Fazlur Khan (1929–1982): reflections on his life and works

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Abstract: Tall buildings, or skyscrapers, are icons of cities, symbols of corporate power, and a mark of national pride. Certain skyscrapers, such as the John Hancock Center and the Sears Tower in Chicago, are also marvels of engineering that have paved the way for ever increasing heights of structural systems. Since the 1960s, a series of new structural systems has been introduced with the objective of achieving economically-competitive and aesthetically-pleasing tall buildings without compromising safety. One of the great structural engineers responsible for the new structural systems was Dr. Fazlur Rahman Khan. This paper provides a biographical sketch of Dr. Khan and discusses some of his innovations pertaining to high-rise buildings. It shows that his contributions led to a new vertical scale for the modern day city.

Key words: aesthetics, architecture, innovation, structural system, tall building.

Résumé : Les grands édifices, ou gratte-ciel, sont l'emblème des villes, la manifestation symbolique des puissances corporatives, et sont représentatifs de la fierté nationale. Certains gratte-ciel, comme le Centre John Hancock et la Tour Sears à Chicago, sont aussi des merveilles d'ingénierie qui ont pavé la voie à des systèmes structuraux atteignant des hauteurs toujours plus grandes. Depuis les années 60, une série de nouveaux systèmes structuraux a été introduite, avec pour objectif la réalisation de grands édifices compétitifs économiquement et plaisants esthétiquement, sans compromettre la sécurité. L'un des grands ingénieurs en structures responsables de ces nouveaux systèmes structuraux est Dr Fazlur Rahman Khan. Cet article présente un aperçu biographique de Dr Khan et discute quelques-unes de ces innovations se rattachant aux gratte-ciel. L'article montre que sa contribution a mené à une nouvelle échelle verticale pour nos villes modernes.

Mots clés : esthétique, architecture, innovation, systèmes structuraux, grand édifice.

[Traduit par la Rédaction]

Introduction

There are three distinct phases in the development of skyscrapers. The first phase occurred in the late 1800s in response to city growth and can be regarded as an economic phenomenon. The buildings in this phase were generally no more than six storeys. Taller buildings were not favoured, primarily because of the lack of a vertical transportation system.

The roots of the second phase were planted in 1855, when Otis demonstrated his invention of the elevator system, and the lack of a vertical transportation system no longer put a limitation on building heights. Around the same time, cast iron replaced stone, bricks, and timber as the construction material of choice, and this was soon replaced by steel. With the change in construction materials, the structural system evolved from masonry bearing walls into a beam–column framing system, providing an economical way to construct tall buildings.

Although the technology was available to build "skyscrapers", actual application and construction using these new developments had to wait until after the Civil War. By that time, stronger sentiments of American identity led to the rejection of what was seen as "imported" European styles. Engineers and architects, like le Baron Jenny and Sullivan, took the lead in establishing what is now known as the First Chicago School of Architecture, paving the way for the creation of a unique American style of design architecture.

In phase two of the evolution of tall buildings, 20- to 30-storey buildings became a common sight on the American city skyline. Aesthetics were derived from the utilitarian qualities of the buildings, and although the advent of the structural steel frame was seen as new and innovative building technology, it also bore witness to the end of large-scale monolithic masonry construction. The height of these buildings was excessively large compared to the width of the major streets, thus leading to the loss of a human scale relationship with the height of the building. These tall buildings also blocked sunlight and air at the street level.

Constructing buildings taller than the norm of the day using beam–column structural frames with masonry infill proved too expensive. So this phase of growth, which lasted until 1950, generally saw 20- to 30-storey buildings, although there were notable exceptions such as the Empire State Building.

Received 26 February 2001. Revised manuscript accepted 6 December 2001. Published on the NRC Research Press Web site at http://cjce.nrc.ca on 19 March 2002.

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Written discussion of this article is welcomed and will be received by the Editor until 31 August 2002.

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DOI: 10.1139/L01-092

By the 1960s, the third phase in the construction of high-rise buildings was under way. In this phase a whole new series of structural systems were developed with the objective of eliminating the traditional premium for resisting lateral loads. These new structural systems, using structural steel, reinforced concrete, and traditional masonry, have evolved to such an extent that buildings up to a hundred or more storeys are now economically feasible.

This third phase in the evolution of the tall building is due mainly to the genius of Dr. Fazlur Rahman Khan, who was not only an outstanding structural engineer but also a highly innovative person. This paper is devoted to remembering this great structural engineer by reviewing some of his work. Dr. Fazlur Rahman Khan's portrait, appearing on a postage stamp of Bangladesh, is presented in Fig. 1.

Biographical synopsis

Fazlur Rahman Khan was born 3 April 1929 in East Bengal in undivided India. The city of his birth, Dhaka, is now in Bangladesh and was previously in East Pakistan. Standing first in his class, Khan received his Bachelor of Engineering from the University of Dhaka in 1950; he taught for two years in Dhaka and then went to the University of Illinois on a Fulbright and a Pakistani scholarship. He completed two masters degrees, one in theoretical and applied mechanics and the other in structural engineering. In 1955, he did his doctorate in structural engineering under the supervision of Professor C.P. Seis. Immediately after obtaining his doctorate degree, Khan started working with Skidmore, Owings and Merril (SOM), architects and engineers in Chicago. In 1957 he returned to Pakistan to fulfill the terms of his scholarship.

By 1958, the Pakistani civilian government was deposed by military rule. As he recalled later, Khan was offered a directorship of Pakistan's Building Research Centre that was soon withdrawn. It is very likely that the free spirit of Khan was greatly affected by the authoritarian rule in Pakistan at the time. During an interview with Civil Engineering — ASCE he recalled, probably ruefully, that "there was a political deal going on" (Morrison 1980).

Khan stayed in Dhaka doing private design work, then went to work for the Karachi Development Authority for a period of time.

In 1960, Khan decided to return to SOM in Chicago. During the same interview cited above, he rationalized his return to the U.S.A.: "Once you are educated in America, you become accustomed to a very sophisticated approach to engineering. I missed the level of technology, the excitement of the responsibility I was given, and the scale of projects there".

From his return to Chicago until his death in 1982, Khan designed a number of buildings, including some of the tallest in the world. His approach to tall building design was new and innovative. Khan had mastered his craft of structural engineering academically and in practical application, but excellence in technical understanding was only a part of his genius. As he put it, "the social and visual impact of buildings is really my motivation for searching out new structural systems", and to get the right visual impact, "a building's natural strength should be expressed".

Fig. 1. Portrait of Dr. Fazlur Rahman Khan on a Bangladeshi postage stamp.

In a symposium organized by the American Society of Civil Engineers (1983) to honour the works of Khan, Professors Billington and Goldsmith (1983) remembered Khan as a man who used his rich imagination to "create new forms for buildings" joining a class of new forms like those created by Maillart for bridges and by Nervi for vaults.

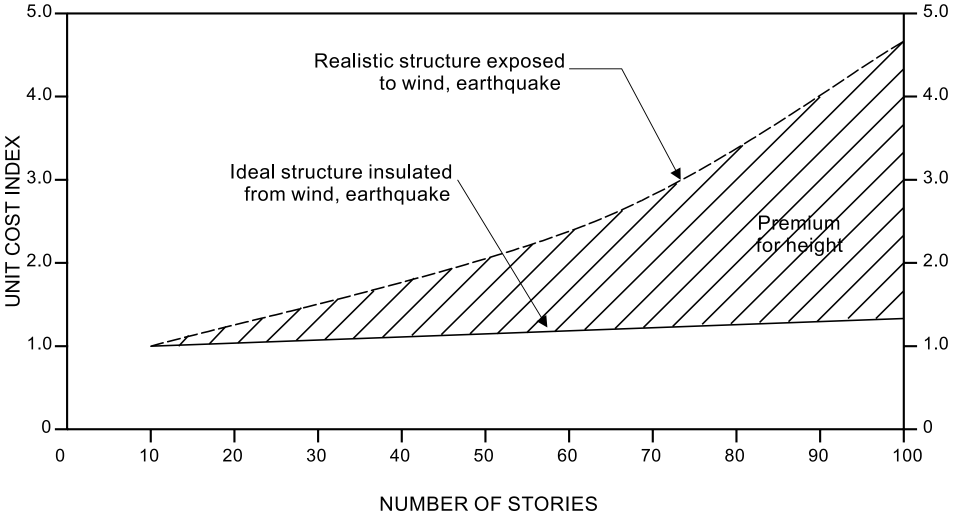
Khan was cited three times by the Engineering News Record (ENR) as one of the "Men who served the best interests of the construction industry". He was presented with the "Chicagoan of the year" award in architecture and civil engineering by the Junior Chamber of Commerce. Khan published a large number of technical papers in engineering and architectural journals and, in 1972, was voted "Constructions' Man of the year". He also received the Wason Medal for the most meritorious paper from ACI in 1971, the Lloyd Kimbrough Medal from AISC in 1973, and the Oscar Faber Medal from the Institution of Structural Engineers, London, in 1973. He received honorary Doctorate degrees from North Western University (1973), Lehigh University (1980), and Die Eidgenossische Technische Hochschule (1980).

Khan lived in a high-rise apartment with his wife Liselotte and his daughter Yasmin. His untimely death on 27 March 1982 in Jeddah, Saudi Arabia, at the age of 52 deprived the structural engineering profession of an outstanding innovator. In paying tribute to Fazlur Khan, the Engineering News Record editor wrote: "His structures will stand for years, and his ideas will never die".

Engineer, innovator, philosopher

Khan's physical appreciation for the way structures behave was so good, he could explain intricate technical problems in terms so simple that even a layman could understand. Khan realized that as buildings become taller their design is governed by their resistance to lateral loads, i.e., those due to wind and earthquakes. The premium cost of constructing buildings to resist these lateral loads is illustrated in chart form, as reproduced in Fig. 2.

Fig. 2. Cost premium for height is largely due to lateral loads.



Iyengar (1997) credits Khan for realizing that different structural forms are economically and structurally suitable for high-rise buildings with different heights. His much-cited charts are reproduced in Figs. 3 and 4 for steel and concrete construction, respectively. It is noted that Khan kept changing these charts, albeit slightly. Khan concluded that a solution optimized on the basis of economy and function must also be aesthetically pleasing. He felt that buildings should result in the creation of a better built environment. The building can only be deemed complete when it is structurally sound and provides a delightful visual experience.

Both engineering and architectural schools of thought saw Khan as a structural wizard and an innovator of varied structural forms. His novel concepts ranged from the Brunswick Building design to the futuristic 160-storey Megastructure, which has not yet been built, and from the Baxter Laboratory Dining Hall to the “tent” roof for the Haj Terminal.

The 38-storey Brunswick Building was the first reinforced cement concrete (RCC) building to utilize interaction between the frame and the shear wall. Consideration of this interaction not only led to economy in design but also reduced the free shortening of exterior columns in extremely cold temperatures.

One Shell Plaza was the first application of Khan’s tube-in-tube concept. In this concept, the outer tube resists the overturning moments due to lateral loads and the inner tube resists the shear to achieve a highly efficient structural system. The 52-storey One Shell Plaza project used the composite tubular system incorporating the best of both steel and concrete structural systems. On one hand, the RCC framed tube is very efficient in resisting horizontal loads, and on the other, the steel framing scores in height and lightness.

One Magnificent Mile and the Sears Tower are based on the concept of bundled tubes. In this concept, integrated framed tubes act together as one tube sharing common side frames. By bundling the tubes, there is an increase in the lateral stiffness and stability of the building.

Khan’s appreciation of aesthetics, space, and form combined with his technical expertise helped make him the only partner at SOM that was an engineer and not an architect. His theory was to expose the natural beauty of the structure rather than hide it behind a contrived facade. Like Ruskin, Khan believed in the concept that “architecture is mother of all art”. In the same vein, he believed that structural engineering is more than a rational application of science.

Although he was a master of the craft of structural engineering, he was always of the opinion that “a technical man shouldn’t be lost in his technology”. He also philosophized that besides technicalities, a man should take some time to enjoy and appreciate life, music, and drama. He could discuss, intelligently, many topics besides engineering with the same ease he exercised explaining the intricacies of novel structural systems. Khan was not a physically towering presence, standing at just 1.70 m, but his sprightly and purposeful walk and his way of getting things done with overwhelming casualness underscored his strength of purpose and confidence. Khan had such an incredible passion for work, for creating new structural systems and finding new ways to economize the total cost of the structure that he used to work even on weekends. He traveled extensively, often from one continent to another. The travel never tired him because he enjoyed his work so much. Because Khan had such a keen perception for architecture and engineering, he could bridge the gap between the concepts of structural form and aesthetics of tall buildings.

Khan worked his entire career in the U.S.A. at Skidmore, Owings and Merril (SOM) in Chicago, collaborating closely with architect Bruce Graham. Together they completed several notable and innovative projects. Throughout his professional career, Khan also worked closely with students at the Illinois Institute of Technology. “Khan feels that teaching is a very important part of his professional life, the work with students helps stimulate new ideas and concepts, as well as think them through” (Fisher 1972).

According to Khan, where tremendous forces must follow the structural form, logic and scientific method should prevail within the broad framework of art and architecture. The need to work as a team in the early formulation of the building design is known as a necessity in all building construction, but Khan believed that this need was even more important in the design of ultra-complex buildings such as the Sears Tower. According to Khan, every professional

Fig. 3. Categories of steel structural systems for high-rise buildings.

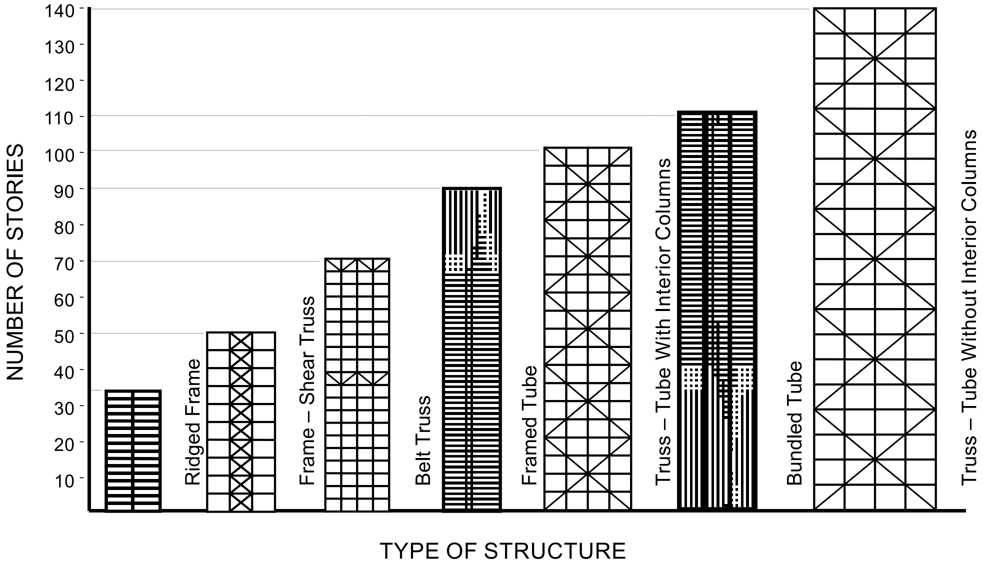
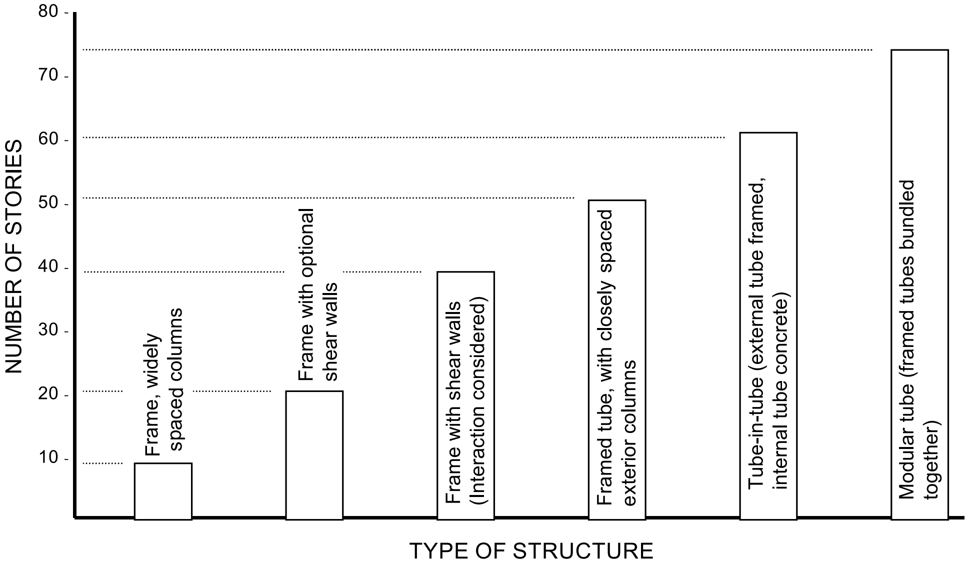


Fig. 4. Categories of concrete structural systems for high-rise buildings.



working on complex problems involved in the design of tall buildings needs to realize the impact that his propositions will have on the other members of the team. Building systems are not independent, but rather they are interrelated from the foundation systems to the construction systems. As such, even in this age of specialization, everyone needs to understand and appreciate this interrelationship of the multitude of systems from the very beginning of the project. Bruce Graham said, “Faz has an extremely rare understanding of architecture. In every phase of a project, we work on alternatives. He even gets involved in interiors and floor planning”.

There are at least five aspects of Khan’s career that deserve special attention. First, his achievements are unlikely to have been so remarkable without sensitive collaboration with some outstanding architects. The fact that he was able to find time from his full-time job to teach part time and to conduct research at a university was a second aspect. The third aspect is identified as the number of extraordinary engineering collaborators who likely helped Khan in defining various structural systems for tall buildings. Khan’s vision of structures as works of art is a distinct fourth aspect to his career. The fifth aspect of his career was wholeness.

A man of distinction, unique ability, and wholeness, Khan was truly an open-minded man. He was brought up in Islamic tradition and culture and loved and respected the best of all other traditions and cultures that he was exposed to. He was known to be benevolent. The 1970 civil war between East and West Pakistan followed a bitter and bloody civil uprising in East Pakistan that led to the cessation of East Pakistan and to the formation of Bangladesh. As a native of Bengal, Khan could understandably have been bitter towards West Pakistan and its people. He may have suffered in sadness but is never known to have condemned the people of

West Pakistan. He was “a whole person”, as Lynn Beedle noted in his lecture at the ASCE (1983) fall meeting. A singer of songs of Bengali Nobel laureate Tagore, and listener of the music of Bach and Brahms, he was truly a modern renaissance man of Islamic civilization.

Innovative structural systems

Khan was able to develop a number of innovative structural systems because of his appreciation for the traditional concept that the union of architecture and engineering is essential for the synthesis of form and function. The First Chicago School, noted earlier, flourished under the leadership of Sullivan and Jenny. Mies Vander Rohe led the Second School. Vander Rohe designed one of the most beautiful and efficient buildings in Chicago, the Lake Shore Drive Apartment Towers. Notwithstanding the remarkable achievements before the 1960s, the height of high-rise buildings could not exceed much beyond 20 or 30 storeys for economic reasons. Simply put, the cost of resisting lateral loads was too great (Khan 1973, as shown in Fig. 2). To overcome this economic limitation on height, Khan developed six novel systems in steel structures, and four in concrete. These systems have been identified in Figs. 3 and 4.

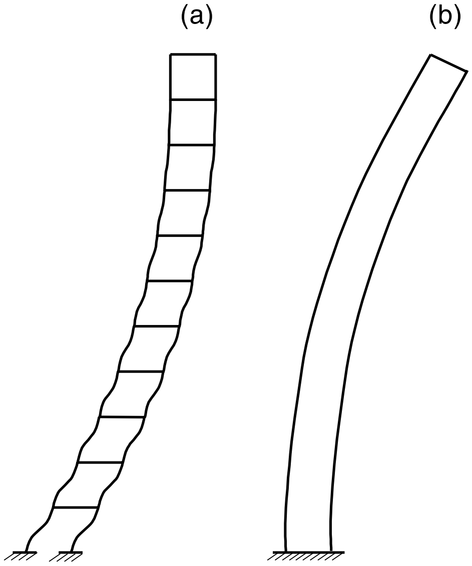
The first novel concept, explained in a number of technical papers by Khan, was based on utilizing the beneficial interaction between rigid frames and shear walls or trusses. As illustrated in Figs. 5*a* and 5*b*, the deformations of a tall rigid frame under uniformly distributed lateral loads have a distinctly different pattern from those of the shear wall or truss under similar loads. The shear wall responds predominantly to shear forces and the truss to mainly bending moments. A combination of the two structural components leads to a highly efficient system, in which the frame carries a larger portion of the lateral loads in the upper portion of the building, and the shear wall or truss resists a larger portion of the lateral loads in the lower portion.

Khan (1966) noted that the use of shear walls in buildings taller than 20 storeys is imperative from the point of view of economy. For such buildings, the consideration of the interaction between the frame and the shear wall is also imperative. The innovation of combining the frame with shear trusses or walls allowed Khan to design buildings up to 40 storeys high without paying excessive price for the height. It was a simple but extraordinary finding. After Khan utilized it, this interaction became a standard feature for 20- to 40-storey buildings constructed in steel or concrete or both.

As Khan described in his characteristically modest way, “it was almost accidental that, in 1961, the author, working together with his architectural partner, Bruce Graham, stumbled on the idea of a hollow thin-walled tube with punched holes as the basic exterior of buildings” (Khan 1973). It can be appreciated readily that by reducing the spacing of exterior columns, the entire system of beams and columns lying on the external perimeter of a building can be made to act as a perforated tube, or a framed tube (Fig. 6).

Khan recognized the efficiency of a framed tube cantilever with its base fixed in the ground. As illustrated in Fig. 7, a framed tube under lateral loads has its columns on the load face in tension and those on the opposite face in compression, thus eliminating bending of individual columns. Once again, it was a simple idea with a profound impact on the design of tall buildings. Khan recognized many practical planning and architectural difficulties in tying all the columns of the building together. His solution within the architectural framework of the rectangular windows was to place exterior columns fairly close to each other so that the column–beam interaction resulted in an optimum design. A larger or smaller spacing of columns would lead to an inefficient solution. Khan recognized that the frame tube concept loses some of its efficiency as a result of the shear lag effect, also illustrated in Fig. 7. The shear lag effect, being similar to that encountered in top flanges of T-beams, is not significant in buildings up to 80 storeys high.

Fig. 5. Deformations under uniformly distributed lateral loads: (*a*) isolated frame and (*b*) isolated shear wall.



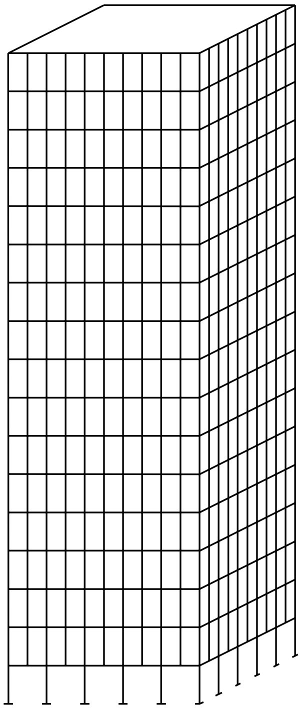
Application of a novel structural system to a tall building

It is remarkable that in his relatively short life of 52 years, Khan was able to develop many innovations and apply them to actual structures. In this short paper, we have chosen to discuss only one of his buildings, the John Hancock Center, Chicago, Illinois, the world’s tallest multi-use steel building based on the truss tube concept.

John Hancock Center

The 100-storey John Hancock Center is “gutsy, masculine and industrial; reflecting the tradition of Chicago where structure is of the essence” (Graham 1980). It is a dominant structure on the imposing Chicago skyline. Initially it was highly controversial. Sculptor Claes Oldenburg compared it with “The Statue of Death” by Lorado Tuft in Chicago’s Graceland Cemetery. The statue, wrote Oldenburg, “has a shape like the Hancock building, and the Hancock building resembles the black slab against which the sculpture stands”. He called the building a “funeral structure” and was “resentful of its scale”. In due course, the building was accepted as a beautiful object and became a landmark for the city and a notable step in the development of architecture and struc-

Fig. 6. Frame tube structural system.



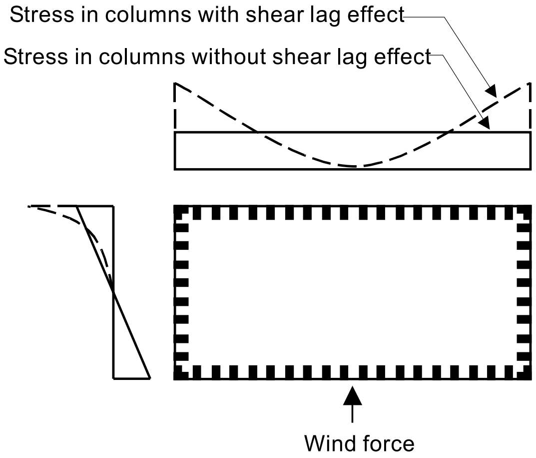
tural engineering. Truth and honesty of structural application make this building an attractive object.

The John Hancock Center was originally designed as two separate buildings: one for residential use and the other for office space, as shown in Fig. 8*a*. This scheme was fraught with a number of difficulties: the blockage of natural light, little public space, and blocked view lines, all common problems in densely populated American city centres. As he noted in 1982, Khan disliked the two-tower solution: “the rather mundane solution based on the program for the project would have also created a sense of congestion at the site and enhanced the canyon character so disliked in many of the urban centres of the industrial world”. Khan and Graham began to search for other alternative solutions and came up with the concept of a single 100- storey building, shown schematically in Fig. 8*b*.

Building shape

The tapering form for the John Hancock Center was a natural outcome of spatial needs. Since the upper floors were designated residential, they required a smaller floor space than the office floors below. Another benefit of tapering the structure was that it created a smaller surface area at the higher levels, thus reducing the wind load. The structure comprises visible diagonal bracing on its exposed faces. The diagonal bracing diminishes in size as the building rises, thus exaggerating the perspective. This effect, combined with the tapering shape, makes the building appear taller than it actually is. The diagonal form also contributes to the sculptural elegance of the space within. Both the architect and the owner wanted to remove the cross bracing above the 90th floor to allow for “purer and unobstructed views”. Khan felt it would be a tragedy to discontinue the diagonals and finally convinced Bruce Graham and the owner to carry the diagonals through the entire height of the building.

Fig. 7. Load distribution in columns of a framed tube.



It is worth recalling the arguments Khan put forth to Bruce Graham and the owner: “However, at the end, the author made an impassioned argument that not having the diagonal on 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” (Khan 1982). It is interesting that the honesty of structural and architectural expression of this landmark building would have been compromised if Khan had not given his arguments in purely engineering and economic terms.

The appearance of this building is perceived in a variety of ways. Architecture critics have referred to it as structural megalomania, and others have praised the honesty of its appearance. These opinions represent two sides of the same coin, because both express reaction to the building’s aesthetics, which, in this case, is created solely by its structural system.

Structural system

As noted earlier, Khan developed the “framed tube” concept and used it to design tall buildings. But even this concept was not suitable for concrete buildings higher than about 50 storeys and for steel buildings of more than 80 storeys. In taller buildings, the shear lag phenomenon, illustrated in Fig. 7, causes the columns near the corners of the building to attract most of the lateral loads. This trend can be changed by stiffening the exterior frames, e.g., by diagonal bracing. Khan introduced the diagonals in the John Hancock building to improve the efficiency of the structure. Khan wrote: “The use of diagonal members to correct the far spaced columns makes the diagonal members themselves act also as columns and therefore they do not normally develop any tension stresses, even under the influence of full wind load. Because these diagonals act both as inclined members, as well as taking a major portion of the wind shear, the efficiency of the structural system generally is very high for tall buildings” (Khan 1973).

The structure of the John Hancock Center was analyzed by Khan et al. (1966) under lateral wind loads with the idealization shown in Fig. 9*a*. The column axial stresses obtained by these analyses are reproduced in Fig. 9*b*. It can be seen in this figure that all columns on the face exposed to

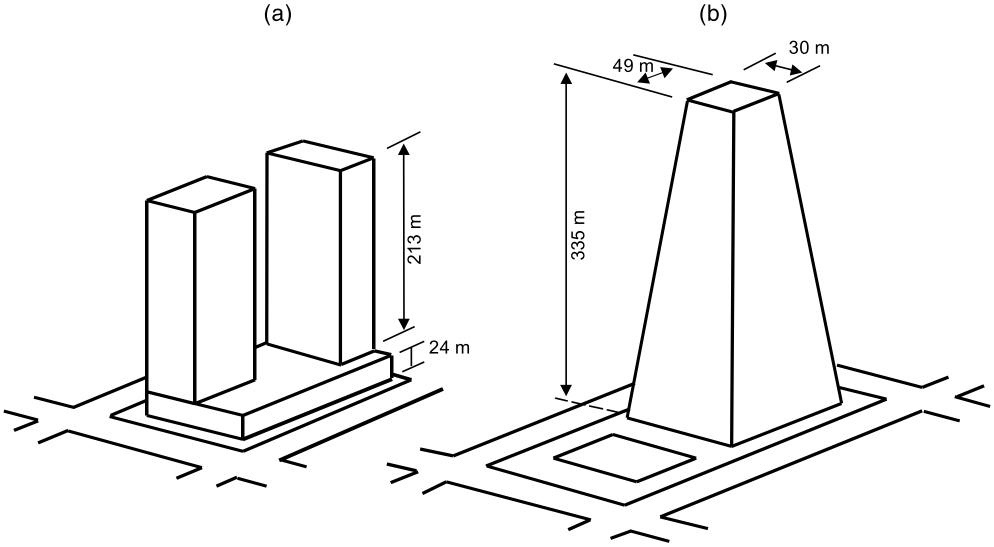


Fig. 8. Architectural concepts for the John Hancock Center: (*a*) initial design and (*b*) final design.

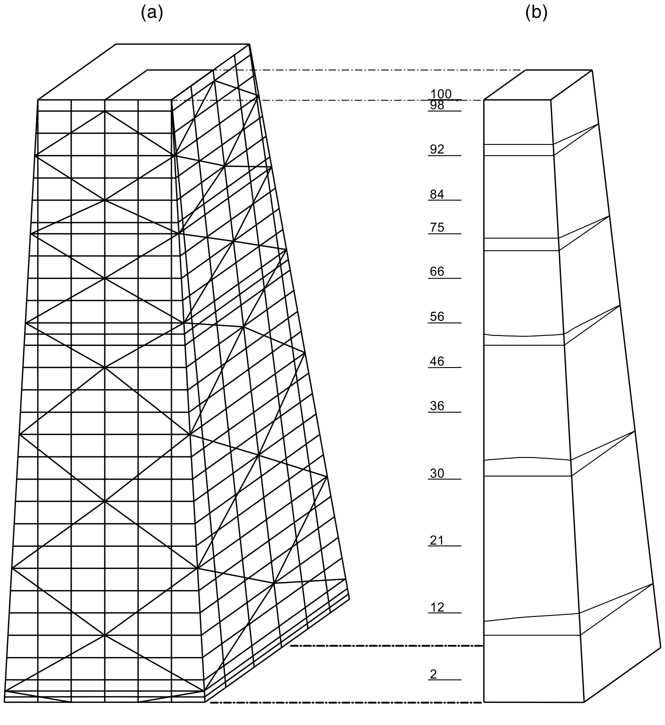


Fig. 9. Column axial stress distribution in truss tube: (*a*) idealized structure and (*b*) axial forces on exterior columns in quarter structure.

wind carry nearly the same axial force, thus confirming that the effect of shear lag is virtually eliminated by the introduction of the diagonals.

The structure of the John Hancock Center is referred to as a truss tube, the use of which is justified for only super tall buildings such as the one under consideration.

Aesthetic considerations and engineer–architect interaction

One of the great triumphs of this building, called the "Big John" in Chicago, is that it was created by the collaboration of an engineer and an architect. As mentioned, Fazlur Khan and Bruce Graham both worked for SOM in their Chicago office. SOM was founded on the concepts of Mies Vander Rohe, the founder of the Second Chicago School of Architecture. One of the main concepts of the school and SOM was that a true architectural aesthetic form must express the nature of itself, or rather the building that is creating it. It is not surprising that SOM was open to the concept of a structural system being used as the basis of aesthetic expression.

A quote of Khan referring to the design of the Hancock building is relevant: "It was an economic problem at first. Bruce said, 'If you create a structure, we'll make architecture out of it'". This quote underscores the fact that Graham did not have preconceived notions about the shape of the building. Such interaction between an engineer and an architect is contrary to the usual practice where the architect decides the shape of the building, and the engineer ensures that the building stands up.

Similar to the Eiffel Tower, the John Hancock Center has become a symbol of the beauty of structure. Its whole appearance is dominated by the cross bracing and the large exterior columns. The building appears like a giant black obelisk placed in the middle of the city. It is an imposing structure. For some, it creates a feeling of strength and security, while for others it might produce unease because of its massive size.

In the tradition of Mies Vander Rohe's Second Chicago School of Architecture, the John Hancock Center is an icon of modern American architecture that owes its appearance more to an engineer than an architect. Maybe we can see in this the architecture of the future, where similar to bridges, the shape of high-rise buildings will be governed by structural considerations. Will the high-rise building engineer be regarded as an artist in the same way as great architects and bridge engineers are recognized?

Conclusions

Undoubtedly, Fazlur Rahman Khan will be remembered as a great structural designer, innovator, educator, speaker, and humanist of the 20th Century. His structural ideas have been incorporated into many tall buildings, including the tallest of all the buildings in the world, the Sears Tower. It is fitting that the street sign leading to the Sears Tower is named "Fazlur R. Khan Way" and a sculpture of Khan, commissioned by the engineers of Illinois (Pitroski 1999), is sitting appropriately in the entrance to the Sears Tower evoking his remarkable qualities.

Trizec owns The Sears Tower. Trizec is a Canadian company, owned by a successful Canadian businessman and an engineer, Peter Munk. In a book about his life, Munk says "If you want to build a skyscraper higher than anyone else, you're asking for problems. So when I say I want to build the highest building, I am challenging fate" (Rumball 1997). Whether Munk knew Khan or not is not known to the authors, but perhaps Munk is echoing the sentiments of Khan who dared to challenge the fates when he designed a super tall structure such as the Sears Tower.

Personal tragedies and vicissitudes of life did not daunt the spirit of this great man. He continued to work as an engineer and an artist until his untimely death in 1982. Those of us who are structural engineers are grateful to Fazlur Rahman Khan for motivating us to aim for heights that sometimes look impossible to scale.

Acknowledgments

The authors wish to acknowledge the assistance of students of Architecture and Civil Engineering, Daltech, who took the course ARCH6206 Research Studies in Technology. Their research reports on the John Hancock Tower, the Sears Tower, and One Shell Plaza were very beneficial in writing this paper; these reports are available from the authors. The authors also wish to gratefully acknowledge the encouragement and help given by Professor D.P. Billington of Princeton University, Professor Lynn S. Beedle of Lehigh University, and Professor Marie-Anne Erki of the Royal Military College of Canada.

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