

- Also in 2009, the 103rd floor observation deck was remodeled to include three protruding glass boxes offering an unimpeded view of Chicago. (Slevin 2009)

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**Figure 4:** Personal sketch, M. Glaeser

**Figure 5 :** Personal sketch, M. Wachter

**Figure 6 :** Khan, YS. *Engineering Architecture*. New York: W.W. Norton & Company, Inc. 2004. 219.



**Figure 1.** *The John Hancock Center*

## John Hancock Center

# John Hancock Center

### Quick Facts

**Location:** 875 N. Michigan Avenue,  
Chicago

**Engineer:** Fazlur Khan

**Architect:** Skidmore, Owings, and Merrill

**Start of Construction:** 1965

**Completion:** 1970

**Height:** 1127 ft (343.5 m)

**Number of Floors:** 100

**Material:** Steel



### ***SOCIAL, POLITICAL and ECONOMIC CONTEXT***

As the nation transitioned into the 1950's, Chicago (along with the nation's other large cities) was faced with the phenomenon of 'white flight' – the tendency of upper and middle-class citizens to abandon the inner-city and move to surrounding suburbs. Over the decade, Chicago's population shrank by nearly 700,000 people, leaving the city center impoverished and in disarray (University of Illinois at Chicago, 2001). To combat this, Chicago's City Council and Mayor Daley implemented the *Chicago 21 Plan*, an urban renewal project focused on improving neighborhoods near downtown and the lakefront. Though the Hancock was not a direct result of the project, the *21 Plan* was responsible for creating the gentrified atmosphere that enabled the construction of a luxurious, mixed-use development.

The original developer of the building, Jerry Wolman, was convinced that the Hancock would be financially viable because of an existing proposal to construct a rapid-transit line in the vicinity of the site. Although the public transportation line was never implemented, demand for high-density development existed due to extensive urban development at the time, as well as the cachet brought about by media attention on the Hancock itself.

## STRUCTURAL SIGNIFICANCE

The Hancock Center debuted Fazlur Khan's "trussed tube" structural system, which employs stiff, multi-story diagonal bracing to assist in carrying gravity loads as well as lateral loads. Prior to the development of the "trussed tube", Khan's "framed tube" was the preeminent structural system for high-rise construction.

SOM's initial calculations for a single mixed-use tower at the Hancock site demonstrated that, for the total square footage desired, a tower of the required height would be unfeasible from a cost perspective due to the amount of structural steel that would be required. When the building was redesigned with the trussed tube system, the unit quantity of steel used for the 100-story tower was equivalent to that required for a traditional building of only 40 or 50 stories (Khan, 2004)

The trussed tube is the natural progression towards achieving purer tube behavior: in the framed tube, only 70% of the total deflection was due to tube action, while 30% was due to the frame action. Where the trussed tube suffered from shear lag due to the flexibility of spandrel beams, the X-braced Hancock behaved "very similar to that expected in a true cantilever tube" (Khan, 1966).

## STRUCTURAL SYSTEM

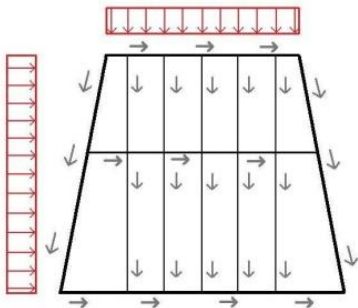
For structures above 60 stories, Khan found using the rigid-box type structure, with all exterior wall elements would act together like the walls of a tube, was the best and most economical solution. This could be achieved either with closely spaced exterior columns and stiff spandrels, closely spaced diagonal members on an exterior wall, or by tying together the exterior columns by adding the minimum number of diagonals in the exterior wall planes (Khan, 1965).

When Khan decided use the "optimum column-diagonal-truss tube," for the structural system, he knew from a research project he had recently worked on with a graduate student at Illinois Institute of Technology that diagonal bracing at approximately 45° (Khan, 1974) could be used to improve lateral stability for structures highly affected by horizontal wind loads.

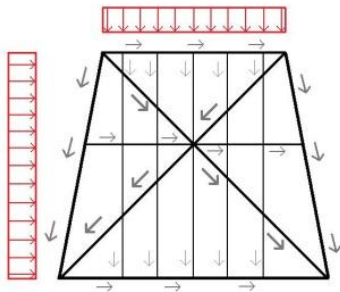
In the John Hancock Center, Khan recognized that bracing would also redistribute loads in the system. *Figure 2*, showing just two levels, illustrates the probable transfer of gravity and wind loads in an un-braced scenario. *Figure 3* qualitatively demonstrates the new load paths, with the loading in both the horizontal spandrels and vertical columns diminished through the

## John Hancock Center

introduction of axial loading in the bracing. As the figures show, the introduction of the diagonal load paths simultaneously relieved horizontal stresses due to wind loads, and vertical stress from gravity loading in the system. Thus the diagonals take the majority of the wind shear while acting also as inclined (Khan, 1972).



**Figure 2.** Un-braced: *Transfer of gravity & wind loads*



**Figure 3.** Braced: *Transfer of gravity & wind loads*

While without bracing the horizontal and vertical loads are largely handled separately, the redistribution of the stresses allows the braced system to handle loads in a more integral manner, and the tube becomes a stiffened box. Ultimately, the system can thus be ideally modeled as if it were a steel beam, responding to lateral loads in bending as a pure cantilever (Tucker, 1985), as shown in Figure 4.

## John Hancock Center

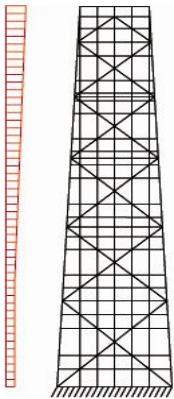


Figure 4. Trussed tube as cantilever

### SPECIAL NOTES

Khan was very involved in the project throughout the construction process. When several construction problems relating to some of the caissons of the foundations were found, he made the difficult but necessary decision of having the rest of the caissons

examined, delaying the construction schedule. It was due to these unforeseen increases in the cost in the project that forced the developer Jerry Wolman, who had started the project in 1964, to sell it to the John Hancock Mutual Life Company only a year after construction had started (Khan YS, 2004).

Khan also involved himself in optimizing the design down to the level of individual apartments. While concrete slab ceilings were usually placed under the beams in most steel buildings, Khan recognized this as an inefficient use of space. In this project, the walls were designed to coincide with the beams, so that the concrete slabs between the beams could be used as the ceilings. This increased the clearance of the apartment buildings from about 8 feet to 9 feet, making the rooms look much larger (Khan YS, 2004).

As of January 1, 2011, the Hancock Center will be home to the “world’s highest ice skating rink”, which will be installed in the building’s observatory on the 94th floor, more than 1000 feet off the ground. (Schwarz J, 2010)



## John Hancock Center

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**Figures 2-4:** Jeremy Chen and Scott Huang

*Chestnut-DeWitt Apartments*



**Figure 12.** *Chestnut-DeWitt Apartments*

## Chestnut-DeWitt Apartments

# Chestnut-DeWitt

### Quick Facts

**Alt Name:** Plaza at DeWitt

**Location:** Chicago

**Architect:** SOM

**Engineer:** SOM

**Start of Construction:** 1963

**Completion:** 1965

**Height:** 373ft

**Number of Floors:** 43

**Material:** Concrete



### ***SOCIAL, POLITICAL and ECONOMIC CONTEXT***

In the 1960's, Chicago experienced a mass movement of people leaving the suburbs to return to the city. This generated a high demand for residential space and accordingly a need to build taller and more efficient. At the time Fazlur Khan and Bruce Graham were hired to design Chestnut-DeWitt Apartments, there were four newly built structures in vicinity of the prospective site. With each building around 20 stories, it was decided to extend the height of Chestnut-DeWitt well above the others to ensure that it would be distinct as well as allow for unobstructed views. Up until this point, however, most concrete structures were no more than 20 stories and employed shear wall practices. Nevertheless, the pressure to build taller influenced Khan to push the envelope with conventional forms.

### ***STRUCTURAL SIGNIFICANCE***

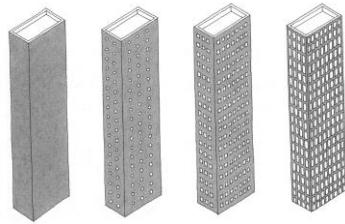
At the completion of construction, this building was the first in the world to incorporate a tubular structural system. Prior to this, the extents for height on concrete structures were limited. However, Khan's ability to recognize the efficiency in using the perimeter, rather than the core, to resist lateral loading not only

## Chestnut-DeWitt Apartments

revolutionized tall building design but also enabled concrete to be a viable material at these great heights.

### **STRUCTURAL SYSTEM**

In evaluating the proposed vision for Chestnut DeWitt, Khan realized that he needed to visualize the global behavior of the structure as it is subjected to wind. In his observation, he reasoned that the stressed due to lateral forces as opposed to gravity forces was the controlling factor for high-rise buildings. With this, Khan was able to see that in response to wind forces, the building's natural tendency is to act as a cantilever. Using this as a template, Khan then realized this ideal behavior is equivalent to a standing hollow box shaped building with a solid wall perimeter. Through his evaluation, Khan realized that as holes were placed into the hollow box, the efficiency of the system is concurrently reduced. Figure 2 shows the concept of replicating pure cantilever behavior. It was from this analysis that Khan discovered that cantilever action is practically achieved by using closely spaced columns around the perimeter to resist lateral loads. Figure 3 shows a typical floor plan of Chestnut-DeWitt



**Figure 2.** *The framed tube concept evolving from the solid perimeter wall to beam-column perimeter grid*



**Figure 3.** *Chestnut-DeWitt Apartments*

## Chestnut-DeWitt Apartments

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*One Magnificent Mile*



**Figure 1.** *One Magnificent Mile*

## One Magnificent Mile

# One Magnificent Mile

### Quick Facts

**Alt Name:** One Mag Mile, 950 N. Michigan

**Location:** Chicago

**Architect:** SOM

**Engineer:** SOM

**Start of Construction:** 1978

**Completion:** 1983

**Height:** 673ft (205m)

**Number of Floors:** 57

**Material:** Concrete



### *SOCIAL, POLITICAL and ECONOMIC CONTEXT*

The Magnificent Mile, also known as The Mag Mile, is located along Michigan Avenue in downtown Chicago. This commercial district serves as a link between the Chicago Loop and the Gold Coast, one of Chicago's wealthiest neighborhoods. In addition to being Chicago's wealthiest shopping district, The Mag Mile is a nucleus for restaurants, entertainment, and hotels. Figure 2 shows a view of the Mag Mile looking south. Mag Mile contains 5 of the tallest 85 buildings in the world. Located at the northern end of this district is One Magnificent Mile, a mixed-used, high rise with commercial, office, and residential space.



Figure 2. View of the Magnificent Mile looking south

## *One Magnificent Mile*

### **STRUCTURAL SYSTEM**

One Mag Mile is a concrete bundled tube where tube heights extend to the following floors: 21, 49 and 57. This type of structural system is an extended version of the frame tube. Designed to act like a three-dimensional hollow tube, the framed tube is able to behave like a cantilever on account of the closely spaced columns on the perimeter. This allows the system to efficiently resist lateral loads. The bundled tube concept is an adaptation of the single framed tube where the building consists of several single frame tubes. In addition to the remarkable amount of stiffness that this system provides at great heights, the bundled tube is not limited by a certain form or configuration. As long as there is a modular arrangement of the tubes, the configurations are essentially infinite. In One Mag Mile, the tubes are in a hexagonal configuration which was found to be most feasible with the site limitations of an L-shaped.

These various tube heights were strategically calculated to minimize the influence of shadows cast on the Oak Street Beach as well as create a variety of different views. Each tube has a sloping roof. Figure 3 shows an aerial view of One Mag Mile. Note in Figure 4 the visible distinction between office and residential space is

revealed with the two story mechanical floor that extends across all three towers.



**Figure 3.** *Aerial view of One Mag Mile*

**Figure 4.** *One Mag Mile*



## *One Magnificent Mile*

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The Magnificent Mile

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accessed 10/20/01

One Magnificent Mile

[http://en.wikipedia.org/wiki/One\\_Magnificent\\_Mile](http://en.wikipedia.org/wiki/One_Magnificent_Mile)  
accessed 10/20/10

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<http://www.aviewoncities.com/buildings/chicago/onemagnificentmile.htm>

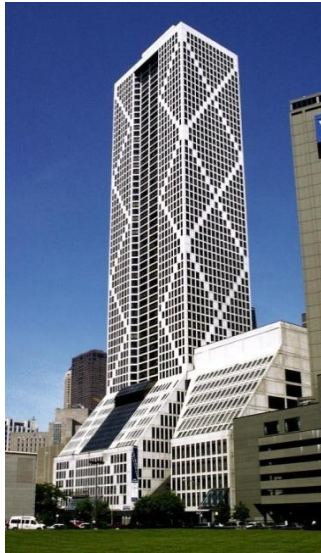
**Figure 2:**

[http://en.wikipedia.org/wiki/File:20070509\\_Foot\\_of\\_Magnificent\\_Mile.JPG](http://en.wikipedia.org/wiki/File:20070509_Foot_of_Magnificent_Mile.JPG)

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**Figure 4 :** <http://two.archiseek.com/2009/1983-one-magnificent-mile-chicago-illinois/>



**Figure 13.** *Onterie Center*



## STRUCTURAL SIGNIFICANCE

Regarded as Fazlur Khan's last major project, the Oterrie Center is a mixed-use development with residential, office, and retail space. Currently the 57<sup>th</sup> tallest building in Chicago, this concrete trussed tube structure is visibly accentuated by its concrete in-fill panels. The Oterrie was the first concrete high-rise in the world to use diagonal shear panels at the perimeter.

## STRUCTURAL SYSTEM

The Oterrie is comprised of two buildings, a 58-story main tower and a 12-story auxiliary tower. Figure 2 shows a street view of the building. The combination of closely spaced perimeter columns and spandrels as well as the integration of diagonal concrete infill panels make up the lateral load-resisting system. As a whole, these infill panels create X-formations on the perimeter serving two purposes. The first is to act as shear panels to resist the effects of lateral loading, and the second is to join the perimeter columns and spandrels to distribute vertical loads. Figure 3 shows an infill panel detail where the reinforcement ties the vertical and horizontal systems together.



Figure 2. Oterrie Center street view

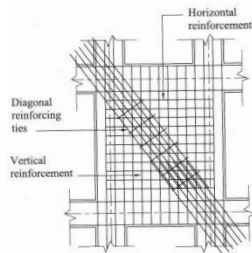
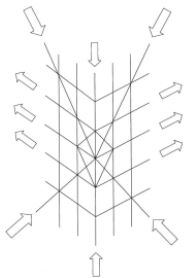


Figure 3. Typical reinforcement detail for infill panels between spandrels and columns

## Onterie

Figure 4. illustrates one challenge with designing this type of structural system. As its shown in the figure below, the horizontal component of the axial force in the diagonals induces a force at each corner where the braces meet. Typically these forces are resisted with the presence of a perimeter tension tie that essentially bounds the structure in place. However, in the case of the Onterie Center, this horizontal thrust is resisted by increasing the depth of the slab and adding additional reinforcement in the spandrels.



**Figure 4.** The forces that occur where the braces meet at the corner of the building

## SPECIAL NOTES

The base of the tower spreads to create more office space and to increase the amount of sunlight that enters. The main public lobby for the main and auxiliary tower contains retail space. Floors 6-10 of the main tower and floors 2-11 on the auxiliary tower are for office space. The additional floors are residential spaces.

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## ***PART 3***

## ***HOUSTON***



One Shell Plaza .....	96
Walker Building (Two Shell Plaza) ..	102

Image left: One Shell Plaza, photo from  
<http://www.skyscraperpicture.com/houston2.htm>



**Figure 14.** *One Shell Plaza*



## One Shell Plaza

# ONE SHELL PLAZA

### Quick Facts<sup>1</sup>

**Location:** Houston, 910 Louisiana St.

**Engineer:** Fazlur Khan

**Architect:** Bruce Graham

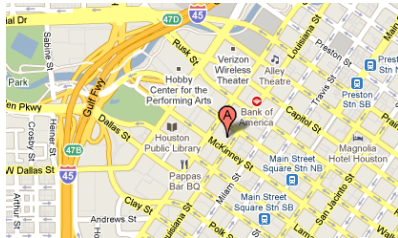
**Start of Construction:** 1967

**Completion:** 1971

**Height:** 714 ft (217.7 m)

**Number of Floors:** 50

**Material:** Lightweight concrete



## *SOCIAL, POLITICAL and ECONOMIC CONTEXT*

In the 1960s United States, there were competing forces when it came to construction: urban expansion and economic inflation. The government saw construction and urban expansion as the future of business growth in the US, as well as the crux in keeping the economy stimulated. However, in the 1960s, multiple instances of economic tension directly correlated with increased construction costs.<sup>2</sup> While these times weren't the most severe that the US had seen, the need to build more economic structures led to the creation of more efficient structural systems.

One Shell Plaza was the first in a series of skyscrapers that went up in the 1970s in Houston. Already known for its residential architecture, Houston wanted to venture into tall building design, to accommodate the growing business culture in the 1960s-70s. At the time, Houston was ranked fourth in construction activity and was the fastest growing city in the US. It furthermore boasted the world's largest domed stadium, the headquarters for NASA's manned spacecraft program, and plans for a new international airport.<sup>2,3</sup> Thus, investor Gerald D. Hines argued, it was only natural for the Shell Oil Company to relocate its corporate headquarters – and 18,000 employees – to Houston.<sup>3</sup>

## One Shell Plaza

The erection of One Shell Plaza marked Houston's desire to become an industrial and commercial hub in the US and the world. It is a place that expresses individualism and yet still works as a large business community. Houston saw One Shell Plaza as the chance to elevate the city's reputation and lead it to being one of the US's most popular cities.<sup>3</sup>

### STRUCTURAL SIGNIFICANCE

One Shell Plaza is the tallest lightweight concrete structure in the world and was one of the first lightweight concrete structures ever built.<sup>2</sup> At the time, the use of lightweight concrete was not considered wise by engineers because of the difficulties that exist in controlling its homogeneity, as well as its susceptibility to creep and shrinkage. Khan developed a rigorous quality control program that was implemented to minimize negative effects of using lightweight concrete for One Shell Plaza.<sup>6</sup> It was entirely successful and creep has not been an issue to this day.<sup>2</sup>

One Shell Plaza was also the first tube-in-tube structure ever built. Khan had already developed the framed tube concept for the Brunswick building in Chicago, but that was effective for only a limited height range. By using lightweight concrete (115 pcf) and the tube-in-tube

system, Khan was able to design the 50-story One Shell Plaza to weigh approximately the same as a 35-story normal-weight concrete structure, with approximately the same cost per square foot of office space.<sup>2,5</sup>

### STRUCTURAL SYSTEM

The tube-in-tube system (Fig. 2) is characterized by increased lateral resistance and added redundancy, which enables the structure to be taller than, lighter than, and equally as stiff as a shorter framed tube building.<sup>2</sup>

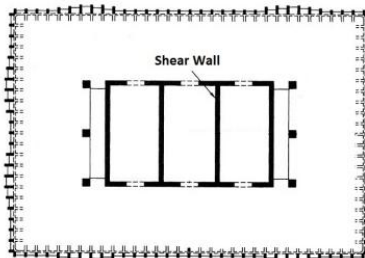


Figure 2. Schematic Floor Plan

## One Shell Plaza

For lateral loads, the building acts like a cantilevered I-beam: the inner core, like the web, resists the shear forces, while the exterior columns, like the flanges, are either in tension (on the side of the wind) or in compression (on the side opposite the wind). The floor does not participate in lateral load resistance.<sup>4</sup>

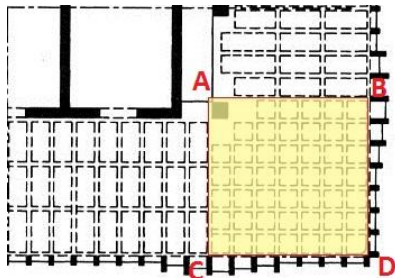


Figure 3. Two-way Slab at Corners

Gravity loads in One Shell Plaza are not uniformly distributed to the columns, as they are in other structures. This is because at each of the building's four corners, the one-way joist system changes to a two-way slab (Fig. 3). The two-way slab redistributes the load such that columns at corners B and C receive the largest

gravity loads among perimeter columns, while the columns at corner D receive the smallest. Khan reflects this in his design by varying the depth of the exterior columns at these points, as seen in the plan.<sup>5,7</sup>

### SPECIAL NOTES

One Shell Plaza was the first all-lightweight concrete building ever built, the first ever tube-in-tube structure, and at the time of its completion in 1971, the tallest building west of the Mississippi and the tallest reinforced concrete building in the world.<sup>2</sup>

It was renovated in the early 1990's to upgrade the electrical and mechanical systems (including elevators) and minor architectural details to the lobby and entranceways.<sup>8</sup>

It has ENERGY STAR certification (1999, 2004, 2009) and has recently obtained LEED Gold certification (2009).<sup>8</sup>

## One Shell Plaza

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**Figure 2:** Ali, Mir M. (2001). *Art of the Skyscraper: the Genius of Fazlur Khan*. New York: Rizzoli International, p. 90.

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*Walker Building (Two Shell Plaza)*



**Figure 1:** *Walker Building*



**Figure 2:** *Walker Building*



**Figure 3:** *Walker from above*

## Walker Building (Two Shell Plaza)

# WALKER BUILDING

### Quick Facts

**Alt Name:** Two Shell Plaza

**Location:** Houston, Walker Street

**Engineer:** Fazlur Khan (SOM)

**Architect:** Bruce Graham

**Start of Construction:** 1971

**Completion:** 1972

**Height:** 341 ft (103.94 m)

**Number of Floors:** 26

**Material:** lightweight concrete



### **SOCIAL, POLITICAL and ECONOMIC CONTEXT**

The Walker building was the first highrise building bought by the real estate company Hines, Inc. and has been largely occupied by Shell Oil Company. Since the discovery of Texas oil in 1901, Houston has emerged as an energy centre vulnerable to oil-controlled economic fluctuations (Advameg 2009). Large urban growth during the 1970s and 1980s, stimulated by federal money post World War II and quotas on oil imports in the 1960s, saw the construction of many office building occupied by energy-related industries and made Houston the fourth largest American city (Fischer 1989). Because Houston has no zoning ordinances, limited urban planning has been driven by the private leadership of oil and financial companies (Fischer 1989). Consequent urban sprawl was exacerbated by low property and income taxes, making Houston favorable for real estate companies like Hines (Fischer 1989). Difficulties in the oil industry in the 1980s were mirrored in a slowing building industry (Fischer 1989).

The construction of Two Shell at the height of Houston expansion provided high density space for a growing city and economy without adding to urban sprawl. Later diversification efforts to strengthen public programs and

## *Walker Building (Two Shell Plaza)*

Houston's economy with investments in technology, science, and finance were mirrored in the diversification of Two Shell's occupants (Fischer 1989).

### **STRUCTURAL SIGNIFICANCE**

One of the biggest challenges Khan faced in concrete design was how to transfer loads from tightly spaced wall columns to widely spaced based columns (Ali 2001). He wanted to find a more efficient solution than the traditional transfer girder or trusses (Ali 2001). The Walker building was one solution and a mid-point between his previous work on the Brunswick building and later work on the Marine Midland Bank (Khan 2004). In the Walker, Khan reduces the wide spandrel and replaces the heavy girder in the Brunswick with an arching pattern of exterior columns to direct flow of axial gravity loads from many columns to a few base columns (Khan 2004). Khan also replaces the traditional beam-column frame with a new framed tube to increase stiffness and raise the height potential of reinforced concrete buildings. (Khan 2004).

The Walker building was constructed at a time when concrete was still a new material in large-scale design; its success provided new design options and helped to gain acceptance of concrete (Saliklis 2008). Kahn proved that there is a "place for structural logic in new

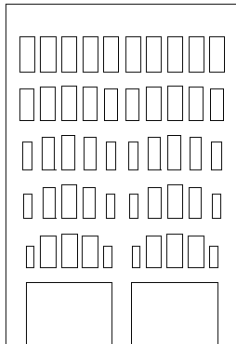
architectural development" (Kahn, cited in Saliklis 2008) and that "a new structural system gives the possibility of a new architectural expression" (Goldsmith, cited in Saliklis 2008). Khan achieved a sound, efficient, and redundant system with "true structural expression" that came "out of the real structural behavior and flow of loads, and not by means of arbitrary architectural facades" (Kahn, cited in Bonowitz 1985). He introduced a successful new solution to the multistory construction of a new material.

### **STRUCTURAL SYSTEM**

There are two main structural systems at play in the Walker building: the framed tube with shear wall core to provide lateral stiffness and resist wind forces and the arching action in the facade to distribute gravity loads.

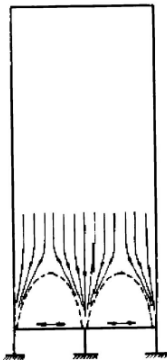


## Walker Building (Two Shell Plaza)



**Figure 5:** "Arch" Pattern

Because the exterior columns are so closely spaced, the walls act like a load-bearing tube with windows cut out (Khan 2004). A pure framed tube responds hybridly to lateral loads, much like a cantilever out of the ground (Khan 2004). However, with the presence of windows, the building also experiences deformations



**Figure 6:** Force Transfer

characteristic of a beam-column frame (Khan 2004). Tube characteristics resist overall moment on the building, while frame characteristics act at each floor to resist shear and bending (Khan 2004). The presence of load-bearing walls on the perimeter also resist overturning moment and increase stiffness (Khan 2004). The frame supports its self-weight and a small portion of load from each floor, while the interior columns carry the majority of the floor loads (Bonowitz 1985). The interior shear walls that span across the short face acts to stiff the axis along the longer face (Khan 2004).

The gradually changing columns and deepening spandrels along each face create step arches that direct force flow from many small columns to the several large columns that support the building at its base (Saliklis 2008). This system enables a more accessible street face, especially for a lower parking levels, as well as increasing redundancy (Khan 2004). Because columns are so close, it enables the transfer of forces from a damaged column to neighboring columns increasing safety and permitting repairs without widespread structural failure (Khan 2004).

## Walker Building (Two Shell Plaza)

recycling system, and the Hines Green Office education program to teach occupants how to reduce their carbon footprints (USGBC 2009).

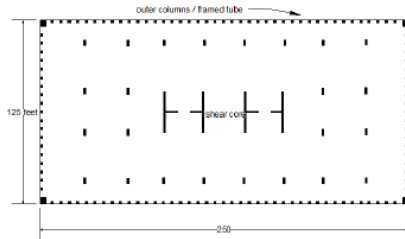


Figure 7. Floor Plan of Framed Tube

### SPECIAL NOTES

In 2009, Hines undertook a renovation of Two Shell Plaza that won them LEED (Leadership in Energy and Environmental Design) gold certification for renovation of existing building (USGBC 2009). The renovations involved water use reductions, purchase of green power renewable energy certificates, low-pressure ductwork, and reflective paving that successfully decreased energy use by 42 percent and save Hines about 1.63 dollars per square foot annually (USGBC 2009). Hines included efforts to change occupants' behaviors with programs to encourage alternative commuting, an extensive

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**Figure 1:** Saliklis 2008

**Figure 2 :**

<http://www.hines.com/property/detail.aspx?id=135>

**Figure 3:** <http://picasaweb.google.com/lh/photo/Quj5CA4a6KCKBGrJS2zBAg>

**Figure 4 :** <http://www.google.com/maps>

**Figure 5:** SOM 1971

**Figure 6:** Saliklis 2008

**Figure 7:** SOM 197

Back cover photo:  
Two Shell Plaza (Princeton University Maillart Archive)

