DR. FAZLUR RAHEMAN KHAN
AESTHETICS, SCIENCE AND STRUCTURES

by

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ABSTRACT

Prevailing theories such as "Structural Expressionism" are based on the belief that structures can create art. In other words, a thorough understanding and correct application of the principles of structures should automatically lead to creation of beautiful forms. This thesis explores one such assumption. The work of the famous Chicago-based structural engineer Dr. Fazlur R. Khan was studied to gain an in-depth understanding of this concept.

However, towards the end of the research, the author began to find problems with her initial hypothesis that structures can create aesthetics. The study of Khan's work revealed that he created beautiful forms not on the basis of structures, but also by transforming himself into an artist. The following thesis is a revised version of the original work and examines how Khan developed into an artist while persuing the technical career of a structural engineer.

The study of Khan's work and philosophies revealed that he never intended to use structures to create art. Instead, this brilliant structural engineer, through interaction with other professionals over the years, became a complex artist whose tools were technical expertise, aesthetic sensitivity and humanitarian vision.

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ACKNOWLEDGEMENTS

The argument pursued in this research has been of great interest to me since I was an undergraduate. I cannot express in words my gratitude to Professor Richard L. Hoag for helping me investigate this subject and for supporting me throughout. I am equally indebted to Professors Torgeir Norheim and W. Mick Charney for their patience while reading the drafts and for their valuable criticism, despite their busy schedules. I am also grateful to Professor Ray Weisenburger for his readiness to help at any time. This work could not have taken its final shape without the patient and careful editorial work of Evelyn Frazier and Patricia Weisenburger. I extend my thanks to John Zils, Jim Crouch, Professors Mir M. Ali and David Sharpe, and Dr. Lynn S. Beedle. Finally, I offer my sincere regards to Professor David P. Billington whose works have been and will be a constant source of inspiration for me.

- Komal Hatti

Chapter 1

INTRODUCTION

Architecture, as defined by Vitruvius in his book *De Architectura*, consists of three essential elements: commodity, firmness and delight. The discipline of Structures focuses upon firmness. However, many times, the aesthetics of a building are inherent in its structural system. The structurally dominated creations shown in Fig.1.1a and b, the Eiffel Tower and the Salginatobel Bridge, create a strong visual tension not only as bold and powerful statements of structural engineering of the twentieth century but also as sculptural or artistic creations.

Although both Gustav Eiffel and Robert Maillart were technical masters and leading structural engineers of their times, we cherish the Eiffel Tower and the Salginatobel Bridge as elegant poetic forms more than engineering achievements. This thesis explores the possibility that a structural engineer can be a scientist and artist at the same time.

Dr. Fazlur Raheman Khan is known as one of the 20^{th} century masters of structural engineering. His structural designs (Fig.1.2a and b) have an aesthetic appeal, an artistic imagery, as powerful as Eiffel's and Maillart's. The following research investigates Khan's projects to understand this paradoxical relationship between aesthetics and science in his structures.

. 1.1a *The Eiffel Tower*, Paris, 1889, by Gustave Eiffel

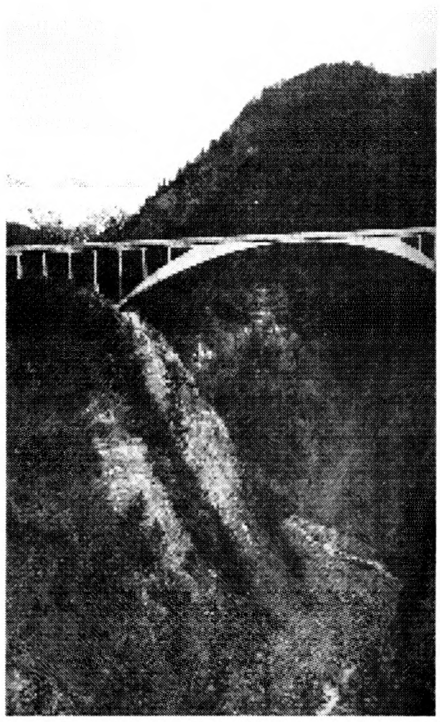

Fig. 1.1b *The Salginatobel Bridge, near Schiers, Switzerland, 1930, by Robert Maillart*

Fig. 1.2a *The Sears Tower*, Chicago, 1974, by Skidmore, Owings and Merrill (Fazlur Khan, structural Designer)

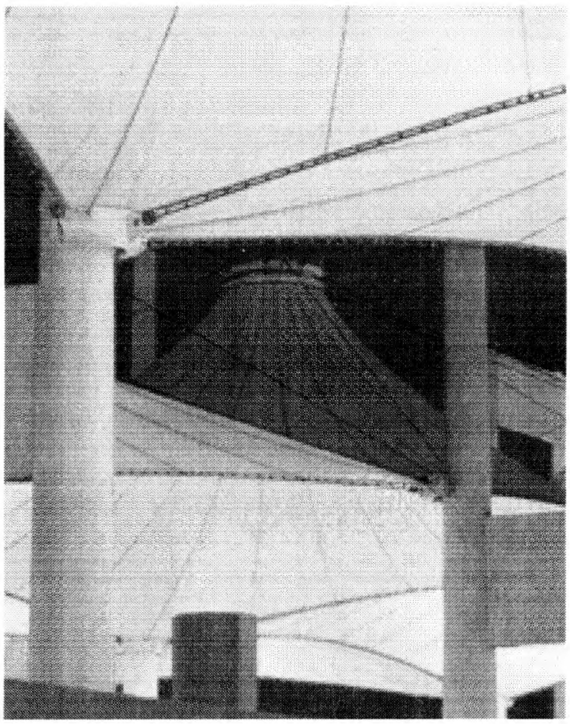

Fig. 1.2b King Abdul Aziz International Airport, *Haj Terminal*, Jeddah, Saudi Arabia, 1982, by Skidmore, Owings and Merrill. (Fazlur Khan, Structural Designer)

Structural designs by Fazlur Khan

Chapter 2

Khan – Early Years

Fazlur R. Khan (Fig. 2.1) was born on April 3, 1929 in Dhaka, Bengladesh. His father, Abdul Raheman Khan, a well-known scholar and mathematician, was granted the title Khan Bahadur by the British empire for his contributions to public education. His mother Khajida Khatun, too, valued education greatly. His parents inculcated in him the commitment to high moral and ethical values through education. The environment at home developed a profound respect for learning and knowledge.[1]

During his school years, Khan loved subjects like mathematics and physics. "I liked physics because of its mystical and abstract aspects," he claimed, "but [I] was good in mathematics and always tinkered with something mechanical."[2] These courses laid a solid foundation for him and naturally led him toward structures when he enrolled in engineering.

Throughout his student life, Khan was exceptionally bright. He finished his bachelor's degree in civil engineering from Shibpur Engineering College, Calcutta, India in 1950. He taught at the Ahesanullah Engineeing College, Bangladesh for two years. In 1952 he

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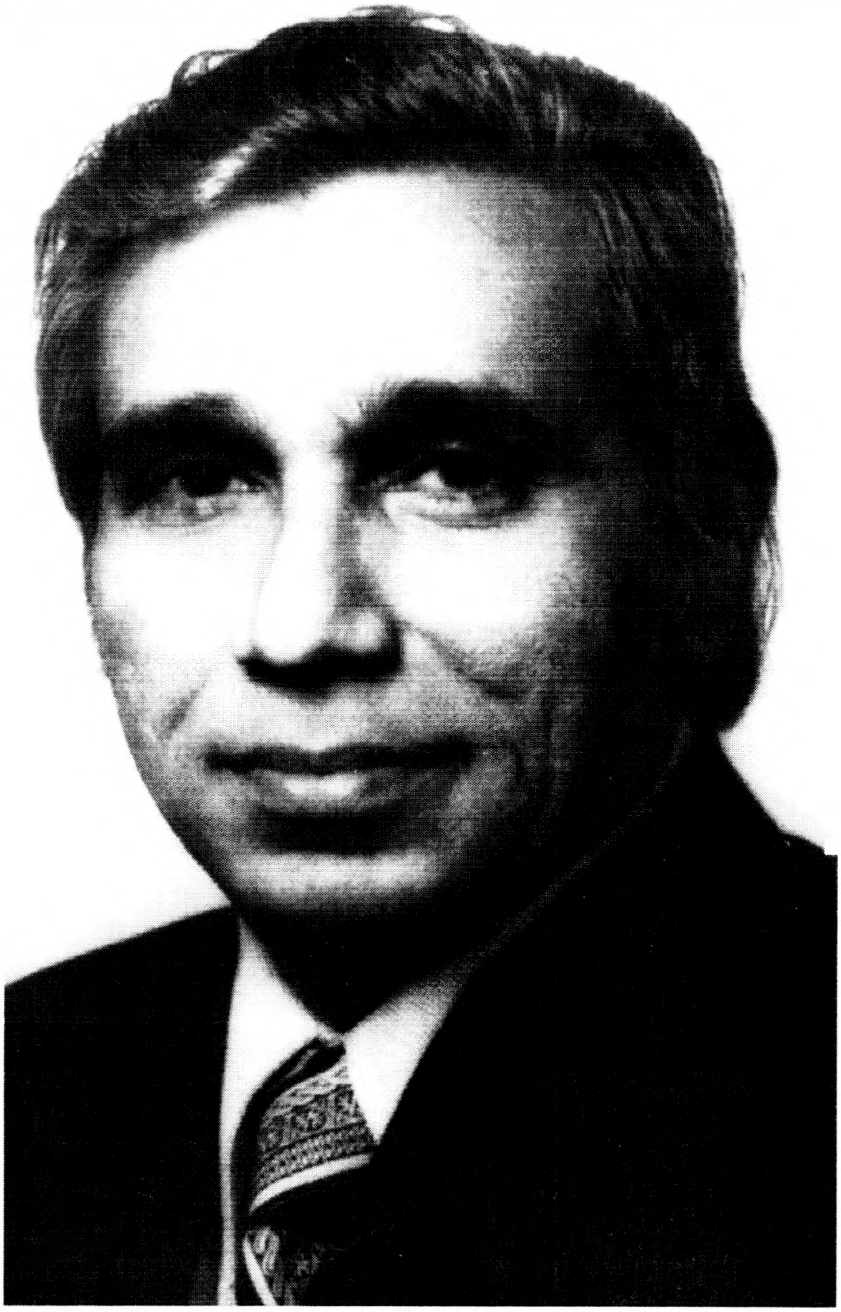
[1] American Association of Bangladeshi Engineers and Architects. *Fund-Raising Dinner for Bangladesh Scholarship in the Memory of Dr. Fazlur R. Khan*, November, 1997, p. 12-14. (Courtesy, Professor Mir M. Ali)

[2] "Construction's Man of the Year: Avant Garde High-Rise Designer Fazlur R. Khan," *Engineering News Record.*, February 10, 1972, p. 25.



"Khan was technically a master of engineering. No one practicing structural engineering since World War II has better understood building structures."[3]

Fig. 2.1: Dr. Fazlur Raheman Khan

[3] American Association of Bangladeshi Engineers and Architects. *Fund-Raising Dinner for Bangladesh Scholarship in the Memory of Dr. Fazlur R. Khan*, November, 1997, p. 13. (Courtesy, Professor Mir M. Ali)

was awarded the Fulbright and Ford Foundation Scholarship for graduate studies at the University of Illinois at Urbana-Champaign in the United States. He received Master of Science degrees in civil engineering, and in theoretical and applied mechanics and in 1955, a doctorate in structural engineering.[4]

At the University of Illinois, Khan studied with professors Chester Siess and Joseph Smith, both well-known for their contributions to the field of engineering, and was highly influenced by them. Khan was, according to his friend Prof. Mir M. Ali, in the right environment at the right time.[5] Pre-stressed concrete was the topic of his doctoral studies.

After completing his Ph. D. in 1955, Khan began his professional career at Skidmore, Owings, and Merrill, Chicago as a structural engineer. During this two year period, his mojar works included a hall for 2000 people at the US Navy Training Center at Great Lakes, using pre-stressed concrete as the structural material, and seven pre-stressed concrete bridges at the US Air Force Academy at Colorado Springs.[6]

Khan was required to return to Bangladesh in 1957 as a condition of the Fulbright and Ford Foundation Scholarship. His position there as technical advisor to the Engineer's Office of Karanchi Development Authority required more managerial and administrative

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[4] Khan was also awarded honorary Doctor of Science from the Northwestern University in 1973. At Lehigh University, a Bangladesh Scholarship has been established in the memory of Khan.
[5] Mir M. Ali. *Telephone conversation*, UIUC, Champaign, October, 1997.
[6] Ibid., August, 1997.

skills than technical abilities. Dissatisfied with the nature of the work, Khan returned to the United States and joined SOM sometime in 1959.[7]

During his stay in Bangladesh, Khan had met Lislette Anna Olga Turba of Vienna, Austria, an artist with a degree in biology, and they were married in 1960. Throughout Khan's career, Lislette was a constant source of inspiration, strength, and advice.[8]

Soon after joining SOM, Khan became senior project engineer and participating associate in 1961. He was promoted to an associate partner in 1966, head of structural/civil division in 1968, and full partner in 1970. Khan died of a heart-attack in March 1982.[9]

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[7] Ibid.

[8] *Fund-Raising Dinner for Bangladesh Scholarship in the Memory of Dr. Fazlur R. Khan*, p. 12.

[9] SOM, Chicago. *Information package on Fazlur Khan*, October, 1997. (Courtesy, John Zils)

Chapter 3

The Rigid Frame

Chicago has a proud history of tall buildings that continues today. In the 1950s, architecture in the city was dominated by structures reaching 20 stories and supported by the rigid frame structural system. Prevalent themes of the Second Chicago School Architecture were structural expressionism, integrity of the materials, rational approach to building, and modernistic forms.[10]

The firm of Skidmore, Owings, and Merrill was modernistic in its architectural design philosophy and a follower of Mies van der Rohe who started the Second Chicago School and was the head of the Department of Architecture at Illinois Institute of Technology (IIT). Miesian vocabulary was reinforced by the large number of IIT graduates working at SOM. During late '50s and '60s, most of the projects that came to the office were high-rise, corporate structures. Khan had worked mainly on pre-stressed structures, none of which were tall buildings, nor did he have any particular interest in tall buildings at that time.[11] However, when he was challenged to design tall structures, he focused on them passionately. With an intuitive understanding of technical aspects of structures, Khan set out to find the right structural system for tall buildings.

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[10] Carl W. Condit. *Chicago, 1930-70, Building, Planning, and Urban Technology*. (Printed in Beyond the International Style: New Chicago Architecture. Chicago: Rizzoli, 1981), p. 43-55.
[11] Ali. *Telephon conversation*, August, 1997.

When Khan turned his attention to tall buildings, "rigid frame" was the structural system most often used. One of its many limitations was that buildings could not exceed 20 stories. However, the pressure from corporate clients to increase efficiency and consequently achieve greater economy was great. Khan, as the designer of structural systems, took this situation seriously. Idealistic and dedicated by nature, he was convinced that there existed a right solution to every structural problem. Thus he started a life-long search for the ideal tall structure.[12]

The civil engineers at SOM were not very busy during 1959, and Khan used this period to apply his theoretical knowledge to practice. He started a series of lectures and seminars on technical issues, mainly about tall structures.[13] Khan's papers during this period show a brilliant structural engineer at work. In them, he focused mostly on structural analysis of various building elements like the rigid connections in a frame, the shear wall, the columns, girders, and similar topics.

He also started a thorough analysis of the codes for tall structures.[14] He realized that the structural formulae specified in design books and used by practicing structural designers were unnecessarily complex. Khan simplified various structural formulae while developing his own approach to designing tall structures.[15] His contention was that the aim of a structural formula is to assure that a building will not fail. Engineers tend to

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[12] John Zils. *Personal interviw*, SOM, Chicago, April, 1998.
[13] Srinivas Iyanger. *Khan Tributes*. (Paid to Khan at his funeral on April 2, 1982, and at the memorial service on May 6, 1982, assembled at SOM and Lehigh University, May 1983).
[1414] Fazlur R. Khan. *Design of High-Rise Buildings*. (Presented at A Symposium on Steel, Chicago, Illinois, Fall, 1965), p. 3-4.

forget this goal and get lost in their own technology. Simplifying a structural problem and the ability to apply it to an actual building was Khan's strength.[16]

Khan's achievements in actual construction during these years probably were not as significant as his theoretical achievements. One of the first projects he worked on was Hartford Fire Insurance Co. office building located in Chicago, Illinois. This was to be a corporate structure with economy as the guiding thought.[17] Khan was an assistant engineer for the project, so his contribution to the structural design was not significant. However, it reveals the background against which Khan started his career. The Hartford used *"rigid frame"* with *"shear walls in the core"* – the two concepts that were to define the direction of Khan's future research, as the following study of his structural designs would reveal.

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[15] Ibid, p. 3-4,7.
[16] Ali. *Telephone conversation*, UIUC, Champaign, October, 1997.
[17] SOM, Chicago. *Information package on Hartford Fire Insurance Company Building, Chicago, Illinois.* (Courtesy, Jim Crouch and John Zils. December, 1997).

1. Hartford Fire Insurance Company Office Building I, 1959-61, Chicago, Illinois

The Hartford Building (Fig.3.1a and b) was to be built economically Its purpose was to provide rental returns as well as owner occupancy. *Architectural Record* says it was, "built at sq. ft. cost competitive with strictly speculative buildings."[18] Economy determined the design of the structural system.

SOM provided the following information.[19]

A tall building with simple expression, almost square, was proposed. The 7 X 9 bays were to reduce the peripheral wall area. The structural system consisted of "shear wall and frame interaction." The external rigid frame was a flat slab concrete structure with twenty-two feet square bays. An off-centered core housed services like electrical, mechanical and plumbing systems. The owner wanted a high quality, prestigious-looking building, a style that SOM had been creating for years. He also insisted on having a masonry structure appearance. The frame, therefore, was clad with light gray granite.

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[18] *Architectural Record.* (September, 1996), p. 122.

[19] SOM, Chicago. *Information package on Hartford Fire Insurance Company Building, Chicago, Illinois.*

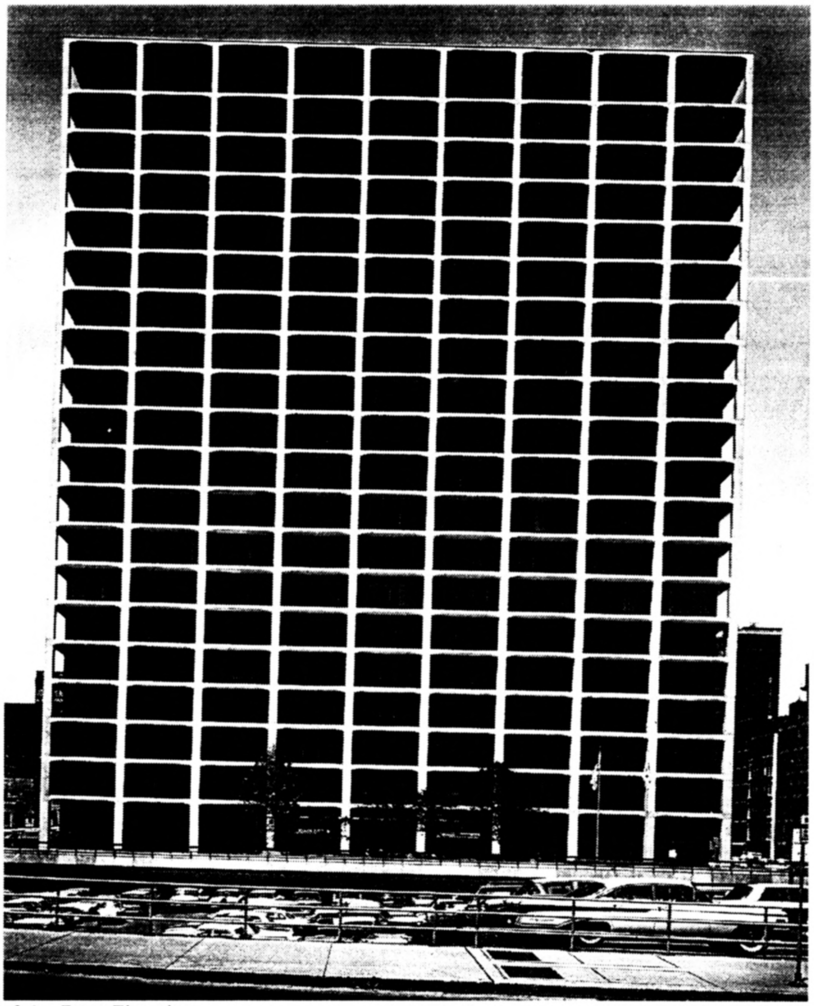

Fig. 3.1a Front Elevation

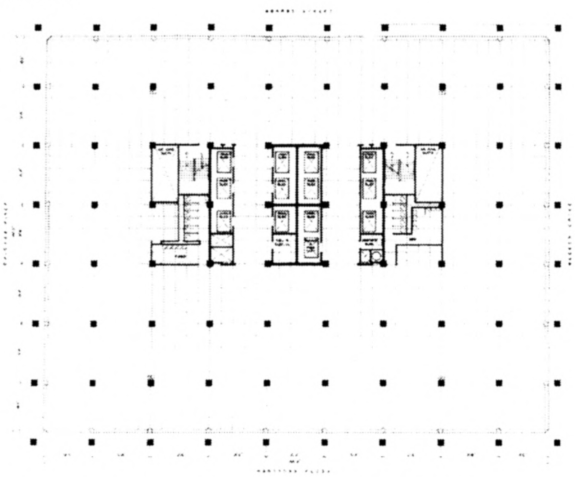

Fig. 3.1b Plan

Hartford Fire Insurance Co. Office Building, Chicago, IL

The glass curtain wall, as shown in Fig. 3.1a, was recessed by four feet and six inches in order to provide sunshade and reduce air-conditioning costs. The balcony could be used for cleaning the windows and maintaining the building. The basic rigid frame structure used concrete flat slabs. Instead of actual beams, cross beams were provided only in the core where gravity and impact loads were much higher than in the peripheral spaces. The columns were haunched when they met the flat slab, in the peripheral (or no-beam) zone.

Khan's Analysis of the Structural System[20]

The structural system involved "rigid frame" and "shear wall core" at the center, with "flat-plate" slab construction. In order to understand the shear wall and frame interaction system and all the other structural systems to be covered in his later projects, it is necessary to understand how the rigid frame system works. It appears that all of the structural systems that Khan innovated were an attempt to improve the rigid frame.

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[20] Fazlur R. Khan. *Design of High-Rise Buildings*. Presented at a Symposium on Steel, Chicago, Illinois, Fall, 1965.

The major forces acting on a tall building are (a) force of gravity due to dead and live loads (vertically downward) and (b) wind loads (horizontal). The frame, when exposed to these two loads, reacts in the following two ways.

1. The building acts like a vertical cantilever, springing from the ground. It bends like a hollow-box beam, (Fig. 3.2a). Twenty percent of the total deflection of the system is caused by this action. This phenomenon is known as *chord drift* wherein the structure bends while resisting the overturning moment.

2. Because the columns and the beams are continuous, when subjected to lateral wind load, each column and beam deflects. The deflection is caused by rotational resistance of the rigid joints in the continuous beams and columns. It is possible to imagine all of the columns and beams in the frame deflected in this manner, under wind load. Gravity load exacerbates this deflection further.

As Fig. 3.2b indicates, the wind load curve is zero at the ground level and maximum at the level of the highest horizontal plane of the building. Also, the increment in the horizontal wind load is not linear but curvilinear. This differential loading pattern in the vertical plane gives rise to a crucial phenomenon called *shear lag* or *frame wracking*.

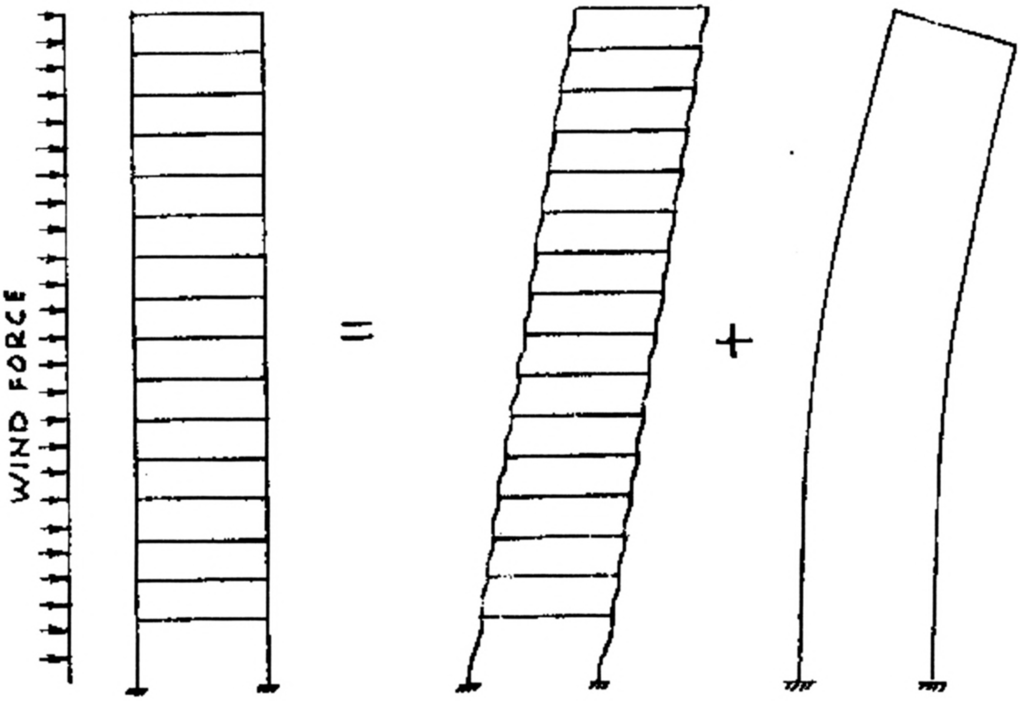


Fig. 3.2a Effect of Wind Force on a Rigid Frame

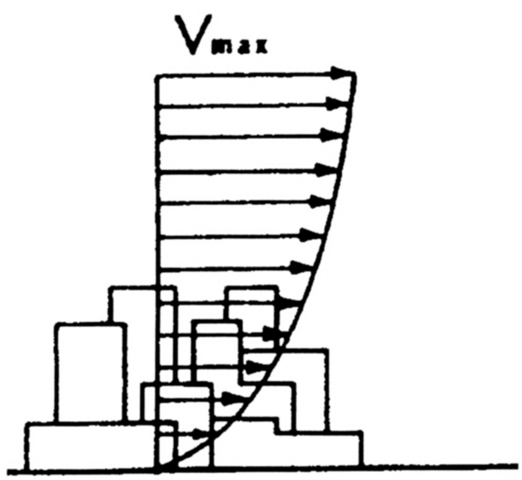


Fig 3.2b Wind Flow Pattern (Also Indicates the Wind Force Pattern)

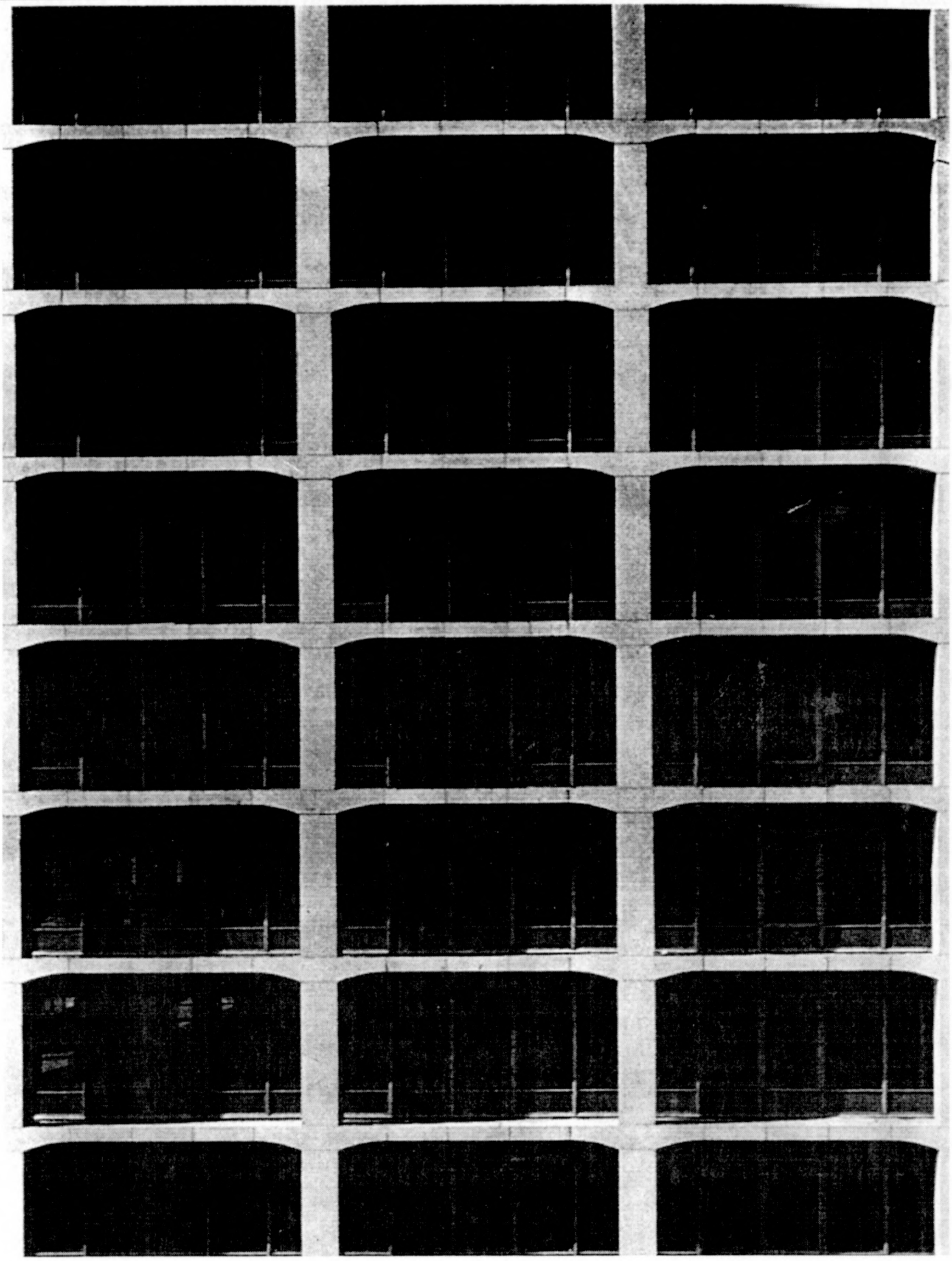
Shear lag implies that the magnitude of wind shear is different for columns and beams at different levels. The flexure, or bending, in each of them causes a deflection in a pattern as shown. This is responsible for 80% of the total deflection of the building due to wind load (15% in beams + 65% in columns). Shear lag or frame wracking is the greatest weakness of any framed structure. To go above 20 stories, the building requires huge structural members and excessive quantities of building material, leading to prohibitive budgets. A costly tall building loses its purpose which is economy.

The prevalant structural system of monolithic concrete walls in the central service core was used in the Hartford Building. These walls were designed to carry not only their share of gravity loads, but also to resist the entire lateral load on the building. Such concrete walls, even though designed primarily for gravity loads, are known as shear walls because they also resist the entire wind shear. The use of shear walls makes it possible to build reinforced concrete buildings up to about 30 stories without increasing the column, slab and wall sizes beyond what is required for carrying the gravity loads.

Aesthetics and Structural System[21]

Khan believed that the structural system determined the architectural expression. Because connections are vulnerable points in a rigid frame, Khan strengthened them by rounding the joints in the façade (Fig. 3.3). This device also served as a dialogue in structural expressionism as it intensified the feel of forces playing within the frame (here, the force

[21] Fazlur R. Khan. "The Nature of High-Rise Buildings," *Inland Architect*, June, 1967, p. 9.



Hartford Fire Insurance Co. Office Building, Chicago, Illinois

Fig.3.3 Aesthetics and Structural System of gravity). Khan wrote in his article *The Nature of High-Rise Buildings*, "An added architectural advantage of using shear walls is that the simplicity of the remaining structure, slab and columns can be aesthetically expressed, as is amply demonstrated in the 20-story Hartford Insurance Building in Chicago."[22]

With this understanding of the nature of structural frame and tall buildings, Khan was now ready to undertake greater challenges. When the Hartford project was completed, he was named the chief structural designer for his next projects with SOM.[23]

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[22] Ibid.
[23] Ali. *Telephone conversation*, August, 1997.

Chapter 4

Search for a Perfectly Rigid Form – Tube

Through his experience during the construction of the Hartford and his research, Fazlur Khan realized that rigidity was the most critical issue in the structural design of a tall building.[24] During early '60s, 1961 to 1966 especially, Khan concentrated on improving the rigidity of tall structures. He proposed "tube" as a structural system sometime in 1962. Gradually he developed and refined the nature of tube through consecutive projects. The structural designs of the Brunswick Office Building and the DeWitt Chestnut Apartments, both located in Chicago and built during this period, illustrate the development of "tube."[25]

Although the Brunswick project came to SOM shortly before the DeWitt Chestnut, the Chestnut building was completed before the Brunswick. Khan worked with Myron Goldsmith, a structuralist architect, on both the projects.[26]

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[24] Fazlur R. Khan. "The Nature of High Rise Buildings'" *Inland Architect*, July, 1967, p. 7-8.
[25] We can not say with certainty as to when Khan proposed the idea of tube. Various books on structures such as *Structures* by Daniel L. Schodek (see Bibliography) state 1962 as this date. An extensive research on Khan's works during this period at SOM, Chicago, a study of the design development and construction documents for his projects (courtesy, Jim Crouch, SOM, Chicago) reveals that Khan conceived the idea of tube sometime during the design development phase of the Brunswick Office Building and applied on a concurrent design - the DeWitt Chestnut Apartments.
[26] Zils. *Personal interview*, April, 1998.

Brunswick Office Building, Chicago, Illinois, 1966

The Brunswick building (Fig.4.1) was to provide offices for downtown Chicago. The critical design issues were economy, large free spans for offices, and an efficient structural system for a 38-story building. As chief structural designer, Khan proposed the use of "shear wall and frame interaction system." His work on the Hartford Building had given him a much better understanding of this structural system.[27]

A deep span was needed for the office spaces, requiring exterior columns to be placed close together. The column spacing was reduced to nine feet and four inches, achieving the span of thirty seven feet between the core shear wall and the exterior frame. This module matched the minimum dimension for office spaces. but the main entrance floors required a much wider column spacing, especially for parking. A huge transfer girder was used to solve this problem. Ten heavy columns supported the girder and transferred the load from the girder to the ground. Structurally, the low column spacing of nine feet and four inches proved to be advantageous because it increased the overall rigidity, minimizing the frame wracking or the shear lag effect.[28]

The shear wall and frame interaction system, used in the Hartford Building, is effective up to 30 stories. Above that, the huge structural components required, become too expensive. In order to build Brunswick, a 37-story structure, without any significant

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[27] "Selected Works of Fazlur R. Khan (1929-1982)," *IABSE Structures*, C-23/82, p. 64-65.
[28] Ibid.

Fig. 4.1a Front Elevation

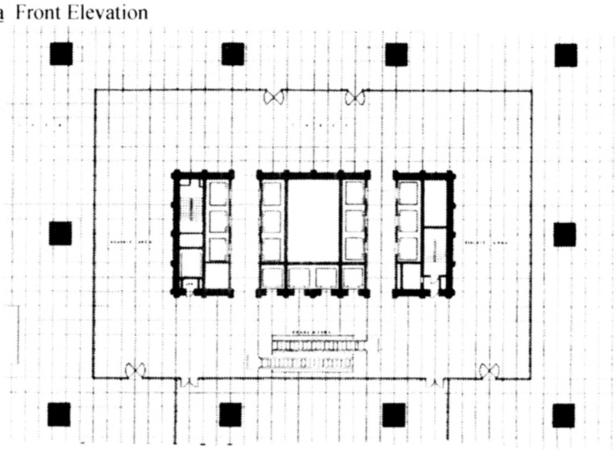

Fig. 4.1b Plan

Brunswick Office Building, Chicago, Illinois increase in the per square foot cost, Khan proposed to place the columns at a spacing of nine feet and four inches, as mentioned above. This resulted in changing the nature of the structural system from a pure "shear wall and frame interaction" to a "tube-in-tube." However, Khan realized this after the design was completed later that the true nature of this building could be satisfactorily explained through the concept of "tube-in-tube."[29] This building lies somewhere between the two systems. It shall be discussed as "tube-in-tube" after discussing the concept of "tube" in the DeWitt Chestnut Building.[30]

This researcher speculates that Khan envisioned "tube" as the system with perfect rigidity during the design phase of the Brunswick, sometime in 1962. He then used it as the structural system for his next project, the DeWitt Chestnut Building.

DeWitt Chestnut Apartments Building, Chicago, Illinois, 1965

Located on Chicago's Near North side, close to Lake Michigan, DeWitt Chestnut Apartments (Fig. 4.2) is a 43-story high structure, containing 407 units. The "shear wall and frame interaction system" was undesirable here because beyond 40 stories the building becomes very weak, regardless of the rigidity of the frame. Shear walls at the core were undesirable since the apartments required greater flexibility.[31]

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[29] Jim Crouch. *E-mail to the author*, 1998.

[30] It was found that different sources presented different information on the structural analysis of these two buildings. As a result, the researcher had to revise her thesis on these two buildings.

[31] Ali. *Telephone conversation*, UIUC, Champaign, August, 1997.

Fig. 4.2a Front Elevation

Fig.4.2b Plan

DeWitt Chestnut Apartments Building, Chicago, Illinois

As a result, Khan proposed the revolutionary concept of "tube."[32] Ideally, a tube structure is a perfectly rigid hollow box beam. In practice, however, it is not possible to eliminate bending altogether.[33]

In the Chestnut DeWitt Apartments, the columns were spaced at five feet and six inches centers. Their cross-section varied from twenty inches square at the base to forteen inches square at the top. Tapering the columns in this manner was a typical detail of SOM's style and served aesthetic, structural and economic purposes. Every other column was omitted at the ground floor to permit an arcade leading to the entry. The overall building was one hundred and twenty-five feet square in plan. Absence of an interior core allowed the desired layout flexibility. The interior column placement need not be as rigid as in previous structural systems because the tube was designed to withstand all the forces.

Structural Concept

The total flexure or the maximum bending moment induced in a structural member, regardless of the support and loading conditions, depends upon the span of the member.

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[32] According to Billington, "There is some question about the origin of the framed-tube idea. Leslie Robertson, structural designer of the World Trade Center, wrote that "in 1962 … perhaps for the first time, the concept of the tube was employed in a high-rise building [the design for the World Trade Center completed in 1972]. Later in 1963, a tubular concept in reinforced concrete was developed for the 43-story DeWitt Chestnut Apartments". "Structural Systems – Theme Report," *Proceedings of the International Conference on Planning and Design of Tall Buildings*, August 21-26, 1972, vol. La: *Tall Building Systems and Concepts* (New York: American Society of Civil Engineers, 1972), p. 405".

This is the only instance where researcher came across contradictory information. Since all other books and articles, and according to the interviews, Khan was the first structural designer to have introduced the concept, researcher decided to follow the argument that Khan was the innovator.

[33] Department of Architecture, IIT, *Video of Fazlur R. Khan's lecture at IIT*; 1973. (Courtesy, Richard L. Hoag)

The larger the span, the greater the flexural deformation and the less the rigidity of the system as a whole. A system may be found which has 100% rigidity or zero flexure within individual structural members. Such a structural system for a tall building would act as a vertical cantilever, as shown in Fig. 4.3a.

In the DeWitt Chestnut Apartments, the exterior envelope consists of closely spaced columns, tied together by deep spandrel beams. The floors function as diaphragms, used to distribute the horizontal wind load evenly to the exterior envelope. All of the lateral wind load should be absorbed by the tubular envelope, but in practice, such a perfectly rigid structure is not possible.[34]

In theory, the framed tube system behaves like a cantilever beam with each column acting as the fiber of the cantilever, either in direct tension or direct compression. Thus, all of the windward side columns have maximum tensile stress with each column equally stressed and all of the leeward side columns have maximum compressive stress with each column equally stressed. At any section 1234 (Fig. 4.3b), the stress diagram is as shown in Fig. 4.3(c); the stress diagram at the horizontal sectional plane 5678 is as shown in Fig. 4.3d.[35]

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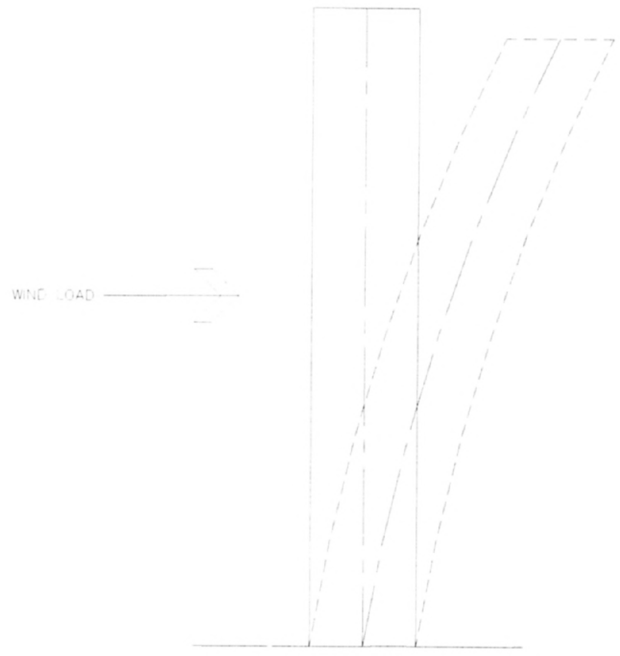
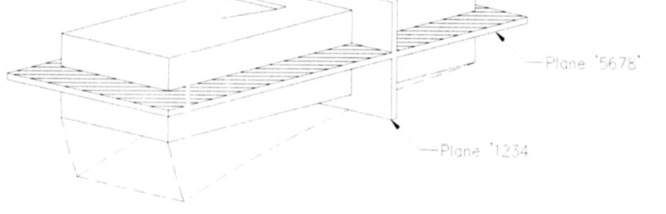
[34] Ibid.

[35] Fazlur R. Khan. "The Nature of High Rise Buildings," *Inland Architect*, July, 1967, p. 9.



<u>Fig. 4.3(a)</u> Behaviour of tube against wind



<u>Fig. 4.3(b)</u> Analysis of tube as a fixed cantilever

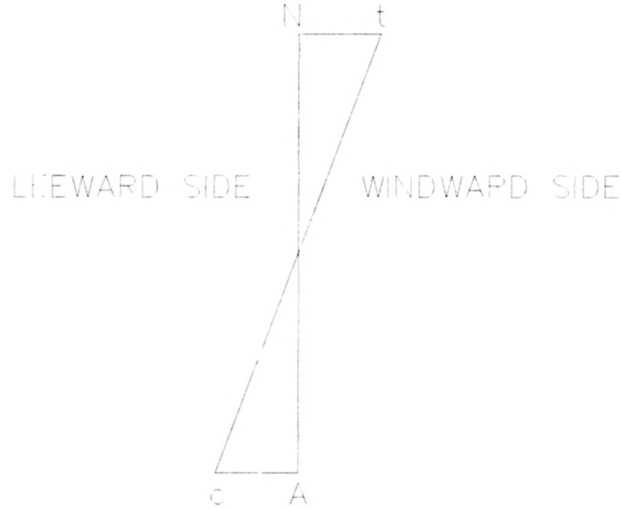


Fig. 4.3(c) Shear force diagram (for a horizontal cross-section of a column)

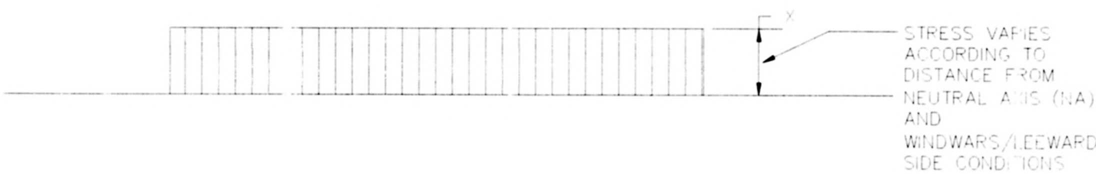


Fig. 4.3(d) Shear force diagram (for a vertical cross-section, parallel to the plane of the neutral axis)

According to Khan, the true behavior of the tube at the Dewitt Chestnut Apartments lies somewhere between that of a pure cantilever and a pure frame. [36] The sides of the tube parallel to the wind tend to act as independent multi-bay rigid frames, given the flexibility of the spandrel beams. This flexibility results in *shear lag*.

The effect of shear lag on the tube action results in non-linear pressure distribution along the column envelope; the columns at the corners of the building are forced to take a higher share of the load than the columns between. Furthermore, the total deflection of the building no longer resembles a cantilever beam.

The shear problem severely affects the efficiency of tubular systems, and all later developments of tubular design attempted to overcome it. The framed tube principle seems to be economical for steel buildings up to 80 stories and for concrete buildings up to 60 stories.[37]

Whether a building is a tube or not depends upon its structural behavior, not upon its appearance. The purpose of a tube is to eliminate bending. Once bending is eliminated, wind sway and cost are reduced and no material is wasted in direct stress, the principle of truss. For example, the column spacing of the John Hancock Center, a tube structure, is comparable to the Hartford Building. But in the Hancock, the diagonals convert the frame-action into a truss-action. In the Hartford the loads are transferred through bending

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[36] Ibid.

[37] Department of Architecture, IIT, *Video of Fazlur R. Khan's lecture at IIT*; 1973. (Courtesy, Richard L. Hoag)

as well through direct stresses, but in the Hancock they are transferred primarily through direct stresses.[38]

Structural Analysis of the Brunswick as a Tube-in-Tube

Most of the books on the structural analysis describe the Brunswick as the first application of "tube-in-tube" system. However, it is essentially a frame and shear wall system. Because of the low spacing of the exterior columns, the structural behavior of the frame approximates that of a tube. A tall building reacts against wind load in two ways: as an overall structure, and as a stacking of floors. The greatest weakness of tube is its lack of overall rigidity. Its foundation is not a solid strip. So at the base, it does not act like a pure cantilever. Depending upon how much the base works as a fixed support, and how much it works as a hinge support, the maximum deflection would be:

$$d = d_1 - d_2$$

Where,

d = Final deflection of a rigid frame

d_1 = Deflection due to beam's behavior as pure rigid beam (Fig. 4.4a)

d_2 = Deflection due to beam's behavior as pure cantilevered beam (Fig. 4.4b)

The final deflected form is determined by superimposing the two.[39]

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[38] David Sharpe. *Interview*, IIT, Chicago, April, 1998.
[39] Ibid.

With the rigid core at the center, the overall behavior of the two tubes changes drastically. Since the core is solid, its rigidity is very high compared with that of the outer tube, and its foundation is continuous. Therefore it acts as a fixed cantilevered beam. The inner tube now pulls the outer tube back [Fig.4.3(c)], resulting in less overall deformation.[40]

Wind load is highest towards the top of a building, so shear force is maximum at the bottom. The wind load is shared by both the outer tube and the inner tube depending upon their respective stiffness, because the amount of load shared is directly proportional to the stiffness of a tube. Most of the wind load at bottom is absorbed by inner tube and by the outer tube near the top.[41]

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[40] Ibid.
[41] Ibid.

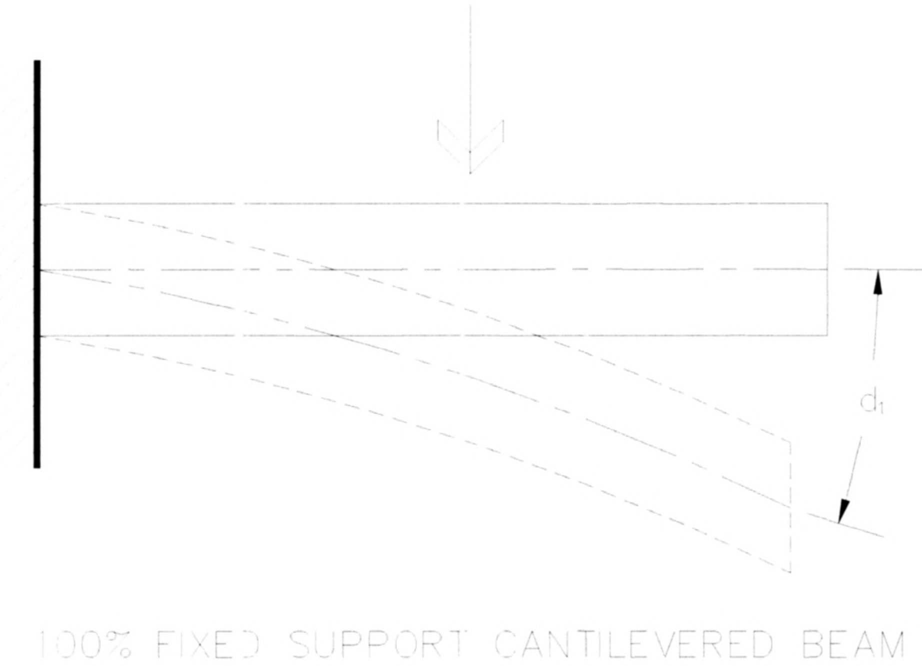

Fig. 4.4(a) 100% fixed support cantilever beam

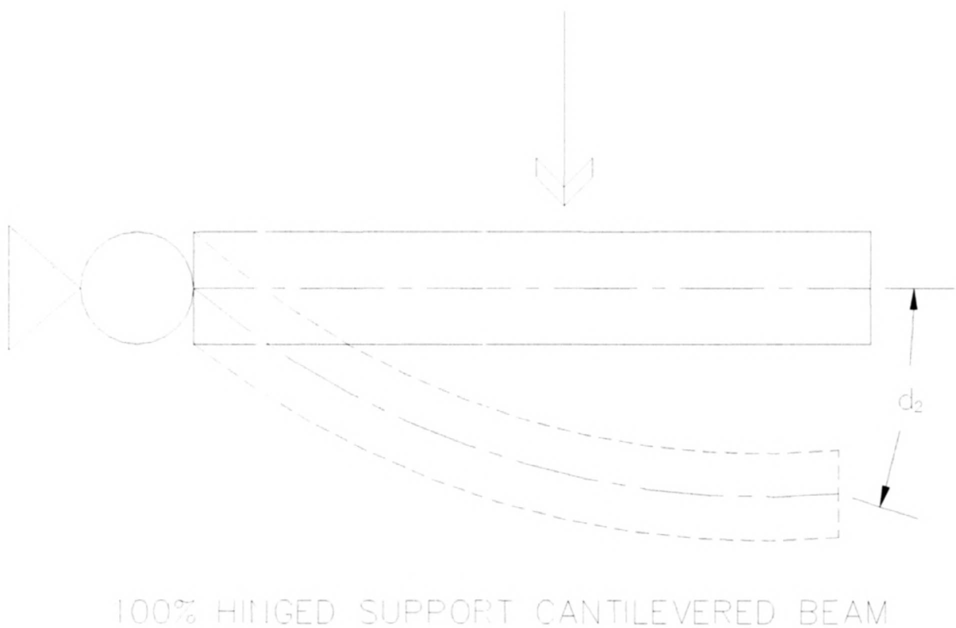

Fig. 4.4(b) 100% hinged support cantilevered beam

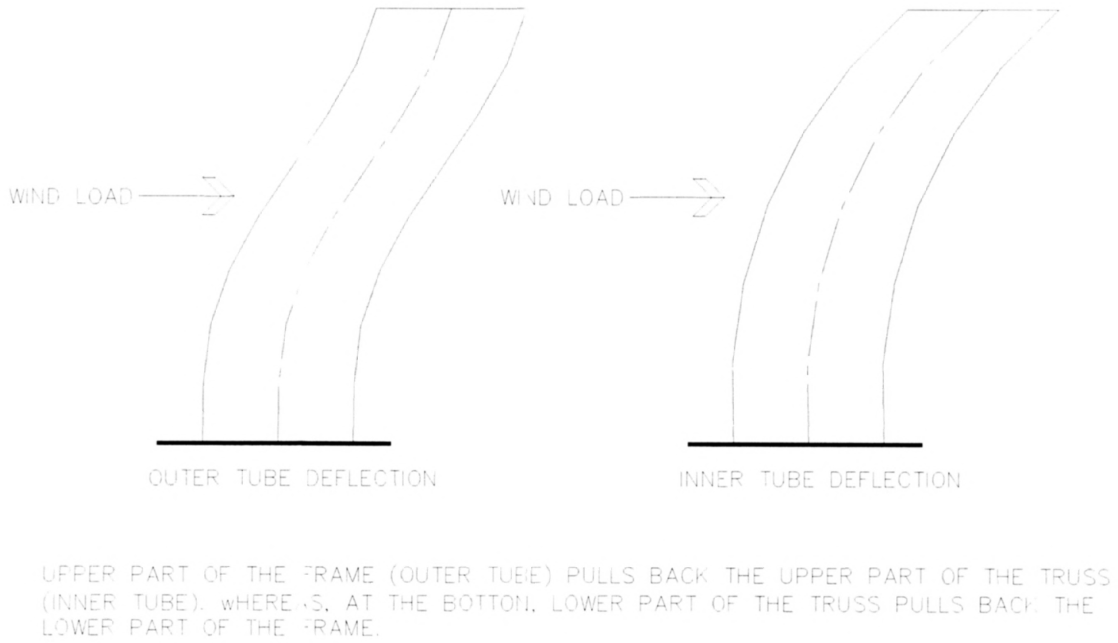

Fig. 4.4(c) Tube-in-tube

Aesthetics and Structural System

Working with architects at SOM and IIT, especially with Myron Goldsmith, Khan became more aware of the artistic potential of structural systems.[41] In the Brunswick Office Building (Fig. 4.5), he used the heavy transfer girder as a structural-aesthetic element. He believed that the girder added meaning and richness to the overall formal composition, while acting as an integral part of the structural system.[42]

With the completion of the Brunswick Building and the DeWitt Chestnut Apartments, Khan reached a thorough understanding of the tube. He was ready to publish his findings and create structural variations in projects such as the Hancock Center and the Sears Tower.

Khan, an adjunct professor at IIT since 1962, was a serious scholar. His academic work and his research were as important as the actual projects. [43] This will be discussed in the following chapters.

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[41] "Tributes to Fazlur R. Khan," *Mimar*, April, 1982.
[42] Deparment of Architecture, IIT. *Video on Fazlur R. Khan's lecture at IIT*, 1973.
[43] Zils, John. *Information package on Fazlur Khan*, October, 1997.

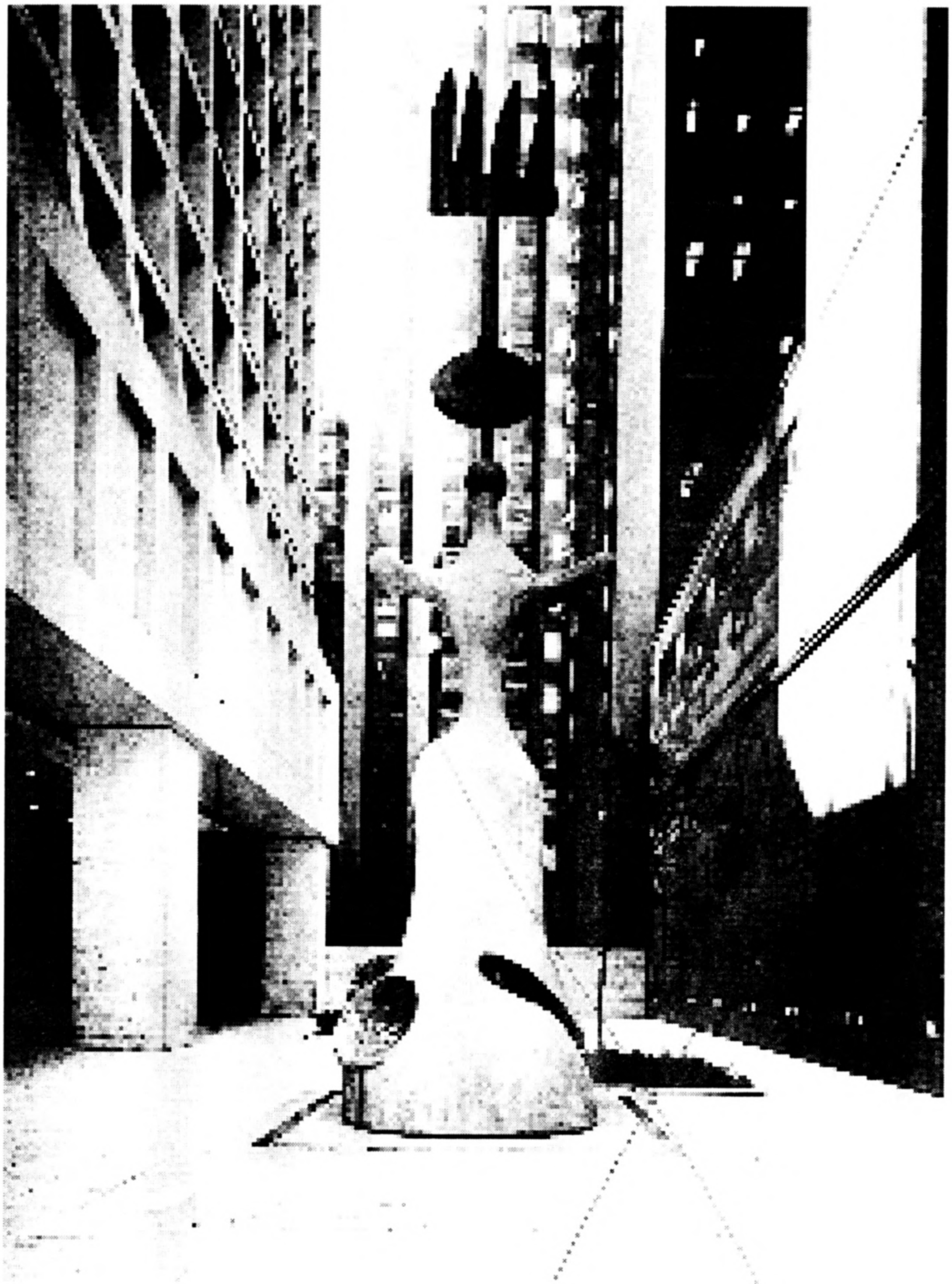

Fig. 4.5 Aesthetics through a structural element

Chapter 5

Tube - Theory of Structural Form

Khan's guiding principle was "The optimum structure for a given project is the one that is least tortuous and evolves into the form most natural for the loads imposed on it."[45] He believed that the structural design of a tall building was influenced by three factors:

1. height-to-width ratio;
2. forces and moments due to lateral loads;
3. sway under lateral loads.

He illustrated the first point through comparative graphs [Fig.5.1(a) & (b)]. It was obvious to him that the wider a building, the higher it could be built. Similarly, the forces and moments due to lateral loads could be determined quantitatively and were obvious aspects of the design. However, the third point, sway under lateral loads, required engineering judgment, experience and analysis. Khan concluded that sway factor was a critical design issue for tall buildings.

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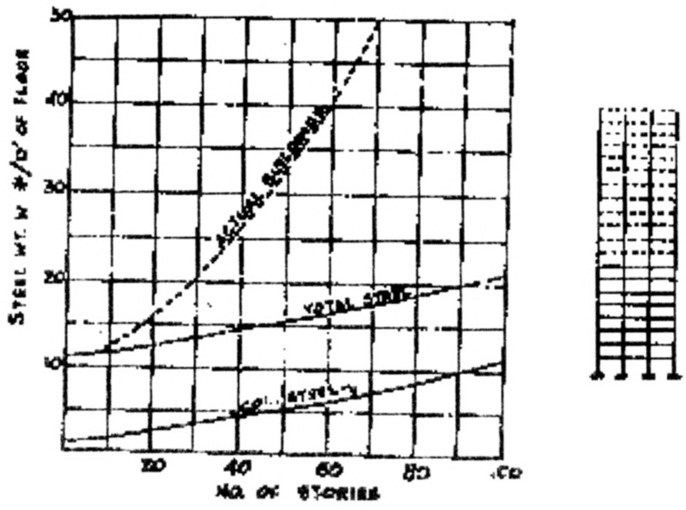
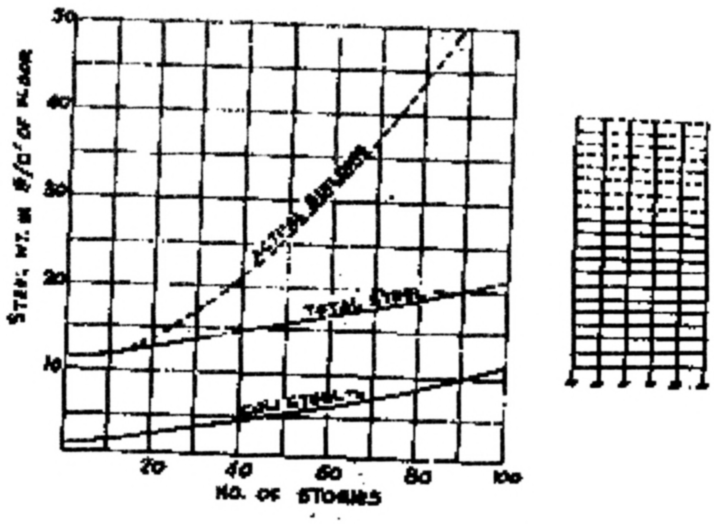
[45] Fazlur R. Khan. *Design of High Rise Buildings*. American Institute of Steel Construction Symposium on Steel Structures, Chicago, Illinois, Fall, 1965, p. 15.



(a)



(b)

Fig. 5.1a and b Effect of height-to-width ratio on cost

Wind affects a tall structure in two ways:

1. The partitions and similar light-weight members may fall, requiring costly repairs.
2. The occupants may perceive the sway to be psychologically uncomfortable.

Therefore, the structural designer must find a system to minimize the sway.

With his conviction that an optimum structure existed and that was "[the] most natural for the loads imposed on it,"[46] Khan studied the nature of wind load and the way it deformed the frame. As Fig. 3.2a on page 15 shows, the frame bends like a vertical cantilever. At the same time, shear wrecking deforms it too, as shown in Fig. 3.2a. Ninety percent of the sway is caused by frame wrecking and only 10% is caused by cantilever bending. Khan concluded that the frame wrecking was the most critical issue to study.

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[46] Ibid.

Khan commonly used the following equation, which was a simplification of the Maney-Goldberg method, to check the wrecking component of sway for preliminary designs.[47]

$$\mathbf{E\Psi = Mn/\Sigma K_{c,n} + Mn/\Sigma K_{c,g}}$$

Where,

Ψ = sway ratio such as 1/600

E = modulus of elasticity in K/in

Mn = Vn x hn = total wrecking moment in Ft. Kips

Vn = total horizontal shear at nth floor

hn = height of nth floor

$\Sigma K_{c,n}$ = sum of total column stiffness Ic/h at nth story

$\Sigma K_{c,g}$ = sum of girder stiffness Ig/l at nth level

This equation shows that sway is dependent upon the stiffness of the columns and girders. Sway would be zero if column and girder stiffness could be infinite. Practically, however, the stiffer the girders and the columns, the less the total sway. Khan drew the following conclusion on the basis of the above equation: "Study of equation ... will readily indicate that the major portion of the sway (about 90% in most cases) is due to the girder flexibility. Therefore, the most efficient way of controlling sway is to increase the stiffness of the girder."[48]

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[47] Ibid, p. 7.
[48] Ibid, p. 8.

While the search for stiffness was Khan's most important technical quest, he also searched for economy. He tried to understand the basic reason behind increase in cost versus height/number of floors. Khan determined that the structural design of a tall building involved two considerations: gravity load and wind load. First the member sizes are calculated for gravity load alone. There is no way to manipulate or minimize such loads. This sets the lower boundary of the design which is the minimum amount of structural material required, regardless of the structural system used. Next, the building is analyzed with respect to the wind loads. The column and beam sizes are increased accordingly, setting the upper boundary of the design or the maximum amount of structural material required, dependent upon the type of structural system used.

The difference between the lower boundary and the upper boundary, or the extra cost of the wind load consideration, is defined as the "premium" due to height. Figures 5.2a and b explain this phenomena for steel and concrete. Khan wrote, "The structural engineer's challenge has to refine a known system or to find and develop newer structural systems to reduce or eliminate the premium for height in any given building."[49]

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[49] Fazlur R. Khan. "Structural Theories and Their Architectural Expression – A Review of Possibilities," *Chicago Architectural Club Magazine*, April, 1981, p. 255.

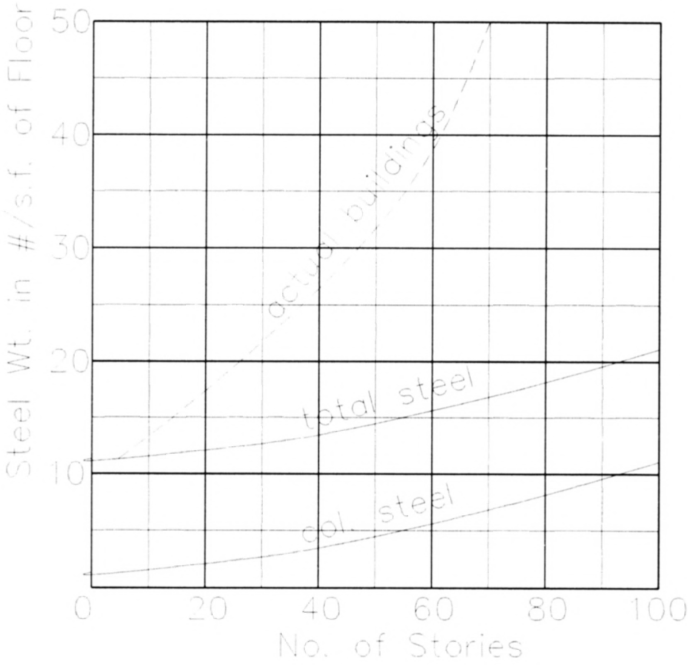

Fig. 5.2(a) "Premium" due to height for steel structures

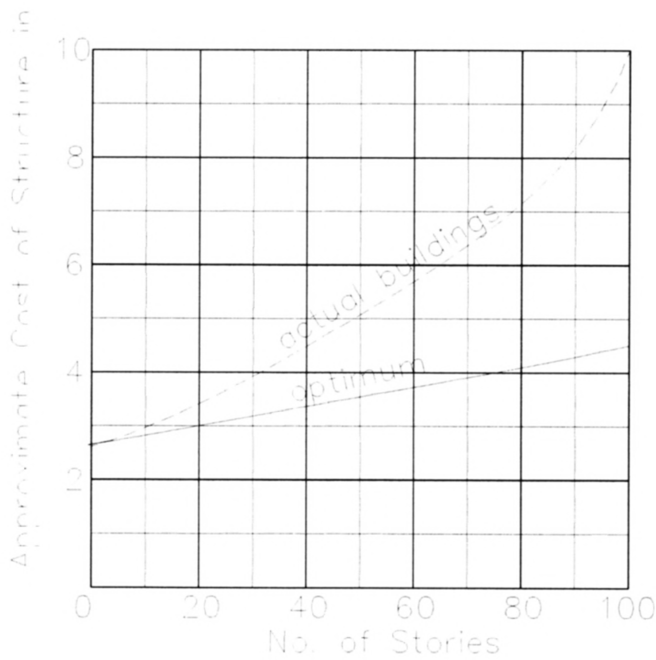

Fig. 5.2(a) "Premium" due to height for concrete structures

At IIT Khan developed various graphs to show the relationship of cost and height of a building. He also developed charts comparing various structural systems for tall buildings.[50] It is interesting to observe that all the structural systems he included in the graph were developed by Khan himself and all of them were refined forms of frame.

It can be seen that Khan's theory for finding an ideal structural form involved stiffness as the solution for wind shear and reduction or elimination of the premium for height as the basic principles.

[50] Mir M. Ali. *Architecture of Tall Buildings.* (New York: McGraw-Hill), 1995.

Chapter 6

Tube – Variations and Refinements

An analysis of Khan's later projects indicates that during his mature years he focused on the following goals:

1. improving the overall stiffness by using tubes in innovative configurations. (Hancock Center, Sears Tower)
2. creating the primary aesthetic vocabulary of the built form through the structural design of the tube, defined as Structural Expressionism. (One Shell Plaza, Houston; Marine Midland Bank, Rochester)

The Hancock Center and the Sears Tower, both located in Chicago, illustrate the first goal. To achieve the required stiffness for the 100 stories in the Hancock Center, Khan used diagonals, combining the concept of tube with that of a truss (Fig.6.1).[51]

In the Sears Tower, he bundled nine tubes together, creating the concept of bundled tube, permitting the structure to rise above 100 stories, giving great freedom in planning and form. The area on every floor was a multiple of each tube's cross-section area. Interesting massing was achieved by cutting individual tubes to varying heights (Fig.6.2).[52]

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[51] Fazlur R. Khan. "100-Story John Hancock Center in Chicago – A Case Study of the Design Process," *IABSE Journal*, J-16/82, p. 29-33.

[52] "Selected Works of Fazlur R. Khan (1929-1982) ," *IABSE Structures*, C-23/82, p. 76-77.

Fig.6.1 Use of Tube in Innovative Configurations - John Hancock Center, Chicago, Illinois

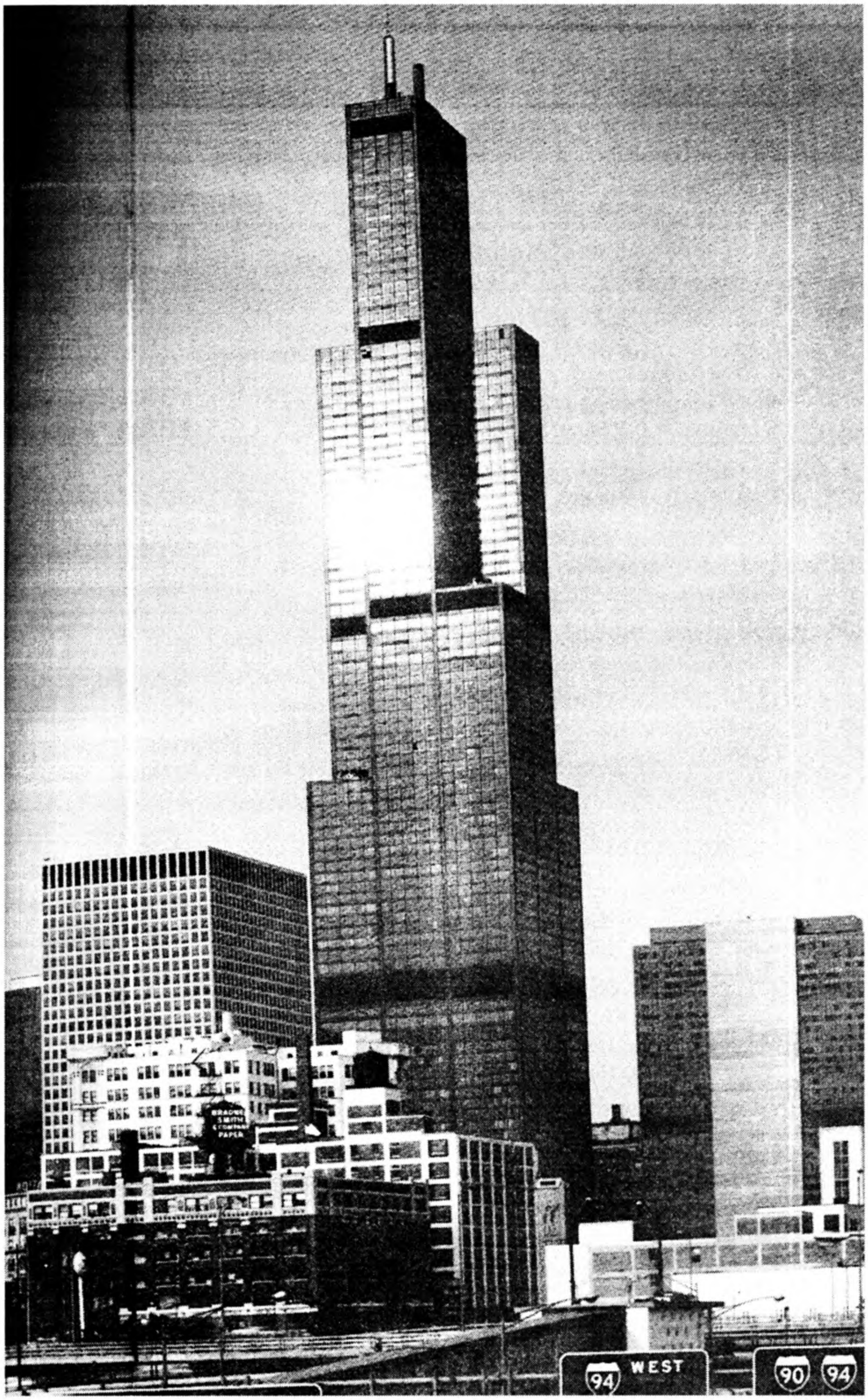

Fig.6.2 Use of Tube in Innovative Configurations - Sears Tower, Chicago, Illinois

Khan succeeded in expressing the "structural action," while looking at "tube" in detail. In his book, *The Tower and The Bridge: The New Art of Structural Engineering*, Professor David P. Billington says, when structural action (and not the structure itself) is expressed through the built form, the concept is understood as "structural expressionism" which may be created by any structural problem, for example, wind load (Eiffel Tower) or bending moment (Nervi's roof, Maillart's Chaisso truss).[53]

Figure 6.3 shows One Shell Plaza in Houston, a tube structure. Billington explains that, the floor framing is a one-way joist system, except for the corners which are two-way waffle slabs.[54] Thirty-two olumns at the transition between one-way system and the waffle slab are larger because they carry more waffle weight. Khan, during his later years, realized the expressive potential of this particular configuration, and used it in the One Shell Plaza Building. As the front view shows, increasing gravity loads in the columns next to the waffle slab can be seen in the undulating exterior, creating structural expressionism in the true sense.

Similarly in Rochester's Marine Midland Bank (Fig.6.4), the tube is beautifully expressed structurally. According to Khan's videotaped lecture, the structure grows like a tree at the base. The form expresses the manner of load transfer vertically in a masonry structure. An arched effect is created by varying the thicknesses of the columns.[55]

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[53] David P. Billington, *The Tower and the Bridge: The New Art of Structural Engineering* (New York: Basic Books Inc., Publishers, 1983), p. 236-237.
[54] Ibid, p. 238.
[55] *Video of Fazlur R. Khan's lecture at IIT*, 1973.

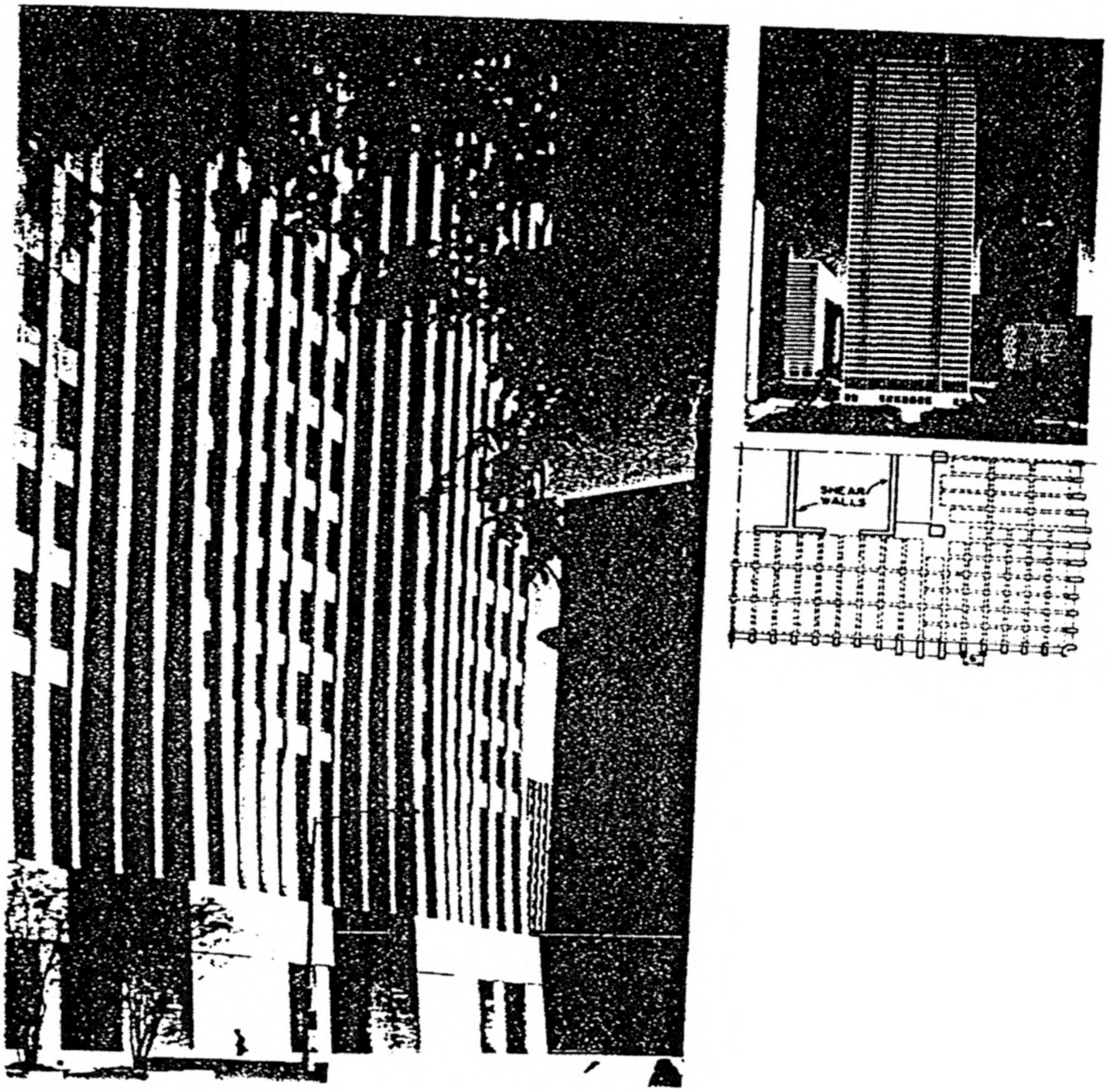

Fig. 6.3 Use of Tube to Create "Structural Expressionism" - One Shell Plaza, Houstan, Texas

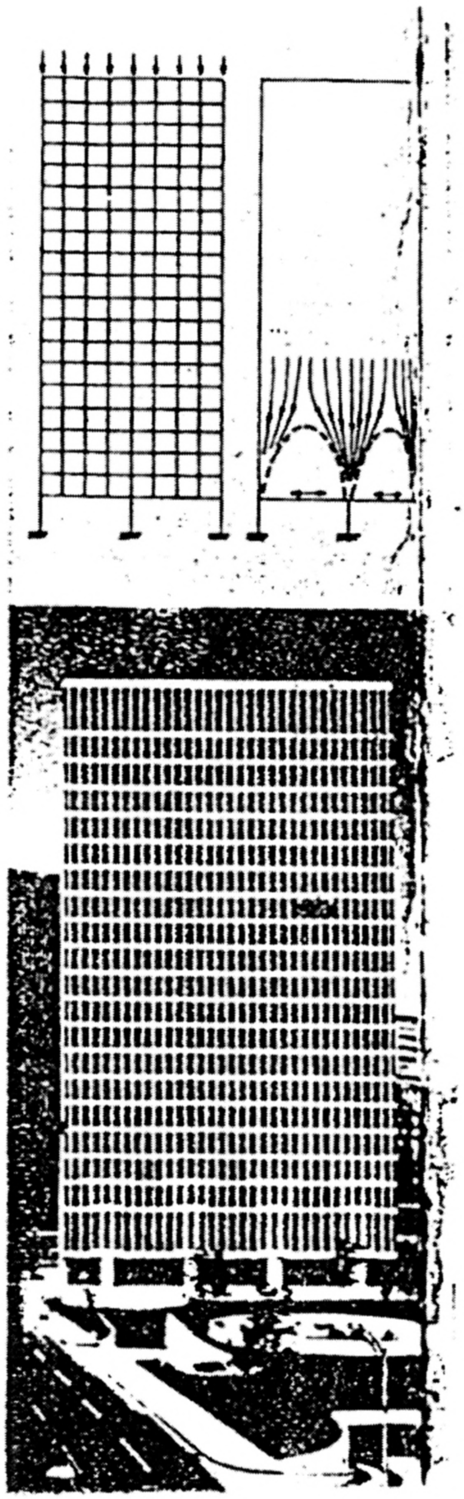

Fig. 6.4 Use of Tube to Create "Structural Expressionism" - Marine Midland Bank, Rochester, New York

Simple as these four buildings and his other projects of this period may seem in their structural concepts, they involved a long series of experimentations. There is no doubt that a thorough study of each of Khan's later works would be a great learning experience and a fascinating discovery. However, because of the vast research that would require, only one building, the John Hancock Center will be examined to illustrate the variations on the tube. John Zils believed that it was Khan's favorite building and the most intense design and building experience.[56] It was also his first famous work, marking a major transition in his career.

John Hancock Center, Chicago, Illinois, 1967

The design concept:

The Hancock Center is known by many people for the boldness of its structural frame, its diagonals and its monumental form, but few know the fascinating series of works and circumstances that gave form to this amazing structure. The building was proposed in 1965 and completed in 1967, but its structural concept had taken shape much earlier at the Illinois Institute of Technology.[57]

Khan and Goldsmith had created an environment at the IIT Department of Architecture, in which structures and aesthetics could be integrated. Mikio Sasaki, a graduate student

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[56] John Zils. *Personal Interview*, April, 1998.
[57] David Sharpe. *Personal interview at IIT*, Chicago, April, 1998.

from Tokyo, wanted to explore the design of a 60-story tall building as his gradute thesis. Khan, Goldsmith, and David Sharpe were members of his thesis committee.[58]

Sasaki wanted to design an office building that would resist earthquake loads. The prevalent theory in late fifties stated that there should be no movement during earthquake; the building should be as rigid as possible. This former theory created shear at the base of the building, resulting often times in the collapse of the first floor and the failure of the building. (Fig.6.5)[59]

Sasaki and his committee realized that there was no way in which a building could be made completely earthquake proof. However, if the frequency of the building was dissimilar to that of the earthquake, the shear problem could be avoided. Therefore, a flexible or non-rigid building might be more appropriate than a rigid one. Such a structure could vibrate with a frequency dissimilar to that of the movement of the earth. Sasaki's thesis began with this concept.[60]

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[58] Ibid.
[59] Ibid.
[60] Ibid.

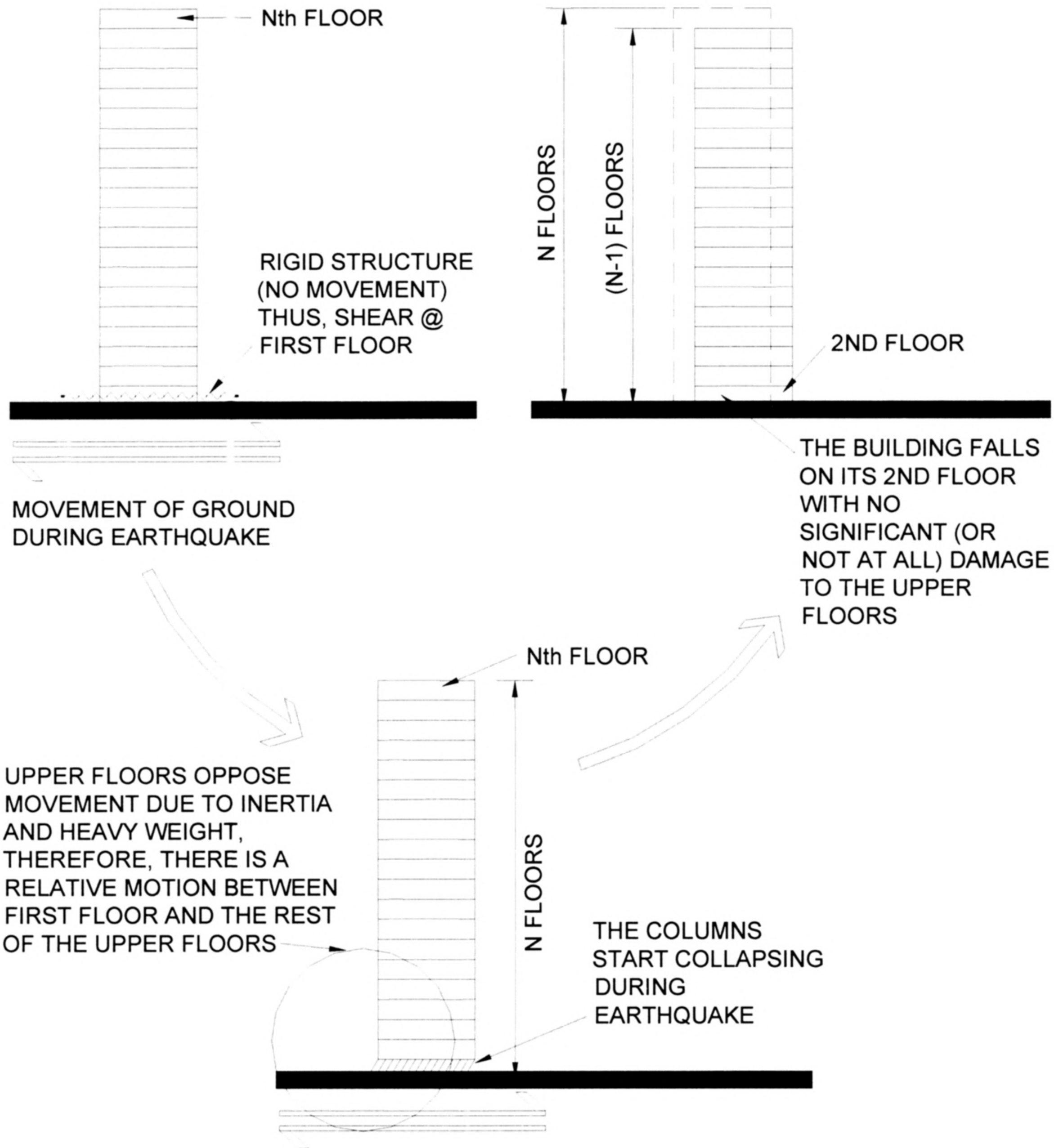

Fig. 6.5 Analysis of the earlier theory that for earthquake, the building should be "rigid"

However, the consideration for wind loads required that tall structures be non-flexible. As a solution, Khan suggested using X-bracing to Sasaki, an idea Myron Goldsmith had developed earlier in his graduate thesis as a student of Mies, but Figure 6.6 shows that Goldsmith's use of X-braces was quite different from Khan's. Thus, Khan and Goldsmith both contributed to the idea.[61]

Sasaki and his advisors adopted the "tube" as the primary structural system and steel as the building material because of its elastic properties (Fig.6.7). The X-braces were expected to handle all of wind load and some of the gravity load. The geometry of the frame was developed according to the structure (Fig.6.8).[62]

Because it was new a new concept, X-bracing had to be thoroughly tested. In the absence of appropriate computer programs, and because of limitations of manual calculations, a model was vigorously tested for wind and earthquake loads. The project was completed in 1962 and would provide background study for the John Hancock Center (Fig. 6.9).[63]

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61 Ibid.
62 Ibid.
63 Fazlur R. Khan, S. H. Iyenger, and J. P. Colaco. "Analysis and Design of the 100-Story John Hancock Center in Chicago (U.S.A.)," *Acier Stahl Steel*, No.6, 1968, p. 271-274.

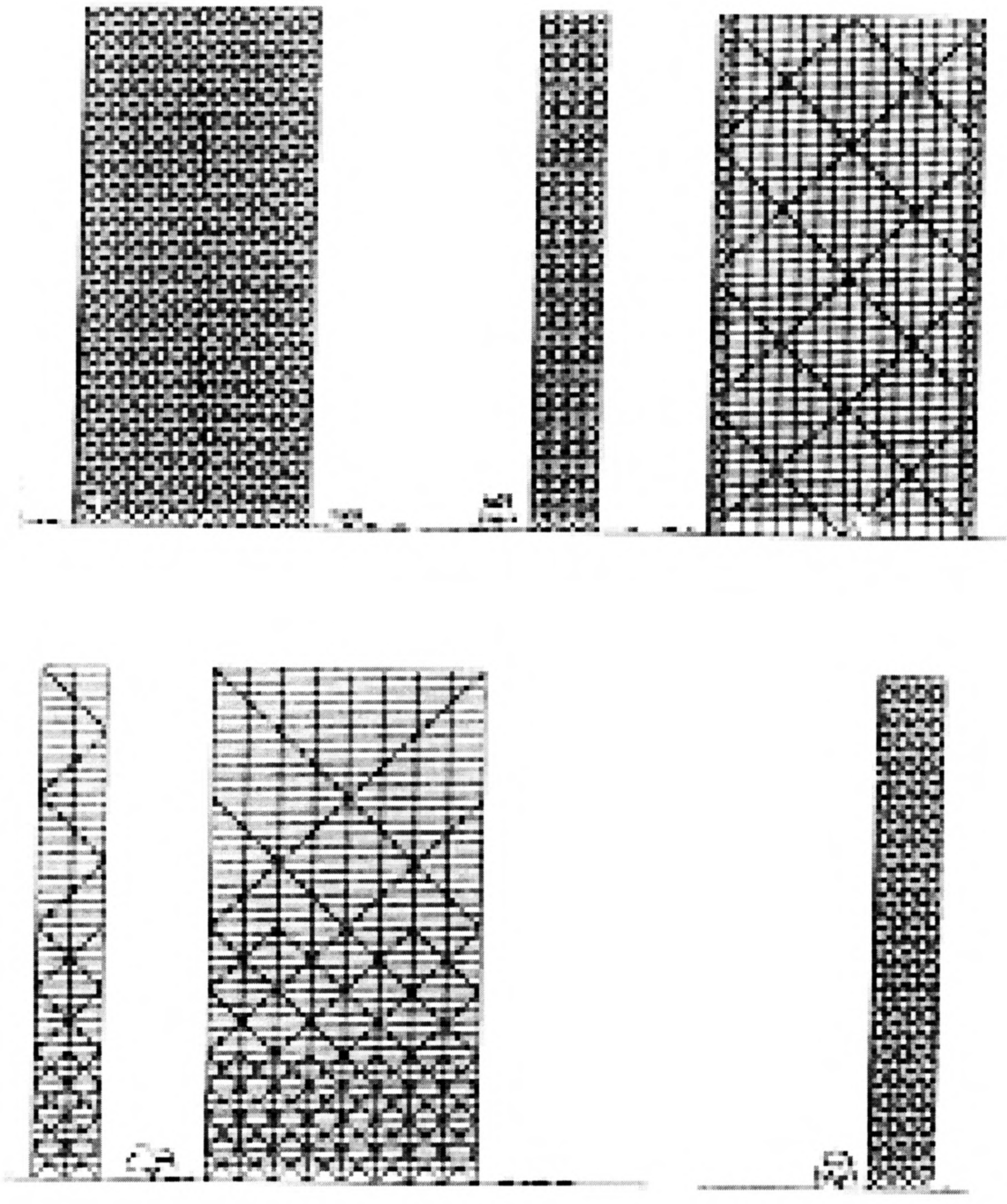


Fig. 6.6 Study of X-braces by Myron Goldsmith at IIT during his Masters program with Mies van der Rohe as his advisor

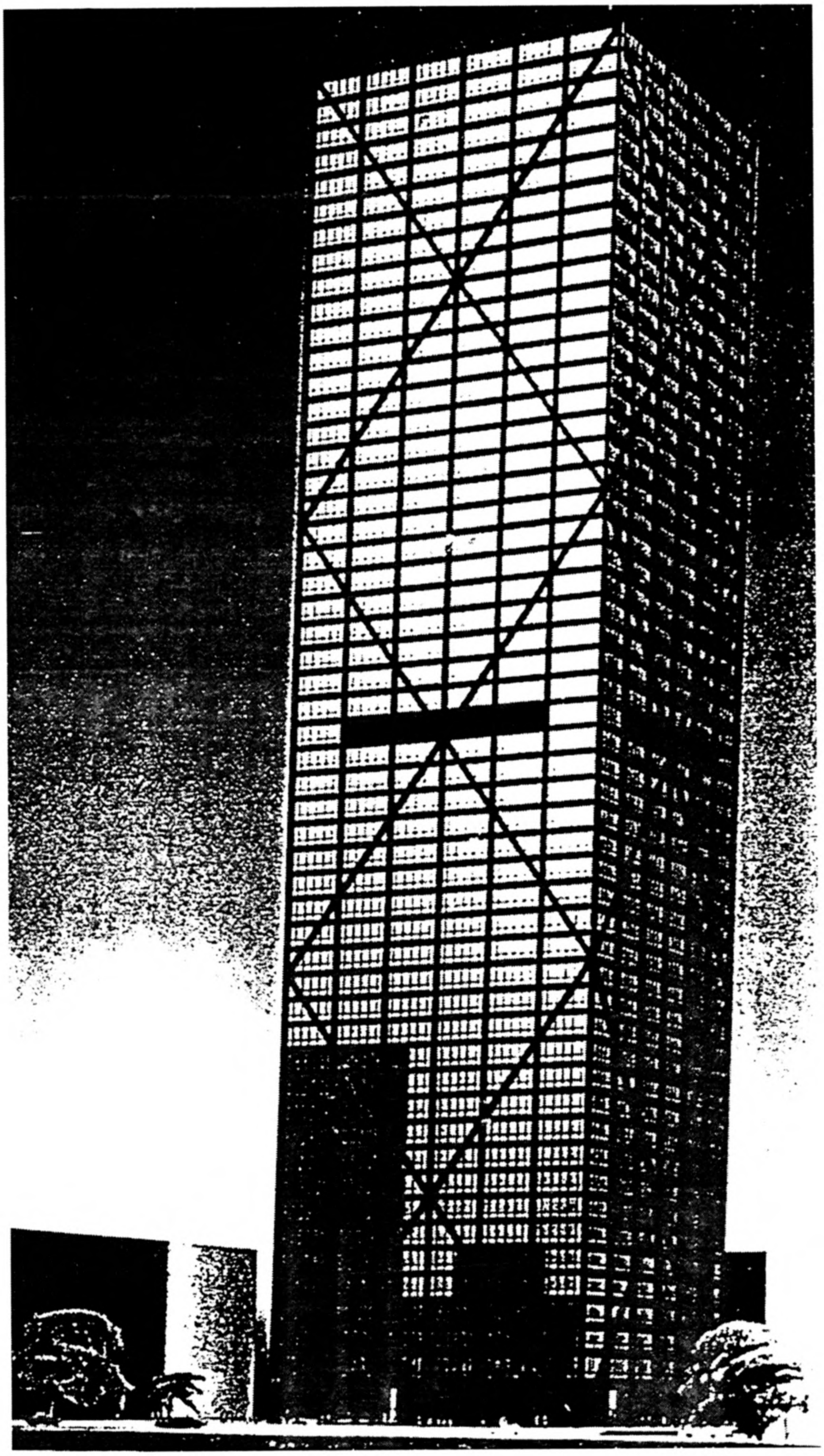
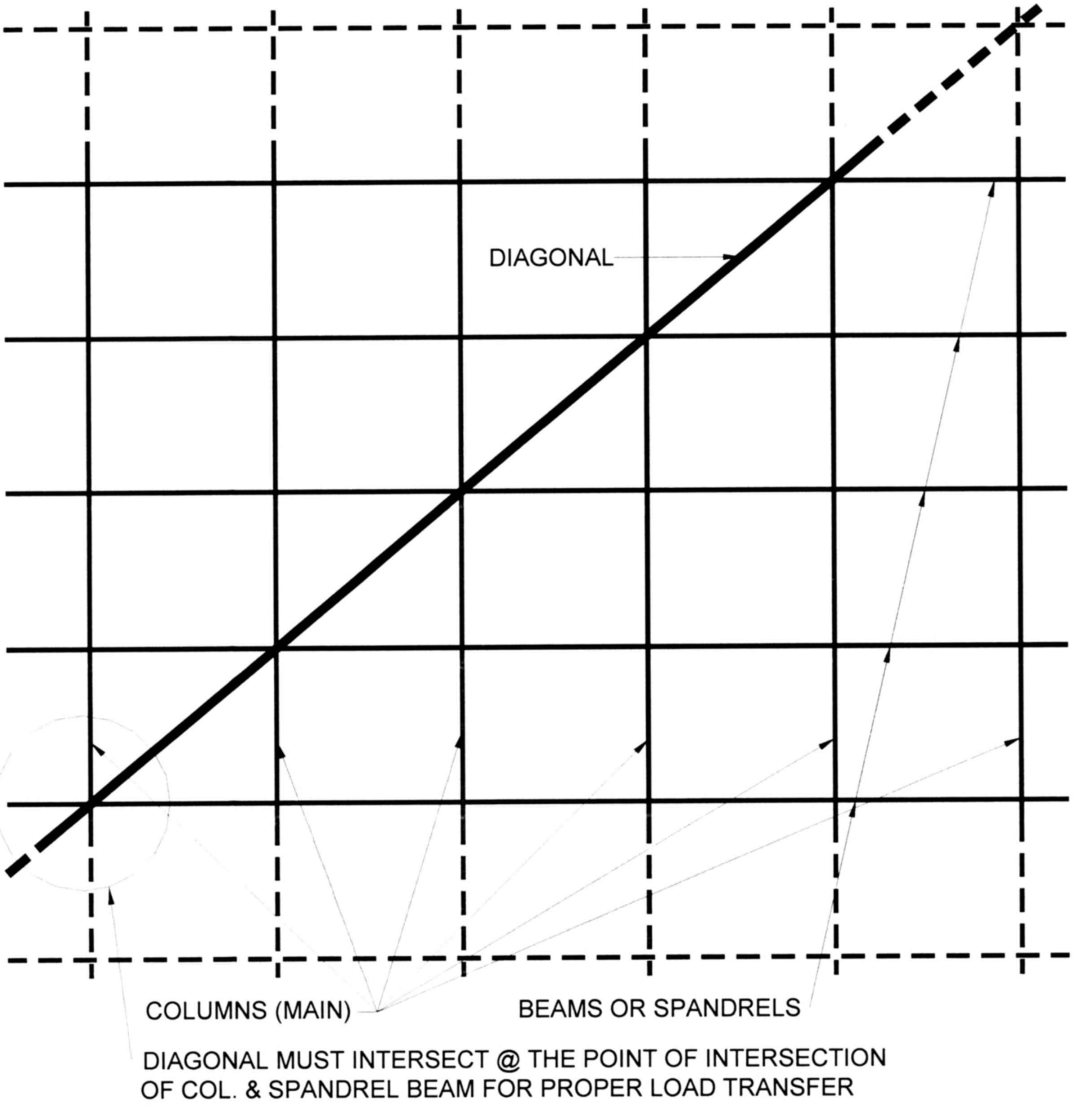


Fig. 6.7 Master's Thesis: Mikio Sasaki (1982)

NOTE: ALL OF THE LOAD OF THE BUILDING IS TRANSFERRED TO THE OUTSIDE (TUBE) AND FINALLY TO THE CORNER COLUMNS..



DEVELOPMENT OF STRUCTURAL CONCEPT THROUGH GEOMETRY

Fig. 6.8 Structural concepts developed through geometry for Sasaki's Project and later applid to John Hancock Center

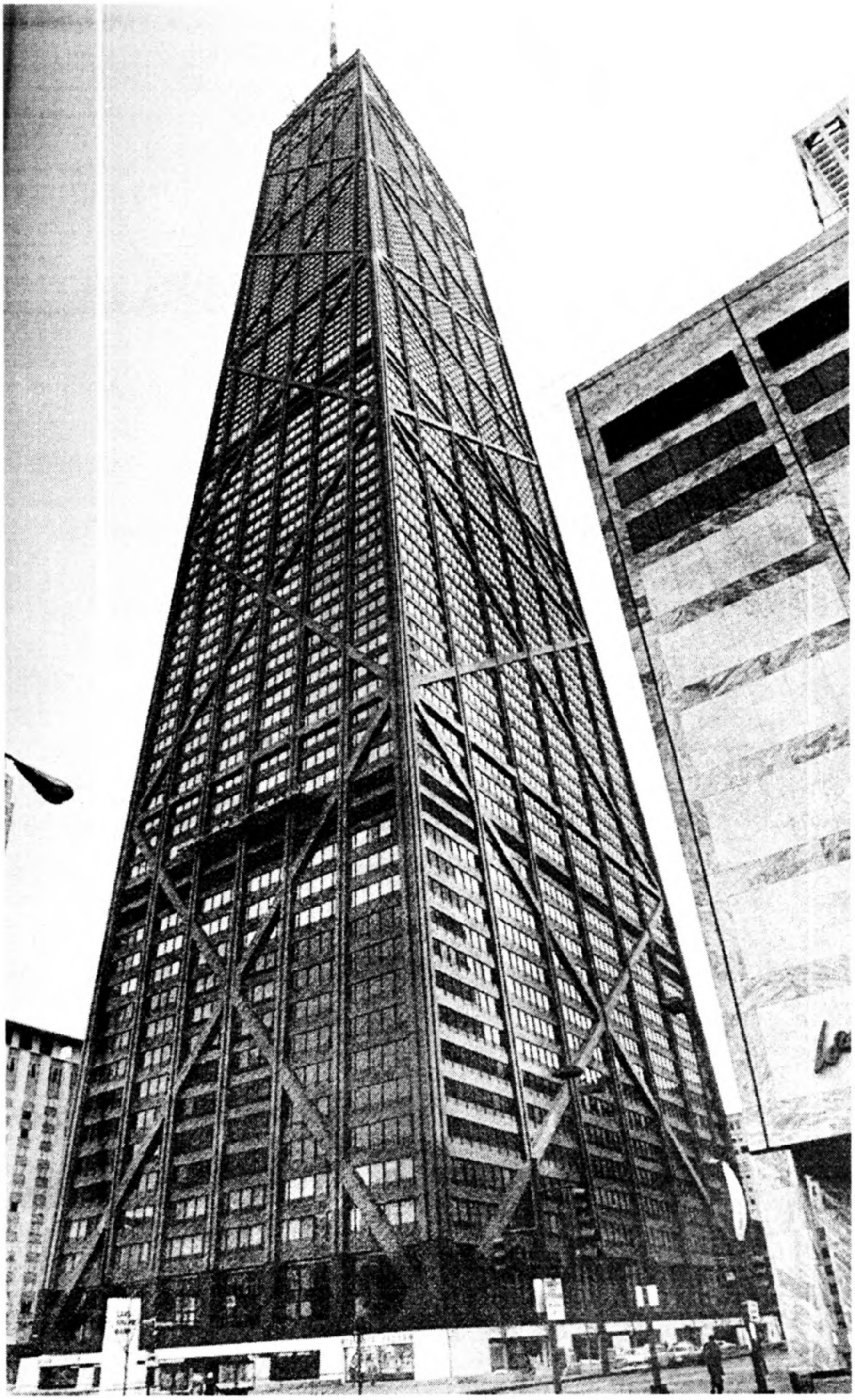


Fig. 6.9 John Hancock Center, Chicago, Illinois

In the early sixties, builder-developer Jerry Wolman consulted SOM as to the best way to develop the land he owned on North Michigan Avenue. Analyzing the nature of the neighborhood, which was made up of both commercial and residential buildings, SOM suggested that Wolman build a multi-use complex, so as to gain continuous income.[64]

Designer-in-charge, Bruce Graham, a staunch Miesian, and his team worked out a two tower scheme: a 45-story office tower and a 70-story residential tower. (Fig. 6.10a) It did not prove satisfactory because the towers took up too much ground area, providing a quiet zone for the lower residential units was difficult to achieve, the towers created environmental problems, and the massing of the two blocks was not aesthetically satisfactory. During the struggle to solve these problems, someone asked, "Why not put one tower on top of the other?" The idea of a single gigantic structure, culminating in the startling form of the Hancock Center was born.[65]

The mixed-use structure had to accommodate shops, offices and various types and sizes of residential units. The apartment tower of the original scheme was placed above the office tower, resulting in a tapering form. The major issue now was to find a structural system to support this 100-story building.[66]

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[64] "Chicago's Multi-Use Giant," *Architectural Record*, January, 1967, p. 137-142.
[65] This paragraph is based on: Hoag, Professor Richard L. *Video on Fazlur R. Khan's lecture at IIT*, 1973.
[66] Fazlur R. Khan. "100-Story John Hancock Center in Chicago – A Case Study of the Design Process," *IABSE Journal*, J-16/82, p. 28-32.

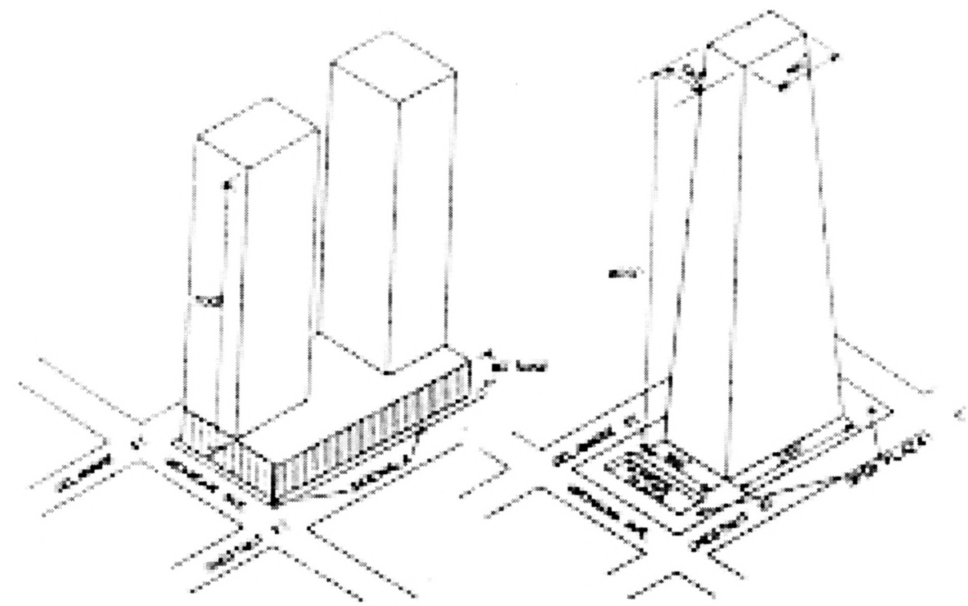

Fig. 6.10(a) Comparison of the traditional and the final architectural concept

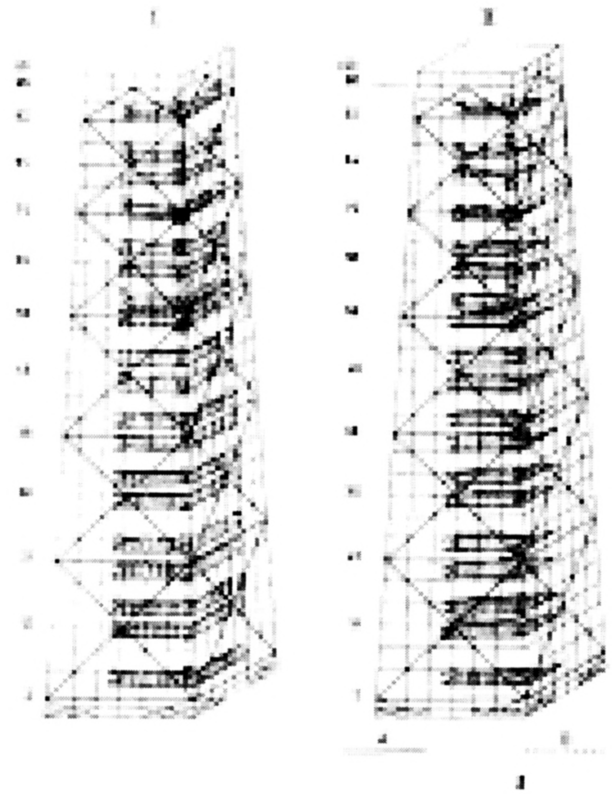

Fig.6.10(b) Structural Steel used for the John Hancock Center

Khan was the chief structural designer for the project. Inspired by Sasaki's thesis, he suggested a tube-in-tube structure with the outer shell being a tapering tube with diagonal braces, resulting in a vertical truss-like structure. Steel was selected as the primary building material because it permitted great heights (Fig. 6.10b).[67]

The Structural Concept

Diagonals increased the stiffness of the tube tremendously, and tied the building to the floors and to the corner columns. These columns were much heavier than the rest of the columns. Each diagonal intersected in such a way that the point of intersection coincided with a floor. Ends of the diagonals met the ends of the other diagonals at the edge columns. The angle of the diagonals was geometrically determined (Fig.6.8). Approximately every eighteenth story acted as a tie for the huge diagonals. This assembly formed the primary structural system. The remainder of the spandrels and columns formed the secondary structural system for the outer tube. The outer tube resisted all of the lateral wind load and part of the gravity load; the inner core shared the rest of the gravity load. The tapering form reduced the total wind load due to "sail effect."[68]

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[67] John Zils. "Personal interview," at SOM, Chicago, April, 1998.

[68] Wind load increases parabolically with height.Therefore, a tapering form with diminishing surface area towards the top withstands wind load more efficiently, compared to a non-tapering form. This concept is understood as "sail effect." Ship design uses this principle, to allow ships to sail fast against the upcoming winds.

Because of this structural system, the amount of steel used was remarkably low, comparable to what would be required for a conventional steel structure half that height. The Hancock Center used 29.7 lbs. per square foot steel of non-high strength type.[69] The structure was tested thoroughly for its response to anticipated wind loads (Fig.6.11a).

Although the structural system was new and the form was huge, SOM accepted Khan's proposal of X-braces because the idea had been thoroughly studied, analyzed, and tested at IIT years before. Convincing the developer took some effort, particularly by Khan.[70]

Planning Phase

Once the basic structural system was determined, the spaces for shops and stores, offices, and residential units of varying requirements and types were considered. The elevator system and the gradually decreasing floor area dictated their location. (Fig.6.11b). Floors one to five would be commercial and service spaces. They were expected to be used heavily throughout the day. The parking area was to be located on floors six to twelve, and office spaces would occupy the thirteenth floor and on, up to the sky lobby which would relieve the elevator loads at the forty-fourth and the forty-fifth floors. The residential units were above this floor to the ninety-third floor.

[69] "Chicago's Multi-Use Giant," *Architectural Record*, January, 1967, p. 137-142.
[70] David Sharpe. *Personal interview*, at IIT, Chicago, April, 1998.

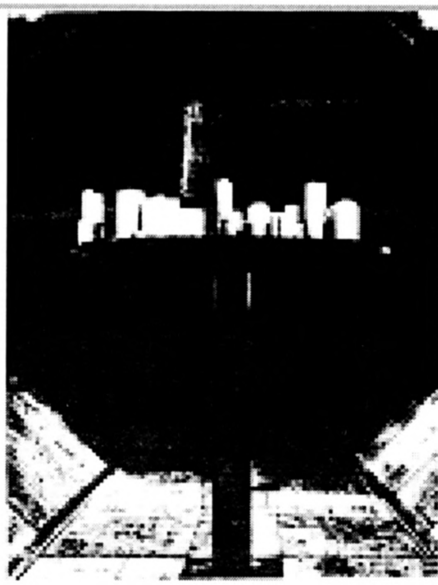

Fig.6.11(a) Wind Load Tests for Hancock Center

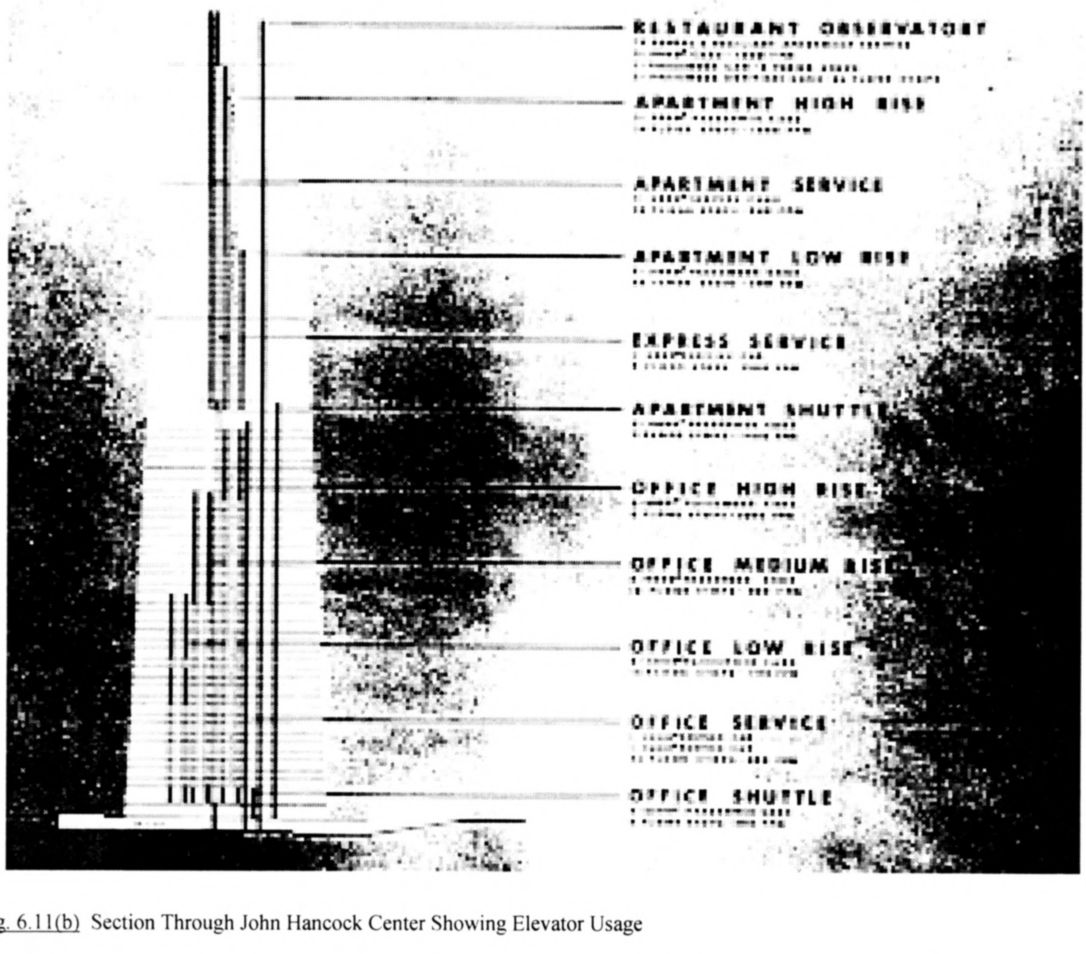

Fig. 6.11(b) Section Through John Hancock Center Showing Elevator Usage

Five typical plans were devised for the residential floors. Studios and efficiencies were on the lower floors. Above that were apartments with two to three bedrooms. The uppermost residential units had four bedrooms. The residential floor plans were symmetrical on the east-west as well as the north-south axes. An observatory was designed at the ninety-fourth floor, a restaurant on the ninety-fifth and the ninety-sixth floors, television rental on the ninety-seventh, and the ninety-ninth and one hundredth floors were designated for the mechanical systems (Fig.6.12, 6.13).[71]

The huge tower, made possible through a revolutionary structural idea, places the Hancock Center at an important juncture in the history of modern architecture.[72] Diagonal bracing to achieve greater rigidity in steel tubes required much less structural materials, and thus made possible the idea of a super tall building at an amazingly low cost per square foot of floor area.[73] This saved the client fifteen million dollars.[74]

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[71] "Chicago's Multi-Use Giant," *Architectural Record*, January, 1967. p. 137-142.
[72] William J. R. Curtis. Modern Architecture Since 1900, (Upper Saddle River, N.J.: Prentice Hall, 1996), p. 558.
[73] "Chicago's Multi-Use Giant," *Architectural Record*, January, 1967, p. 137-142.
[74] Ibid.

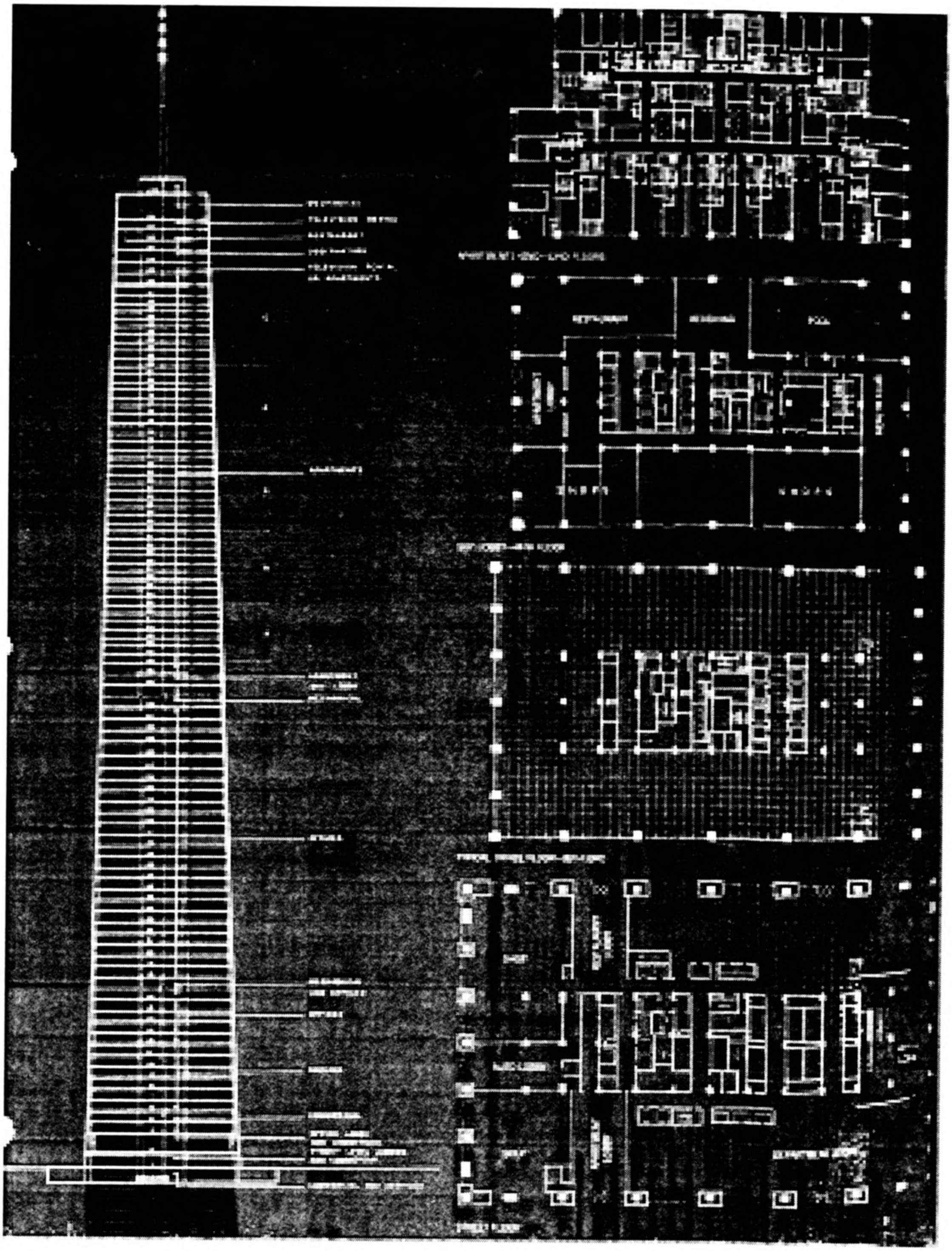

Fig. 6.12 Plan(s) and Section for John Hancock Center

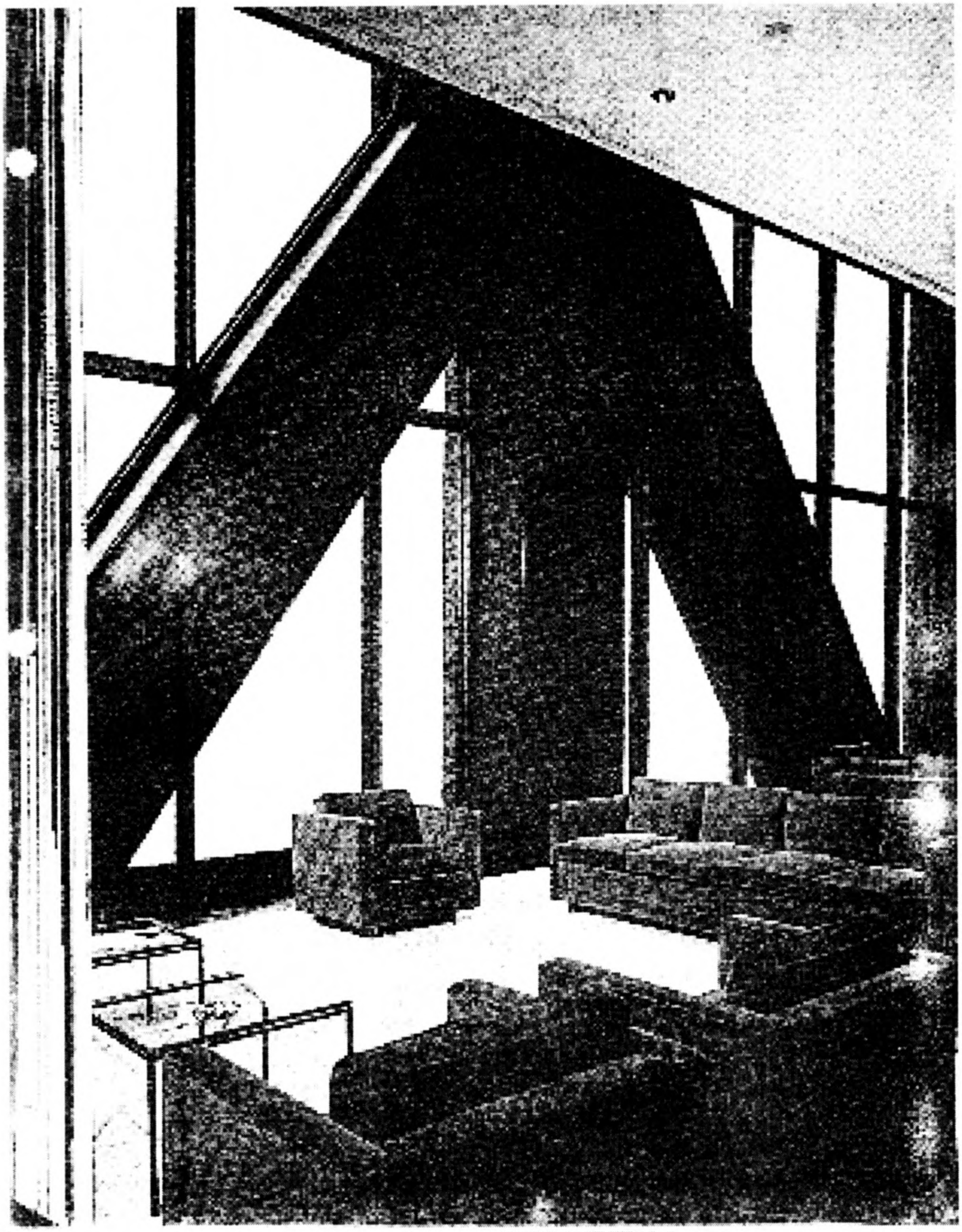

Fig. 6.13 Interior View Showing X-braces As the Most Domineering Aesthetic Element of the Interiors

Structural System – An Aesthetic Statement

Khan's suggestion of diagonal braces was more than a structural consideration. He was also inspired by the aesthetic elegance of X-braces, convinced that, if continued to the top of the building, they would create a monumental impact and spiritual aesthetics. Structurally, the diagonal braces could have been terminated above the 90th floor, but Khan insisted on continuing the diagonals, not only to improve the structural system, but to maintain aesthetic elegance and integrity of form. He revealed this in his article "100-Story John Hancock Center in Chicago - A Case Study of the Design Process" posthumously published in *IABSE JOURNAL J-16/82*.

> "As the building was being developed and its structural architectural form was taking shape, the architectural team responding to the owner's concern wanted to take the diagonals on the exterior of the building only up to the 90th floor leaving the top few floors above the tube system [fig.6.14]. It was vehemently argued by the architectural team that the diagonals above that level would jeopardize the viewing and the interior openness to the outside which was presumed to be an imperative for studios and restaurants at those levels. First renderings of the building were developed without showing the top ten floors having any diagonals. Although one may argue that from a structural point of view one could have designed a building without diagonals in the upper two floors, from a philosophic point of view and from a structural visual continuity of the system itself, it would be a tragedy to terminate the diagonals abruptly on the 90th floor. In various discussions this appeared to be a main point of difference between the architectural team and the author. However, at the end, the author made an impassioned argument that not having the diagonals in the upper ten floors would add a tremendous amount of additional steel to the building, the cost would skyrocket, and it might, in fact, be too flexible causing motion discomfort on those floors. This argument finally won out and

> the diagonals in the upper ten floors were put back. The author, the structural engineer, and Bruce Graham, the architect, are now of the same opinion that the integrity of the structural-architectural expression of the building was indeed enhanced and recaptured by continuing the diagonal scheme all the way to the top of the building."[75]

Today the Hancock Center stands as a widely-known structure, because of its innovative and amazing form. Developed with commercial motives, it looks more like an isolated monument. Its form, diagonal braces and its taper, transcend engineering logistics, and present themselves as a coherent artistic expression. It has somehow acquired a haunting imagery, a sculptural aura.

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[75] Fazlur R.. Khan. "100-Story John Hancock Center in Chicago – A Case Study of the Design Process," *IABSE JOURNAL*, J-16/82, p. 31-32.

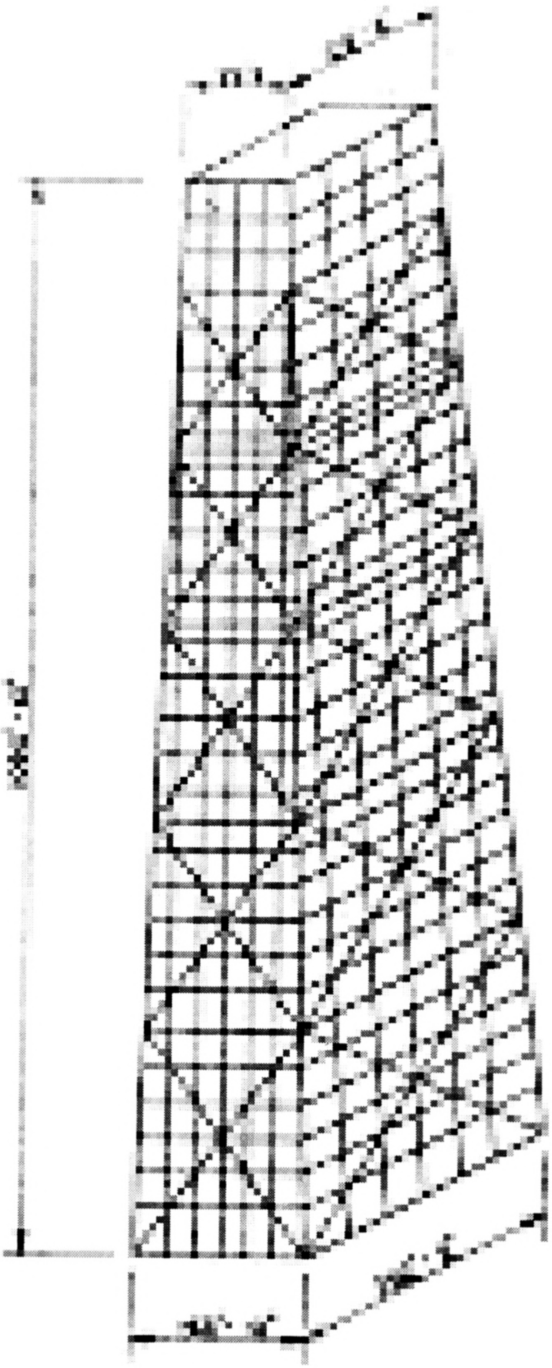

Fig. 6.14 Truss tube structure without diagonals above the 90th floor

Chapter 7

KHAN'S PHILOSOPHY

To those who are familiar with his works, Fazlur Khan is known as a technical expert. But to those few who knew him personally, he was a great humanist, a philosopher, and an understanding friend – then a great structural innovator. He claimed that "[the] social and visual impact of buildings [was] really my motivation for searching for new structural systems."[76]

Empathy for People

Khan developed the ability to understand people and their problems. His fully devoted involvement in the political upheaval of Bangladesh, the numerous occasions when he was entrusted with the role of the negotiator, and his ability to communicate complex technical ideas in very simple terms are indicators of his empathy for human beings. As Lynn S. Beedle, Director of the Council on Tall Buildings and Urban Habitat, stated, "When he became Chairman of the Tall Building Council, we already knew of his easy way of dealing with people and of his clarity of thought in technical matters."[77]

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[76] "Construction's Man of the Year: Avant Garde High-Rise Designer Fazlur R. Khan," *Engineering News Record*, February 10, 1972, p. 23.
[77] Lynn S. Beedle. *Khan Tributes*. (Paid to Khan at his funeral on April 2, 1982, and at the memorial service on May 6, 1982, assembled at SOM and Lehigh University, May 1983).

Khan worked hard to develop his understanding of human nature and the human condition. According to his wife Liselotte Khan,

> "It may be hard for most of you to believe that as a child Fazlur, I was told, was very hard to manage and often displayed his temper and stubbornness. In fact, whenever Fazlur went to spend vacation with some of his relatives, his father would always send along a letter with exact instructions on how to deal with him.
>
> "As Fazlur grew up, however, he realized that he disliked many of his personal traits and with his father's encouragement, he started to make himself into the person he considered his ideal. So, as a young man when his peers read novels and stories of adventure, Fazlur read the works of many of the great philosophers and psychologists. That was when he started to develop his life's philosophy and his knowledge of [sic] psychological process. Thus, Fazlur really had to work hard to acquire his knowledge of man. In fact, quite often, when he discussed some incidents, he would write it [sic] down to make sure he would not forget the next time how people reacted to such a situation. He would talk to people, he would read about people, he would read novels, in order to get a large reservoir of knowledge of human personalities that would provide him insight in dealing with other people in future situations because he felt his intuitive knowledge of people was very limited."[78]

Empathy for Structures

While Khan's understanding of human nature was acquired through intense study, the understanding of structures came quite naturally and intuitively. Lisolette explained,

[78] Liselotte Khan. *Khan Tributes*. (Paid to Khan at his funeral on April 2, 1982, and at the memorial service on May 6, 1982, assembled at SOM and Lehigh University, May 1983).

"On the other hand, however, what was totally innate to him was his feeling as a physical scientist. Fazlur's great strength and the sources of his creativity as an engineer were his intuitive understanding of the materials and the forces of nature. He told me once that when he designed a building, he became the building. He was able to sense and feel all the forces that would go through the building, the wind that blew at it, the gravity that pulled it. And he knew exactly where it had to be reinforced and where it did not require. Because to him, the building was him. His intuition took him into the nature of matter and into physical forces of nature. And that's why he was able to design buildings that were so totally natural."[79]

Khan worked closely with Srinivasa Iyengar, structural engineer and SOM partner. Iyengar stated,

"His initial period at SOM was devoted to innovation and inquiry within the area of structural analysis and design. His approach was always to devise simple solutions to rigorous mathematical problems. He developed simple techniques to extract primary influences from a complicated mathematical process. This allowed him to mentally observe a wide range of problems and absorb the essential structural behavior. Together with an excellent grasp of geometry, his visual imagery of structural load flow was key to his ability to innovate systems. This intensive scrutiny into structural behavior allowed him to develop strong intuitive feelings toward the structures he designed.

"His intimacy with structures led him to define a set of natural order of structures to best deal with forces of nature for each project. Forced and devious solutions were anathema to his philosophy. This process of naturalizing the structure has resulted in many direct expressions of structure in architecture. He firmly believed in low technology and direct design approaches for resolution of high technology systems and problems. His clear message to all engineers was: 'Develop

[79] Ibid.

> basic understanding of the behavioral aspects of structures and don't get lost in the details of your own technology."[80]

Second Chicago School, Modernism, and Khan

Khan was one of the leaders in the "rationalist" strand of modernism. He believed that every design decision must be based on rational or practical logic. He had humanitarian vision and compassion for human beings, probably heightened by the struggles and dire state of his native people. Technology was his tool and he believed in the honesty of expression in structures and materials. Influenced by Bruce Graham and Myron Goldsmith, both followers of Mies, and the Chicago environment, Khan developed the ideologies of the Second Chicago School.

Khan opposed post-modernism. Observing the decline of structural logic with the advent of post-modernism, Khan said, "Today it seems, the pendulum has swung back again towards architecture that is unrelated to technology and does not consciously represent the logic of structure. Nostalgia for the thirties and even earlier times has hit a large segment of the architectural profession; in many cases façade-making has become the predominant occupation."[81]

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[80] Srinivas Iyanger. *Khan Tributes*. (Paid to Khan at his funeral on April 2, 1982, and at the memorial service on May 6, 1982, assembled at SOM and Lehigh University, May 1983).
[81] Mir M. Ali. *Architecture of Tall Buildings.* (New York: McGraw-Hill, 1995), p. 281.

With post-modernism, the creative role of structures was diminished. Khan speculated that the new generation of engineers became problem-solvers but did not that of think of a problem in wholistic fashion. He blamed overspecialization for this: "The logic of structure has become irrelevant once again. This attitude in architecture suits many engineers because of their overspecialization in engineering schools which treats the solution of the problem as the ultimate goal, and not the critical development of the problem . . . any structure can be made to work with many engineers gladly willing to play with computers and come up with answers to hold up the building."[82]

Sense of Aesthetics

Though Khan was a structural engineer, his natural willingness to learn and his ability to talk with architects gradually refined his aesthetic sensitivity. Myron Goldsmith summed up the development of Khan's aesthetic sensibilities: "We are not born with refined aesthetic judgments. In the early years of his teaching, Fazlur deferred to the architects, but he developed these sensibilities and, in his mature years, he participated as an equal in these discussions and judgments–and, in fact, brought to them a fresh perspective. He no longer confined his interest solely to the technical factors of a solution, but the aesthetic, cultural, and social aspects as well."[83]

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[82] Ibid.
[83] Myron Goldsmith. *Khan Tributes*. (Paid to Khan at his funeral on April 2, 1982, and at the memorial service on May 6, 1982, assembled at SOM and Lehigh University, May 1983).

Khan's wife, Liselotte, also observed his efforts to improve his aesthetic sensitivity: " . . . he had a strong sense of aesthetics, and he even read books about aesthetics, as for instance he read often Santayana *On the Nature of Beauty*. So the forms he created, they were both natural to the material and to the physical forces required–and thus they also became beautiful shapes and forms and spaces."[84]

In 1970, Khan was made a general partner of SOM along with 19 architects.[85] "The greatest step the building team has made in the past decade," Khan wrote, "is that the engineer, as part of the team, is finally looking at the whole structure with architecture integrated as part of the whole. This group thinking results in a systems building that satisfies all requirements."[86]

Paul Weidlinger, also a structural engineer and one of Khan's closest friends, said, "Faz excels in engineering because he talks to architects. He can talk to them because he's conscious of aesthetics."[87]

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[84] Liselotte Khan. *Khan Tributes*. (Paid to Khan at his funeral on April 2, 1982, and at the memorial service on May 6, 1982, assembled at SOM and Lehigh University, May 1983).
[85] SOM, Chicago. *Information package,* October, 1997. (Courtesy, John Zils)
[86] "Construction's Man of the Year: Avant Garde High-Rise Designer Fazlur R. Khan," *Engineering News Record*, February 10, 1972, p. 21.
[87] Ibid.

Belief in Teamwork

Collaboration or team-work was the keyword in Khan's engineering practice. He rejected the idea of compartmentalizing various tasks among the team-members. Khan could realize his visions because he worked as a collaborator with his design partner, usually Bruce Graham, neither leading him nor following him. He believed strongly in the exchange of ideas and creative efforts to design and build a structure. The John Hancock Center illustrates the importance of team-work in building process.

Khan was well-known and highly respected at SOM for introducing the cross-breeding of ideas between various experts in a building team. "Many architects are brought up to think that they are the only creators and that the engineers are technicians." Khan claimed. "This must stop. The engineer has to be an architect to the extent that the architect has to be an engineer so that in combination they produce a creative building."[88]

Both Khan's personality as well as the freedom and respect he enjoyed at SOM allowed him to develop his structural philosophy so effectively. Nathaniel A. Owings of SOM said, "There exists here a fine equation involving the interaction of two mysterious forces. One force is Faz Khan. The other is the complex body of dedicated anonymous workers in SOM within which framework Faz accomplished new heights in creative design through the use of enhanced engineering principles working collaboratively with

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[88] Ibid, p. 23.

his architectural peers. But the anonymity and the autonomous character of the nerve centers of the firm gave Faz Khan the freedom of action he needed."[89]

Not only in actual projects, but also at IIT, Khan was well-known for his team-approach. It was through the collaboration of academia and his profession that many innovative ideas were realized. He often used to say to his students, "Some day, we will find a building where these ideas will be used."[90] And he did use them in two Chicago projects, the Hancock Center and the multi-use Onteri Center complex.

Value of Education

Khan's dedication to IIT students is proof that he valued education. It was from his parents and the environment of his home that he developed a profound faith in learning. He contributed to education and research by publishing more than 75 technical papers, giving lectures and seminars all over the world and by teaching at IIT. Lehigh University has established a Bangladesh Scholarship in the memory of Fazlur Khan.[91]

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[89] Nathaniel A. Owings. *Khan Tributes*. (Paid to Khan at his funeral on April 2, 1982, and at the memorial service on May 6, 1982, assembled at SOM and Lehigh University, May 1983).

[90] Ibid.

[91] American Association of Bangladeshi Engineers and Architects. *Fund-Raising Dinner for Bangladesh Scholarship in the Memory of Dr. Fazlur R. Khan*, p. 3.

Humanizing Technology

Khan used technology to create human comfort. He didn't believe in technology for the sake of technology itself. For him, technology, was just a tool. As Myron Goldsmith, himself a great proponent of structures as art and the integration of environment and technology, stated concerning their joint efforts: "It may have seemed to some that we were interested only in high-rise and long-span buildings, but we were much more ambitious than that. The goal was to humanize technology. The vision was structure as art."[92] If architects and engineers wanted to improve the social and human condition, Khan and Goldsmith believed they had to devise ways of integrating technology with life to create a less technically dominated appearance. For example, in the Haj Terminal at Jeddah, they used a tent structure because of its cultural significance (Fig. 1.2b, page 3). Khan preferred a simple or a low technology instead of a more sophisticated and complex technology.

[92] Myron Goldsmith. *Khan Tributes*. (Paid to Khan at his funeral on April 2, 1982, and at the memorial service on May 6, 1982, assembled at SOM and Lehigh University, May 1983).

Epilogue

Vitruvius writes that architecture consists of three essential components: commodity, firmness and delight. Yet, theories abound postulating that consideration of commodity alone may automatically lead to delight (*functional rationalism*) or delight may be created by correctly following the principles of firmness (*structural rationalism*).

The prevailing theories of Structural Expressionism and Honesty of Materials advocate that if a structural system or the building material is expressed honestly, beautiful forms will result as an automatic and direct consequence. They also hint that there exist magical structural formulae, which if understood and used, will lead to aesthetically rich forms.

In fact, this research project began with similar assumptions. Khan was selected as the subject because he was a brilliant structural engineer who created art. It was this researcher's belief that he somehow understood structures as a combination of art and science. Ironically, the investigation refutes the researcher's initial assumption that structures can be both an art and a science.

Influenced by a general understanding of structural rationalism, the author truly believed that she could find Khan's structural knowledge at the root of his aesthetic creations. Khan developed some of the greatest structural concepts of the twentieth century. Yet, the author could not find any direct connection or inter-dependence between aesthetics and structures in Khan's works. It was only after this research was analyzed for a second time with an open attitude that a conclusion could be drawn. There really is not a direct relationship between structures and aesthetics. Rather, it is the consideration of both at the same time that leads to creations as beautiful as the Hancock Tower or the Salginatobel Bridge.

Khan never found the magical formula that leads to beautiful forms. Rather, during a twenty year career, he developed himself into a rich and complex artist, whose toolbox included structural genius, aesthetic sensitivity, and humanitarianism.

Intuitive understanding of structures was undoubtedly Khan's greatest strength. From his childhood, Khan was deeply involved in understanding the nature of material and its structural behavior.

At the beginning of his career Khan was a pure technician. But at SOM and IIT, he worked with many architects and gradually became deeply interested in aesthetics. His ability to converse with others and his strong inclination to learn helped him understand the significance of formal aesthetics in creating architecture.

Khan came to realize that engineers needed to play a larger role in the overall process of designing and building. "The greatest step the building team has made in the past decade," Khan wrote, "is that the engineer, as part of the team, is finally looking at the whole structure with architecture integrated as part of the whole."[93]

Looking at Khan in this light, it is not surprising that when arguing for the continuation of the X-braces, Khan was an artist, a passionate designer, who can't justify his decisions through rational argument. It is clear that he, at this point, was led by purely aesthetic motives. In his mind, the aesthetic quality of the structure carried more importance than functional considerations. A close examination of his posthumously published article on the Hancock Center in the *IABSE Journal* reveals that Khan used his strong position at SOM to get his aesthetic vision accepted.[94] He was no longer only a structural engineer, responsible for making a building stand up with minimum cost. The structural-philosophical aspect of design was equally important to him.

Khan's life reveals that structural design is not both a science and an art, but that the structural engineer must be both a scientist and an artist. He learned from everyone and grew into a richer and more complex human being. He successfully integrated science, aesthetics, and humanitarian vision to create elegant structures.

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[93] "Construction's Man of the Year: Avant Garde High-Rise Designer Fazlur R. Khan," *Engineering News Record*, February 10, 1972, p. 21.
[94] Fazlur R. Khan. "100-Story John Hancock Center in Chicago – A Case Study of the Design Process," *IABSE Journal*, J-16/82, p. 31.

Appendix – A
List of Projects by Fazlur R. Khan

1. Hartford Fire Insurance Company, Office Building I, 1961; and II, 1971, Chicago, Illinois
2. Building to house 60 inch Solar Telescope, 1962, Kitt Peak, Arizona
3. United Air Lines, Executive Office Building, 1962, Elk Grove Village, Illinois
4. United States Air Force Academy, 1962, Colorado Springs, Colorado
5. Container Corporation of America, Corrugator Plant, 1963, Carol Stream, Illinois
6. Brunswick Office Building, 1965, Chicago, Illinois
7. Chestnut DeWitt, Apartment Building, 1965, Chicago, Illinois
8. Equitable Life Assurance Society of the United States, Office Building, 1965
9. Illinois Central Air Rights, Master Plan, 1965, Chicago, Illinois
10. University of Illinois, Circle Campus, Master Plan and Phases I, II, III, IV, 1965, Chicago, Illinois
11. Broken Hill Proprietary, Corporate Headquarters, 1967, Melbourne, Australia
12. Spectrum Arena, 1967, Philadelphia, Pennsylvania
13. Chicago Transit Authority, 13 Rapid Transit Stations, 1969, Chicago, Illinois
14. John Hancock Center, Multi-Use Complex, 1970, Chicago, Illinois
15. Control Data Center, Corporate Headquarters, 1971, Houston, Texas
16. One Shell Plaza, Office Building, 1971, Houston Texas
17. 1010 Common Street, Office Building, 1971, New Orleans, Louisiana
18. Crosstown Expressway, Multi-Disciplinary Comprehensive Transportation Corridor Plan, 1972, Chicago, Illinois

19. Gateway Center, Office Building III, 1972, Chicago, Illinois

20. One Shell Square, Office Building, 1972, New Orleans, Louisiana

21. Bu Ali Sina University, Design Development, 1974, Hamadan, Iran

22. Royal Gazette Ltd., Newspaper Plant and Office Building, 1974, Hamilton, Bermuda

23. Sears Tower, Corporate Headquarters, 1974, Chicago, Illinois

24. W. D. & H. O. Wills, Corporate Headquarters and Tobacco Processing Facility, 1974, Bristol, England

25. Bandar Shahpour New Town, Development Plan, Master Plan, Management Program and Short-Term Housing, 1975, Bandar, Shahpour, Iran

26. Baxter Travenol Laboratories, Inc., Corporate Headquarters, 1975, Deerfield, Illinois

27. Centre Sofil, Office Building, Design, 1975, Beirut, Lebanon

28. Ohio National Bank, 1976, Columbus, Ohio

29. Hyatt International Hotels, Hotel and Cultural Center, 1978, Kuwait City, Kuwait

30. King Abdul Aziz University, Makkah Campus Master Plan, 1978, Makkah, Kingdom of Saudi Arabia

31. Europoint IV, Office Building, 1979, Rotterdam, The Netherlands

32. Edmonton Center, Multi-Use Complex, 1980, Edmonton, Alberta, Canada

33. King Abdul Aziz International Airport Facility, Master Plan, Design and Engineering, 1980, Jeddah, Kingdom of Saudi Arabia

34. Universiti Kebangsaan Sabah Campus, Master Plan, 1981, Kota Kinabalu, East Malaysia

35. Onterie Center, Multi-Use Complex, 1984, Chicago, Illinois

SOM did not provide author with dates for the following projects:

1. National Life Building, Nashville, Tennessee

2. 500 North Michigan Building, Chicago, Illinois
3. Latter and Meltzer Building, New Orleans, Louisiana
4. Marine Midland Bank Building, Rochester, New York
5. One Shell Plaza, Houston, Texas
6. First Wisconsin Bank Building, Millwaukee, Wisconsin
7. G. S. A. Geological Survey Building, Reston, Virginia
8. C. D. S. Building, Houston, Texas
9. Overbeek Building, Rotterdam, Holland
10. Harris Trust, Chicago, Illinois
11. Fourth National Bank & Trust Company, Wichita, Kansas
12. GAC Properties Services, Inc., Poinciana, Florida
13. Edmonton Center, Edmonton, Alberta, Canada
14. St. Joseph Valley Bank Headquarters Bldg., Elkhart, Indiana
15. Illinois National Bank, Springfield, Illinois
16. New World Center, Hong Kong, B. C. C.

Appendix – B
List of Publications and Presentations by Fazlur R. Khan

Khan, F. R. *Study of Tests on Prestressed Concrete Beams*. Third Progress Report on Investigation of Prestressed Concrete for Highway Bridges, Engineering Experiment Station, University of Illinois, June, 1954.

Khan, F. R., N. Khachaturian, and C.P. Siess. *Analytical Studies of Relations Among Various Design Criteria for Prestressed Concrete Beams*. Structural Engineering Research Series No. 105, University of Illinois, October, 1955.

Brown, A. J. and F. R. Khan. *Gantries Set Prestressed Bridge Beams*. Engineering News Record Magazine, January, 1958.

Khan F. R. and A. J. Brown. *Load Test of 120 Foot Precast, Prestressed Bridge Girder*. American Concrete Institute Journal, July, 1958.

Khan, F. R. *Proposed Revision of Building Code Requirements for Reinforced Concrete*. American Concrete Institute Journal, November, 1962 (ACI318-56).

Khan, F. R. *Proposed Recommended Practice for Concrete Formwork*. American Institute of Concrete Journal, March, 1963.

Khan, F. R. *Use of Electronic Computers for Analysis and Design of Multi-Story Buildings*. Proceedings, Conference on Use of Computers for Analysis and Design of Structures, Illinois Iinstitute of Technology Research Institute, June, 1963.

Khan, F. R. and J. A. Sbarounis. *Interaction of Sheer Walls and Frames in Concrete Structures Under Lateral Loads*. Journal of the American Society of Civil Engineers, June, 1964.

Khan, F. R. *Methods of Bracing and Structure Deflections*. Proceedings, APIC 9, American Society of Civil Engineers, June, 1964.

Khan, F. R. *Design of Shear Walls*. Proceedings, EPIC 9, American Society of Civil Engineers, St. Louis, Missouri, March, 1965.

Khan, F. R. *Design of High Rise Buildings*. American Institute of Steel Construction Symposium on Steel Structures, Chicago, Illinois, Fall, 1965.

Fintel, Mark, and Fazlur Khan. *Effects of Column Exposure in Tall Structures, Part A – Temperature Variations and Their Effects*. Journal of the American Concrete Institute, December 1965.

Khan, F. R. *Current Trends in Concrete High Rise Buildings*. Proceedings, Symposium on Tall Buildings, University of Southampton, England, April, 1966.

Khan, F. R. *On Some Special Problems of Analysis and Design of Shear Wall Structures*. Proceedings, Symposium on Tall Buildings, University of Southampton, England, April, 1966.

Khan, F. R. *Optimization of Building Structures*. Proceedings, Structural Engineering Conference, University of Illinois, Chicago, Illinois, May 14, 1966.

Khan, F. R. and Mark Fintel. *Effect of Column Exposure in Tall Structures, Part B – Analysis for Length Changes of Exposed Columns*. Journal of the American Concrete Institute, August, 1966.

Khan, F. R. *The Bearing Wall*. Architectural and Engineering News, September, 1966.

Khan, F. R. *Voies Nouvelles Dans la Conception des Ossatures Metalliques de Batiments. Construction Metallique, Centre d'Etudes Superiures*. Journal Construction Metallique, December, 1966.

Khan, F. R., S. H. Iyengar, and J. P. Colaco. *Computer Design of the 100 Story John Hancock Center*. Journal of the American Society of Civil Engineers, December, 1966.

Khan, F. R. *The John Hancock Center*. Civil Engineering Magazine, October, 1967, and AISC National Engineering Conference, San Francisco, Calif., April, 1967.

Fintel, Mark and Fazlur Khan. *Temperature Effects of High Rise Buildings*. Proceedings, Building Research Institute Conference, Washington, D.C., Spring, 1967.

Khan, F. R. *Optimum Design of Glass in Buildings*. Proceedings, Building Research Institute Conference, Washington, D.C., May, 1967.

Khan, F. R. *Nature of High Rise Buildings*. Indian Builder, Journal of the Indian Builders' Association, Bombay, India, June, 1967, and Inland Architect, July, 1967.

Khan, F. R. and Mark Fintel. *Effects of Column Exposure in Tall Structures, Part C – Design Considerations and Field Observations of Buildings*. Journal of the American Concrete Institute, February, 1968.

Khan, F. R. *Office Tower Design Cuts Framing Costs*. Engineering News Record, February 15, 1968.

Khan, F. R. and Mark Fintel. *Shock Absorbing Soft Story Concept for Multi-Story Earthquake Structures*. 64th Annual ACI Convention, Los Angeles, Calif., March, 1968.

Khan, F. R. and Mark Fintel. *Effects of Column Creep and Shrinkage in Tall Structures*. American Society of Civil Engineers Specialty Conference, Chicago, Illinois, June, 1968.

Khan, F. R., S. H. Iyengar, and J. P. Colaco. *Analysis and Design of the 100 Story John Hancock Center in Chicago (U.S.A.)*. Acier Stahl Steel Magazine, June, 1968.

Khan, F. R. and Mark Fintel. *Effects of Column Temperature, Creep and Shrinkage in Tall Structures*. Eighth Congress, International Association for Bridge and Structural Engineering, New York, September, 1968.

Khan, F. R. *Column Free Multi-Story Buildings With and Without Rigid Cores*. Eighth Congress, International Association for Bridge and Structural Engineering, September, 1968.

Khan, F. R. *The Bearing Wall Comes of Age*. Architectural and Engineering News, October, 1968.

Khan, F. R. *Framed Tubes and Interacting Framed Tubes and Shear Walls*. Report to the American Concrete Institute Lateral Load Committee 421, June, 1969.

Khan, F. R. *The Chicago School Grows Up*. Architectural and Engineering News, Annual Convention Supplement, June, 1969.

Khan, F. R. and Clyde N. Baker. *Caisson Construction Problems and Methods of Correction*. ASCE Convention, Chicago, Illinois, October, 1969.

Khan, F. R. *Recent Structural Systems in Steel for High-Rise Buildings*. BCSA Conference on Steel in Architecture, London, England, November, 1969.

Fintel, Mark, and Fazlur Khan. *Effects of Column Creep and Shrinkage in Tall Structures – Prediction of Inelastic Column Shortening*. Journal of the American Concrete Institute, December 1969.

Khan, F. R. (Panel Discussion). *Structural Engineer Looks at the Stability Provisions of the 1969 AISC Specifications*. Column Research Council Proceedings, Bethlehm, Pennsylvania, 1970.

Khan, F. R. *Rational Method for the Design of Curtain Walls*. Proceedings, Conference on Wind Effects on High Rise Buildings, Northwestern University, Evanston, Illinois, March, 1970.

Khan, F. R. *Lightweight Concrete for Total Design of One Shell Plaza*. American Concrete Institute Convention, New York, April, 1970.

Khan, F. R. *New Structural Systems in Steel*. American Institute of Steel Construction Annual Convention, Pittsburgh, Pennsylvania, April, 1970.

Khan, F. R., J. Stockbridge, and E. Brown. *Quality Control of High Strength Lightweight Concrete for One Shell Plaza*. American Concrete Institute Annual Convention, Pittsburgh, Pennsylvania, April, 1970.

Khan, F. R. and Mark Fintel. *Conceptual Details for Creep, Shrinkage and Temperature in Ultra High Rise Buildings*. American Concrete Institute Annual Convention, New York, April, 1970.

Khan, F. R. and Mark Fintel. *Effects of Column Creep and Shrinkage in Tall Structures: Analysis for Differential Shortening of Columns and Field Observations of Structures*. American Concrete Institute Annual Convention, New York, April, 1970.

Khan, F. R. *New Design Approach to High Rise Construction*. Proceedings, American Society of Civil Engineers, Rochester Section, Conference on Urban Environment, May 15, 1970.

Khan F. R. and A. F. Nassetta. *Temperature Effects on Tall Steel Framed Buildings*. Engineering Journal, American Institute of Steel Construction, October, 1970.

Khan, F. R. (Member, American Concrete Institute Committee 118). *Survey of Procedures for Acceptance of Electronic Computer Calculations by Building Officials*. Journal of the American Concrete Institute, January, 1971.

ACI Committee 442 (F. R. Khan member). *Response of Buildings to Lateral Forces*. Journal of American Concrete Institute, February, 1971.

Khan, F. R. *Innovations in Structural Steel Systems for Tall Buildings*. Canadian Institute of Structural Concrete Proceedings, May, 1971.

Khan, F. R. *Tendances Actuelles dans la Construction des Immeubles de Grande Hauteur a Structure en Betn Arme et en Acier*. Anales de L'Institut Technique du Batiment et des Travaux Publics, Sepplement au no. 281, May, 1971.

Khan, F. R. *Building Design Reduces Steel with Concrete-Tube Wind Bracing*. Engineering News Record, June, 1971.

Report by American Concrete Institute Ad Hoc Board Committee on Concrete (F. R. Khan member). *Concrete – Year 2000*. Journal of the American Concrete Institute, August, 1971.

Khan, F. R. and R. A. Parmelee. *Service Criteria for Tall Buildings for Wind Loading*. Proceedings, Third International Conference on Wind Effects on Buildings and Structures, Tokyo, Japan, September, 1971.

Khan, F. R. *Buildings*. 1972 McGraw-Hill Yearbook of Science and Technology.

Khan, F. R. *New Concepts in High Rise Buildings*. American Iron and Steel Institute Seminar for Journalists, New York, January, 1972.

Khan, F. R. and S. H. Iyengar. *Optimization Approach for Concrete High-Rise Structures*. Paper SP36-4, American Concrete Institute Convention in Dallas, Texas, March 1972.

Khan, F. R. *Influence of Design Criteria on Selection of Structural Systems for Tall Buildings*. Canadian National Structural Engineering Conference, Montreal, Canada, March, 1972.

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