The Trussed Tube John Hancock Center

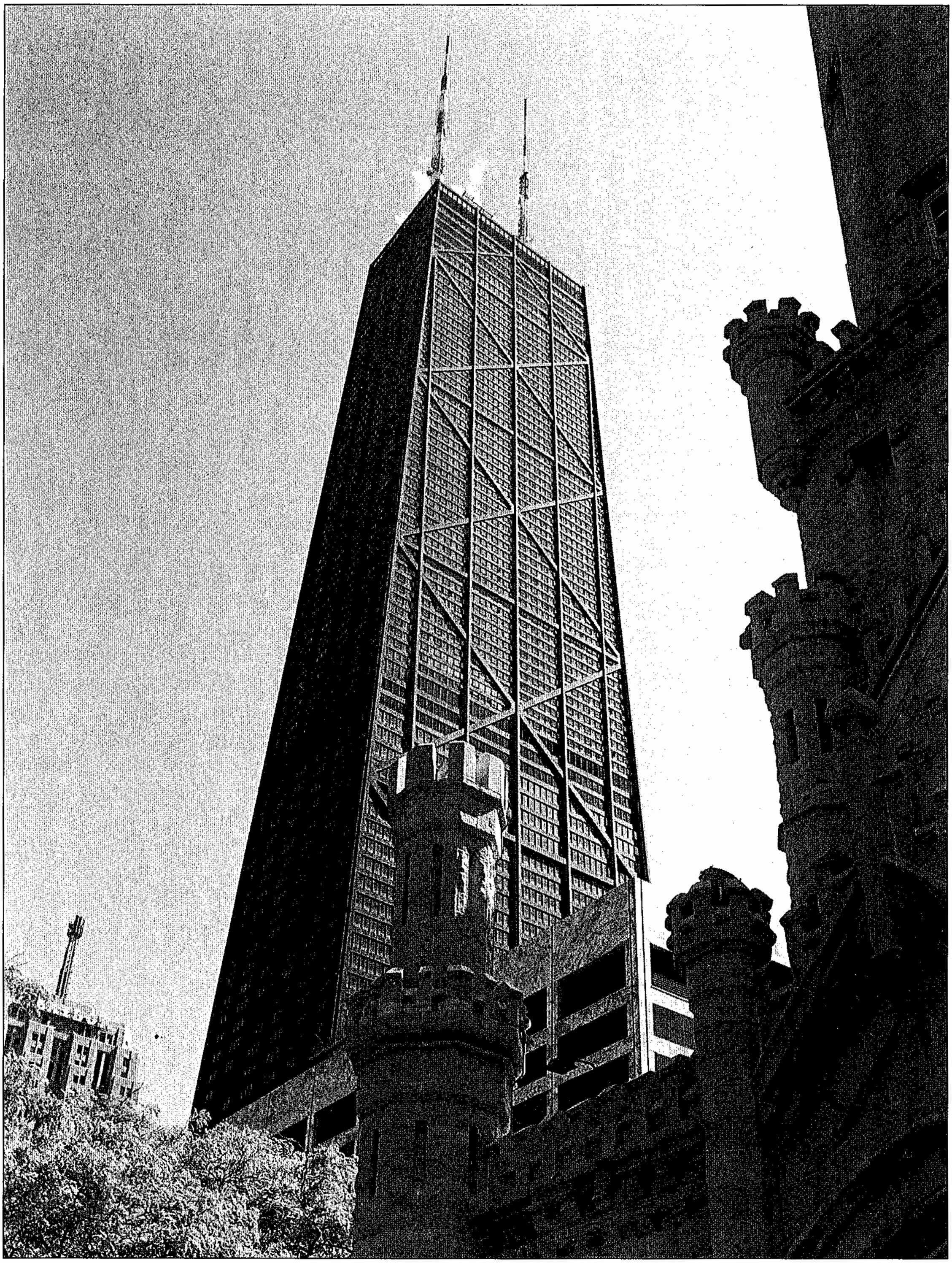
This excerpt from a biography of the noted structural engineer, Fazlur Khan, tells the story of one of his most famous accomplishments.

YASMIN SABINA KHAN

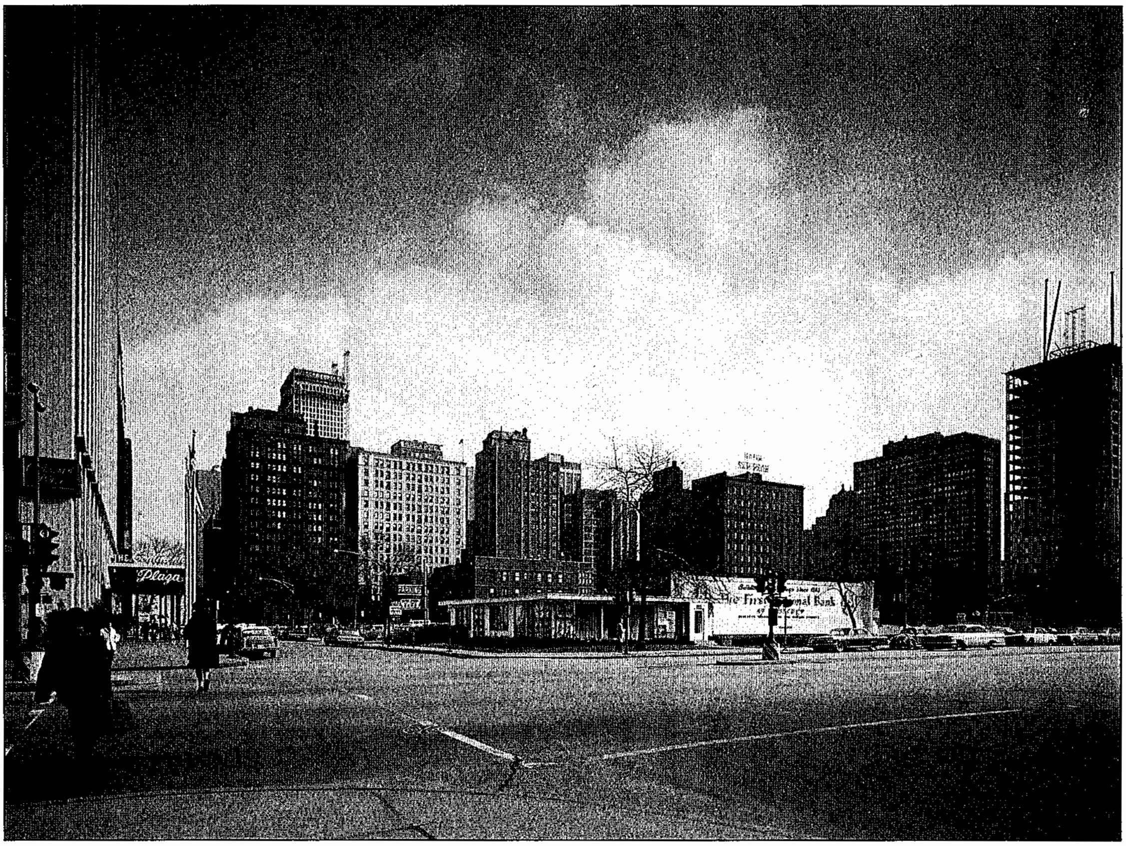
Upon announcement of Skidmore, Owings & Merrill's (SOM) 100-story design for Chicago's John Hancock Center in 1965, design professionals immediately recognized the achievement that it represented. The design was exceptional not only because of the building height, but also, and more significantly, for the "fantastic degree of mutual understanding and collaboration" between structural engineer and architect that it revealed.[1] The structural clarity of the architectural design confirmed the active role that structural engineering innovation could assume in the evolution of high-rise architecture. Possessing a cadenced vigor that is both familiar and novel, the trussed tower's identifiable image quickly became a city icon.

Construction of the John Hancock Center had exceptional personal significance for Fazlur Khan. In addition to the uncommon scale of this project — 2.8 million square feet of program area, a 1,127-foot-tall building, caissons attaining depths of up to 190 feet — the structural system that it initiated realized the still-nascent tubular concept in an altogether new way. The successful implementation of this untried system, Khan believed, depended on his determination and deep commitment to the realization of the structural concept; as a result, the John Hancock Center brought about "the most emotional involvement" with a building of his career.[2]

Khan was thirty-five years old when the builder/developer Jerry Wolman approached SOM in 1964 about a site that he had acquired on North Michigan Avenue. Plans for public transportation in the vicinity — a proposed rapid-transit line, which was not built — enhanced the value of the property and suggested the viability of high-density development. SOM encouraged Wolman to allocate program area to residential as well as office use. The location of the building site was suited to each type of occupancy, and a mixed-use development (a budding idea in the 1960s) would ensure 24-hour activity and land use. The architectural building program was thus divided between office space of close to one million square feet, apartment space of another million square feet, and commercial and parking space of 800,000 square feet.



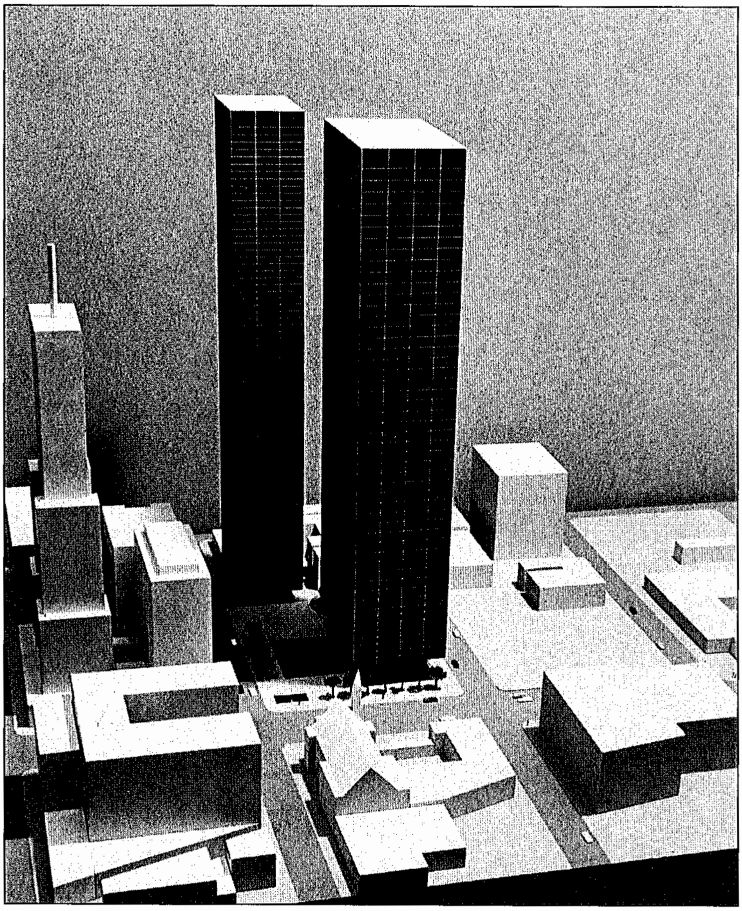
South face of the John Hancock Center. The building's novel form, in conjunction with the cross bracing of the structural frame, guided its architectural expression. (Photograph by Hedrich-Blessing, courtesy of Skidmore, Owings & Merrill LLP.)



Building site prior to demolition. Much of the area behind the low-rise bank building was used for surface parking. (Photograph by Bill Engdahl, Hedrich-Blessing, courtesy of Skidmore, Owings & Merrill LLP.)

Bruce Graham and project architect Robert Diamant, together with Al Picardi and Fazlur Khan, contemplated two alternatives for the office and apartment areas — one that joined these occupancies in a single tower, and one that separated them into two towers. For the single-tower scheme, they positioned residential space above the office, commercial and parking areas, creating a supertall high rise. Preliminary calculations for a shear-truss frame structural system, however, indicated that such a tall tower would not be economically competitive with a two-tower alternative. In the two-tower scheme, the designers separated the office and apartment space, and the two buildings rose either from the street level or from a low-rise base that housed commercial and parking space. Khan studied a number of possible arrangements for the buildings, including one cruciform plan for the apartment building, and talked over the advantages and costs of steel construction and concrete construction with Graham and the rest of the team. For the office building, he leaned toward a steel shear-truss frame structure; for the apartment building, a concrete framed tube with interior shear walls.[3]

The two-tower scheme appeared to be preferable from a financial viewpoint but other issues associated with it raised concern. The size of the building site, in Graham's view, was not adequate to allow for a comfortable separation of the two towers: daylight and views would be obstructed for occupants, and privacy would be compromised. At the same time, a full-site low-rise with two buildings rising above would create a disturbingly crowded environment at the street level. The more the design team examined the two-



When SOM began work on the Wolman/John Hancock Project in 1964, it studied a two-tower scheme. The addition of a site-consuming podium housing commercial and parking space was also considered. (Photograph by Williams & Meyer, courtesy of Skidmore, Owings & Merrill LLP.)

building option, the more they appreciated the benefits of a single tower.

Perceiving that a single-tower scheme deserved further consideration, but that it would necessarily involve a new type of structural system, Khan decided to present a new concept for supertall building design to Picardi and Graham.

He had recently substantiated a type of tubular structural system, he informed them, that would likely be appropriate for the proportions of the proposed single tower. This structural type, which he termed the optimum column–diagonal-truss tube, involved a break not only from the conventional moment-resisting beam–column frame system, but also from the framed tube that they had initiated in a previous project at the Chestnut-DeWitt Apartments (a large-scale residential tower in a lakefront neighborhood north of the Loop in Chicago). Although also a vertically cantilevered tube form, this structural type did not require the closely spaced columns that defined the framed tube. Instead, the optimum column–diagonal-truss tube, or simply "trussed tube," made use of large diagonal members that extended vertically across numerous stories at the building's exterior to create a stiff perimeter form. In contrast to the narrow windows imposed by the framed tube structural system, the windowpanes could be broad; large diagonal members, however, would cross through some of them. If the architects could accept this condition, then a building of requisite height to locate residential space above office, commercial and parking space could, he predicted, be economically feasible.

Khan was able to boldly present this building concept for consideration because of his involvement at the Illinois Institute of Technology (IIT). In 1963–1964, a graduate student, Mikio Sasaki, had expressed interest in working out an efficient solution for a tall steel building subject to high wind and seismic forces. Sasaki chose to employ diagonal bracing in his design project, a structural element contemplated by his architectural advisor, Myron Goldsmith, in his own thesis in 1953. Khan worked with Sasaki as his structural thesis advisor and recommended that the bracing be configured to create a perimeter tubular form. What they developed was a structural system that integrated multistory diagonals with columns and spandrel beams in the exterior frames of a 168-foot-square, 700-foot-tall building. Integrated into the frame structure, the diagonals in this application differed from traditional bracing elements, which restrain beam–column frames from swaying under wind but are not intended for carrying gravity loads. Diagonals in this new structural system, in contrast, were part of the framework that supported gravity loads and lateral loads; in addition, the diagonal column elements distributed load to the vertical columns of each frame. For the overall structure, the X-form diagonals had a transforming effect, unifying the four exterior frames into a tube system through their connection at the building corners. The structural organization minimized shear-lag effect and suggested a superb economy of material.

The student thesis was necessarily limited in scope. Since a complete analysis could not be performed, the actual flow of load in the structure was not certain. Nonetheless, computations and a simple model test showed that their premise was correct: lateral stiffness could be enhanced with the introduction of a minimum number of rigid diagonals into the exterior wall planes. Rather than behaving as a frame or truss structure, the tower would act as a cantilevered tube. For wind load conditions, this system appeared ideal. (Khan later concluded that the cross-braced system was overly rigid and insufficiently ductile for use in high seismic zones.) Having obtained preliminary confirmation of his intuitive understanding of this structural type, Khan put his faith in the new concept.

After performing preliminary calculations to satisfy himself, he assured the SOM partners, and then the project developer, that a design for an approximately 1,100-foot-tall structure could be accomplished within the project constraints. One constraint was a short design schedule; the design phase was to be completed within one year, with structural steel scope documents bid several months before the completion of the drawings. (Large investments in preconstruction items — land, in particular — raise to prominence the criterion of obtaining income from a development project as quickly as possible.) The decision hung on an economic analysis of the schematic designs, comparing the single tower to several two-tower alternatives. As Khan had predicted, the analysis demonstrated the trussed tube system's unparalleled structural efficiency. Convinced of its advantages and structural validity, Jerry Wolman agreed to this progressive design scheme and authorized SOM to proceed into design development.

Although the SOM partners had agreed to the firm's initiation of Khan's proposed structural scheme, they remained anxious to obtain assurance that the concept could indeed translate into judicious construction for a 100-story tower. Design review by a few outside engineers had been incorporated into the design process on other SOM projects and had appeared to be productive. So, for Wolman's project the firm sought similar independent critiques, focusing attention on the structural concept and analysis of the system. Some engineers, it found, were initially skeptical of the structural concept. This response, however, was not the most disturbing in Khan's view. Instead, proposals that were put forward by two design firms to assume full or shared responsibility for structural engineering on the project distressed him most. The structural consultants suggested that, rather than review it, they should perform the design.

The legitimacy of these suggestions gave the SOM team pause. One of the design firms was structural engineer on the World Trade Center Project in New York. The firm's studies, its partners reported to SOM, showed that the Vierendeel truss system was more economical and practical for a 100-story building than the trussed tube system that Khan was proposing. Furthermore, they had commissioned an extensive research project for determining the effect of building sway on occupants, an issue that was of concern to any designer of a flexible, modern high rise. If their firm were given responsibility for the structural engineering on the Wolman Project, the results of the costly investigation sponsored by the Port Authority of New York and New Jersey would be available to the design team.[2,4-6]

Confounded by the prospect of SOM either conceding the implementation of the advanced structural scheme to a structural consultant or abandoning it altogether and allowing another firm to step in, Khan argued fervently against such a scenario to the partners. Why else retain talented engineers in the architectural and engineering firm, he questioned, if not to expect them to apply their skills and assume the responsibility of which they were capable? On his part, he resolved — the only time in his twenty-four-year career with SOM — to leave the firm if the design responsibility was given to an outside consultant.

Khan was asking the partners to make a painfully difficult decision to move forward with a potentially valuable innovation recommended solely on the basis of a young engineer's evaluation. Though the matter remained undecided for about six weeks that winter, Khan was relieved to know that Bill Hartmann, the managing partner on the project, was not inclined to trust other preliminary evaluations over his, nor were the other partners. SOM decided to retain control of the structural engineering on the project and declined the consultants' proposals for involvement. Khan would be able to shepherd the engineering design from conceptual planning to construction completion.

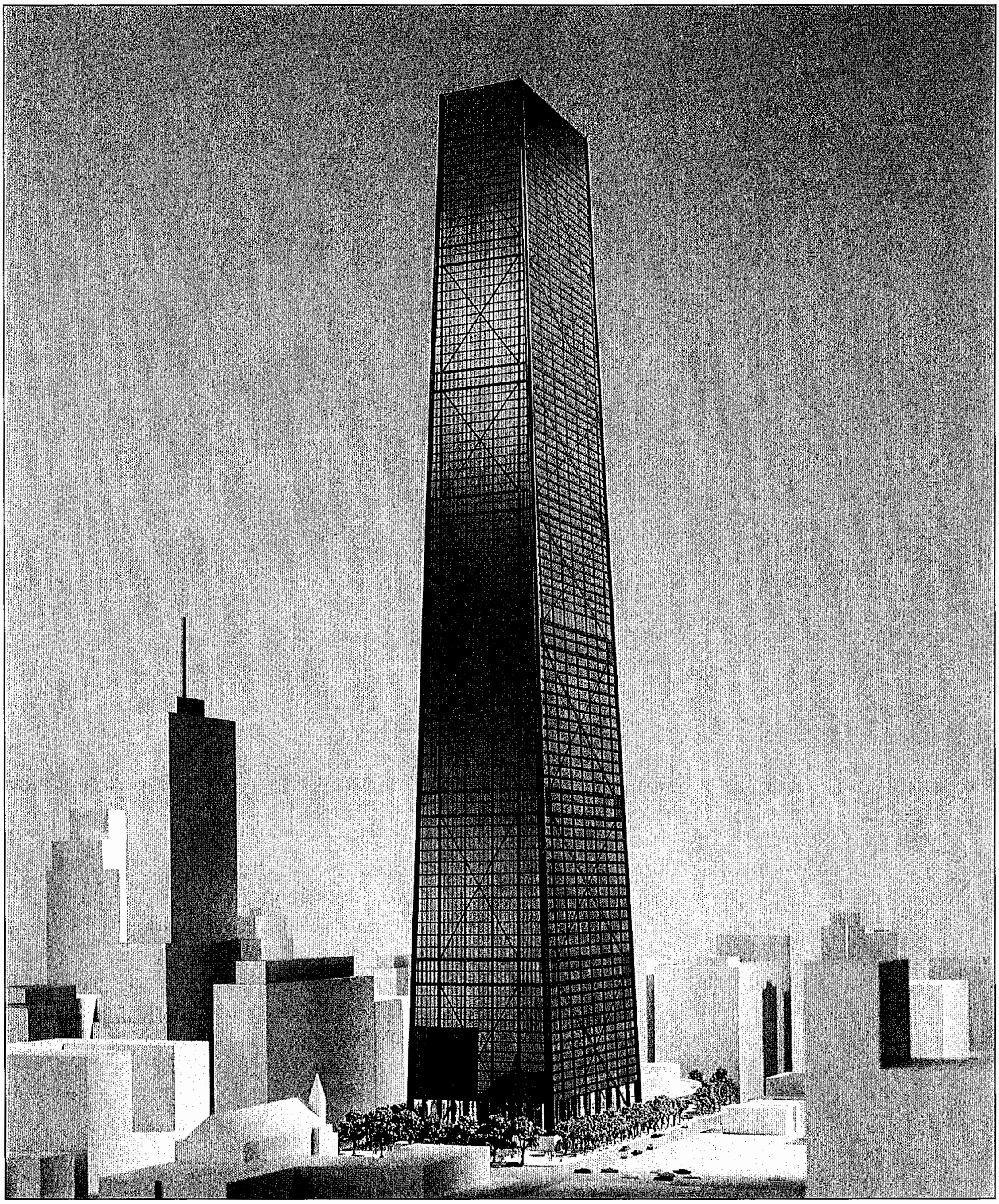
Looking back, Khan felt that his determination, attention and belief in the structural concept had been essential in keeping the project on track. His visual understanding of the system and his intuitive assessment of the quality of load flow enabled him to persist in the face of inherent design difficulties.

Analysis of the Structure

An intense schedule, a building system without precedent, a soaring height above ground and tremendous depth below grade required the unwavering commitment of the design team. As project structural engineer on the Wolman project (by 1965 called the John Hancock Center since the John Hancock Mutual Life Insurance Company, along with four banks, agreed to provide financing for the project), Khan insisted on putting together an engineering team that could handle the strenuous pressure caused by the schedule and the uncertainties of an innovative undertaking. The architects, likewise, had to cope with, even thrive on, demands on their resources and energies.

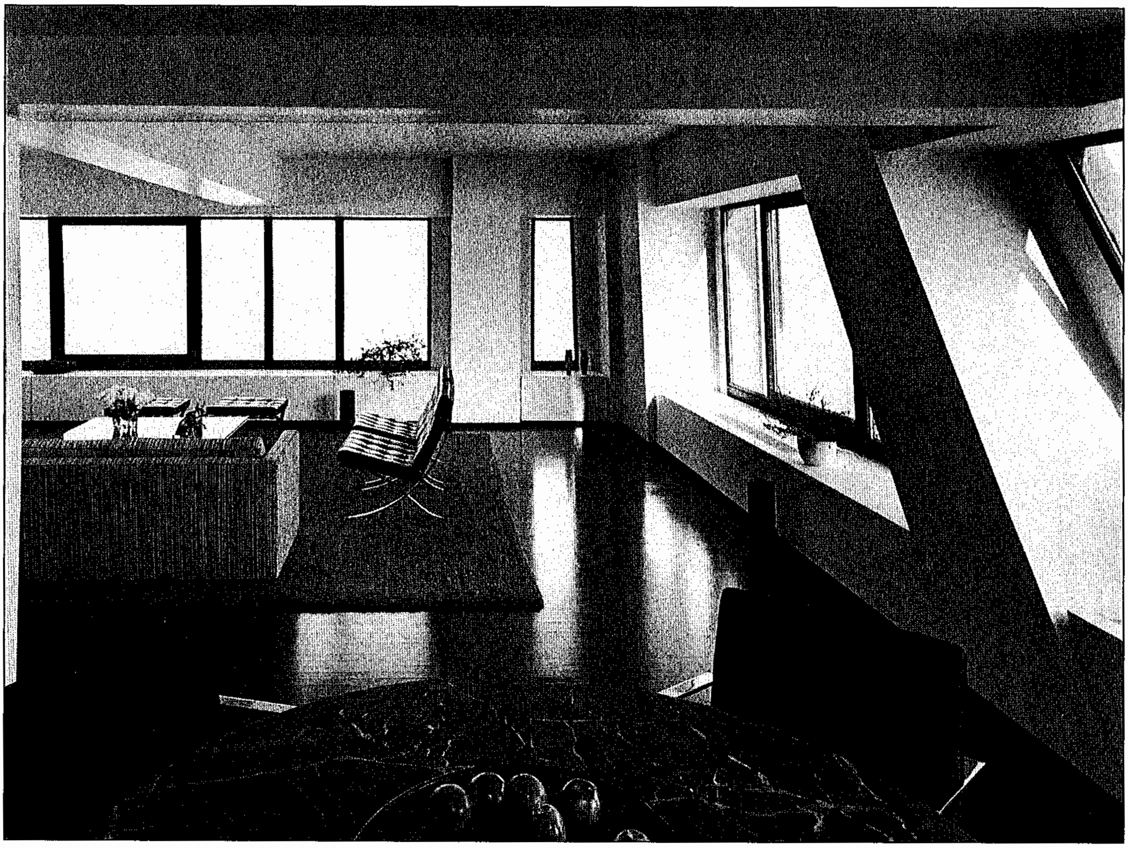
The two main occupancies of the single tower called for different building proportions, which had to be resolved early on. Whereas large areas of unencumbered floor space were preferable for office use in the lower portion of the tower, the apartments housed in the upper portion needed a narrow floor plan for maximum window exposure. A common resolution of these contending building program criteria would indicate a stepped building elevation. But this configuration would not have worked with the structural system that offered the efficient 100-story structure. In response to these programmatic objectives, Graham, Khan and the rest of the team developed a building solution utilizing sloped exterior walls. With a gentle taper from base to roof, a notable reduction in building cross-section could be achieved.

From Sasaki's thesis project at IIT, Khan knew that the diagonals should be placed near to 45 degrees with the horizontal for maximum structural efficiency. To satisfy this criterion, SOM's initial organization of primary members represented an overlay of a uniform band of cross-braced tiers on an elevation of sloped sides. This arrangement required adjustment, however, since it was essential to tube action that the diagonals from adjacent building faces intersect at the building corners, together with a corner column and the primary spandrel beams. The designers realized that, to meet these additional criteria and maintain an approximately uniform tier height, the angle to the horizontal of each tier's diagonal members would have to differ slightly along the height of any elevation and to differ significantly between broad and narrow elevations. There were other adjustments that had to be made to accommodate the tapered building form: a constant floor-to-floor height, for instance, was not possible. Within the bounding modules, or tiers, set by the diagonals and the spandrel beams, floor-to-floor heights were allowed to vary within certain ranges: 9 to 10 feet for the apartment stories and 12 to 13 feet for the office stories. Based on the numerous structural and program requirements, the designers tested sev-



An early model for the 100-story tower, released for public announcement of the project in April 1965. (Photograph by Bill Hedrich, Hedrich-Blessing, courtesy of Skidmore, Owings & Merrill LLP.)

eral dozen variations of building geometry to determine a suitable base footprint and degree of taper. The form they settled on tapered gradually from a 165- by 265-foot structure footprint at the ground level (with approximately 44,000 square feet of program area) to 100 by 160 feet (16,000 square feet) at the tower's main roof, 1,107 feet above street level.



An 82nd floor apartment in the John Hancock Center; the diagonals assert themselves into the experience of the interior space. (Ezra Stoller © Esto.)

Above the main roof, a smaller penthouse structure rose to 1,127 feet.

The clarity that came about due to the geometric necessity of extending the diagonals out to the sloped corner columns can be readily appreciated when comparing the original scheme with the built elevation (see the illustrations on pages 13 and 8). It is apparent that an unambiguous architectural narrative emerged from the designers' acceptance and appreciation of structural realities; by heeding the structural logic of the system, the architecture gained integrity and substance.

The notion of large diagonals interrupting window glass was at first an unpromising aspect of the structural system. But with further review, the project team became favorably disposed to the condition, as did later architectural critics and building occupants. The diagonals were not an arbitrary feature of the façade, after all. Rather, the elevation coherently expressed the building structure and carried on Chicago's heritage of structural and architectural integration. The intrusion of diagonals on the interior at windows, moreover, was not generally disagreeable to occupants, owing to a certain sculptural effect and the unusual nook-like spaces that the diagonals created. In his article "'Living in the Sky' Is Almost Heaven," architecture critic Rob Cuscaden remarked that apartments in the John Hancock Center possessed window patterns "far more interesting than the usual box-like openings in box-like suburban homes."[7] Residential units received the further benefit of magnificent views that encompassed seemingly infinite expanses of lake and sky to the east, and city and sky in the other three directions.

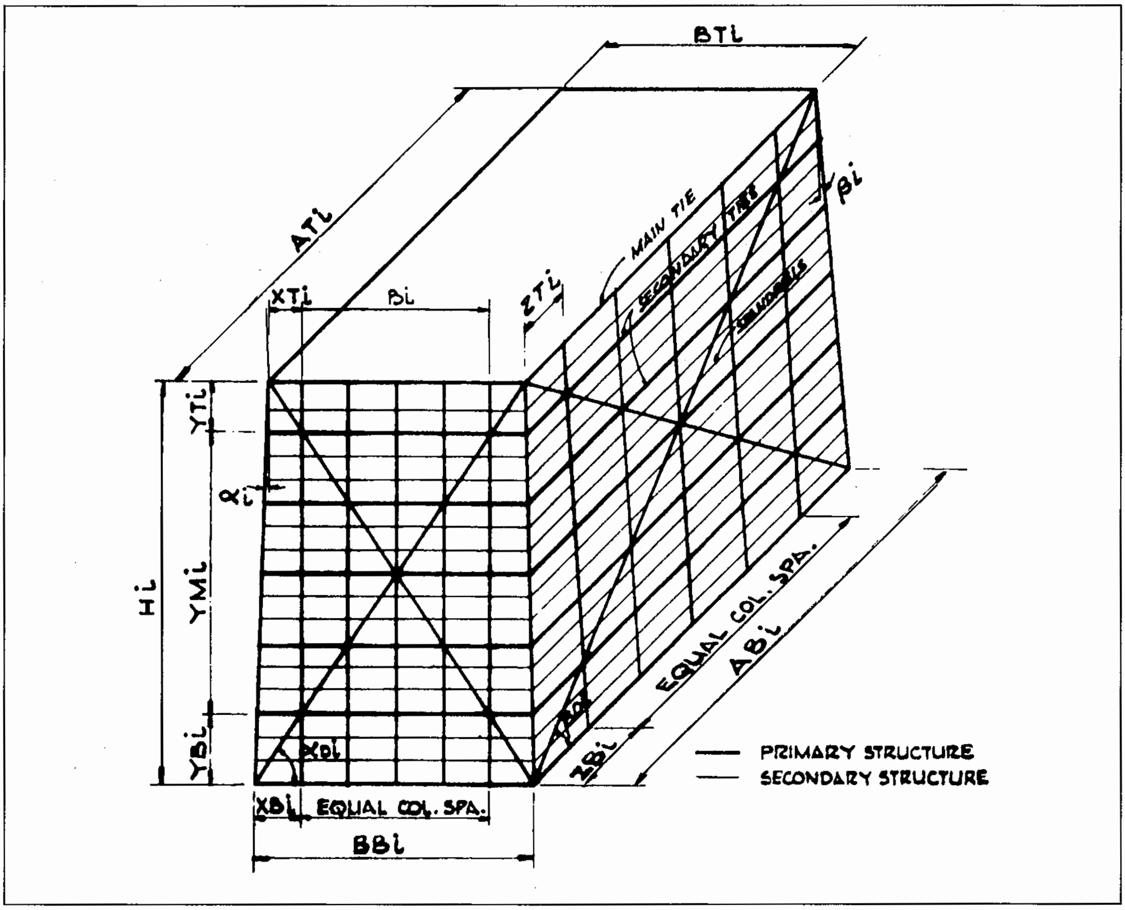
For analysis of the structure for wind load, Khan obtained data from the U.S. Weather Bureau and established design wind pressures 20 percent beyond those recommended in the

Chicago building code. His determination of this increase raised considerable dispute, however, since the independent consultant retained by the building's owner, John Hancock Mutual Life, argued for an even higher multiplier. After much discussion with SOM's own advisors, Khan agreed to use a design wind pressure 25 percent beyond code. To further satisfy the consultant's concerns, he checked that member stresses remained below the allowable stresses when the pressures were increased by 40 percent. In addition to these measures, he introduced a second type of wind load condition: anticipating the limit level adopted a few years later, the structural design evaluated building members when wind pressures equal to 2.0 times the pressures recommended in the Chicago building code were applied, concurrent with gravity loads, to ensure that they neither yielded or buckled at this high stress level. Ultimately, the structural members were negligibly affected by wind-induced stresses, due to the efficient trussed tube structure.

Since SOM had acquired its first computer system in 1961, the office had developed adequate programs in-house to make extensive use of this powerful tool for the John Hancock Center design (the computer initially served only to check manual calculations). The structural engineers developed computer programs and subprograms for the geometric and architectural program analyses necessitated by the atypical building form, for the study of relationships among members to establish optimum member sizes, for preliminary wind load computations and for column load calculation. In order to study the exterior tube structure, the engineers divided the 100-story tower into braced tier sections for more manageable computation. Employing a technique similar to that used when Khan first introduced the framed tube concept, they reduced the structure for analysis into equivalent models. The procedure would not provide an "exact" solution for the static wind load condition, but they expected that the results would be reasonable, especially for preliminary member sizing. The design team also scrutinized exterior frame member proportions, with the goal of optimizing total material quantity. Hal Iyengar and Joseph Colaco, who were working full time with Khan on the project, developed a computer program to aid in this analysis. (Khan later recounted a lesson from his former professor, Chester Siess, in this period about the importance of critical thinking versus specific knowledge. When preparing for this project and looking for an engineer to assist in the analysis, Khan had talked with Siess, who recommended Colaco, a student of his at the University of Illinois. When Khan seemed hesitant to contact Colaco because of his field of study — reinforced concrete — Siess asked Khan what had been the subject of his doctoral study — prestressed concrete design.[8])

Once the structural members had been sized, more exact analyses of the structural frame were undertaken on large-capacity computers by structural consultants retained by SOM. One consultant, Paul Weidlinger, suggested that it would be prudent to obtain more than one mathematical solution. He wrote in March 1965, "I have reviewed the wind bracing system rather carefully, and I am of the opinion that the proposed method is excellent." But due to "the very magnitude of the analytical problem . . . it may be warranted to perform this work by two distinct methods independently, to ensure reliability."[9] SOM favored a duplicative approach, as it was, since this would help to calm any lingering unease regarding the trussed tube structural system.

Employing models that represented one-quarter of the building frame, John E. Goldberg, of Purdue University, and Weidlinger performed independent space frame and space truss analyses, and Steven Fenves, of the University of Illinois, and Robert Logcher, of the Massachusetts Institute of Technology (MIT), worked on a STRuctural Engineering System Solver (STRESS) analysis, which had been developed by Fenves and Logcher, along with Samuel Mauch. The set criteria required the various computer programs to consistently interpret the structural system. Member design would not be finalized until the load flows and exterior tube member stresses calculated by the various programs were in agreement. This confirmation was intended to satisfy SOM and the owner; the designers also

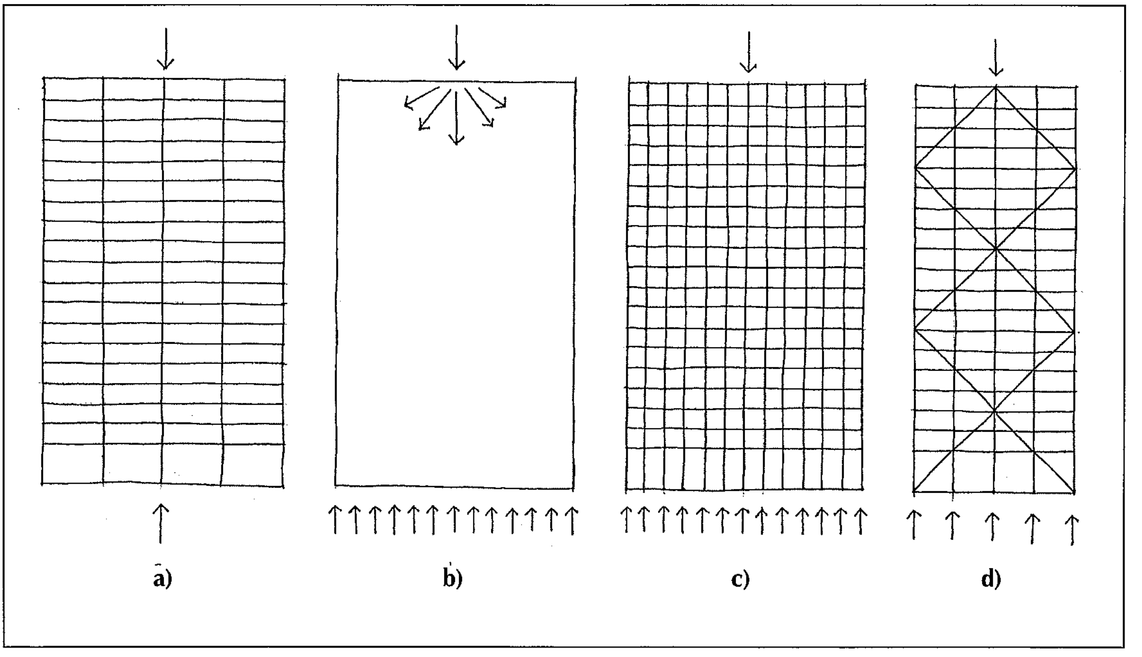


Single tier module for analysis. (Courtesy of Skidmore, Owings & Merrill LLP.)

met regularly with the engineers at the city building department to ensure the city's agreement with the new structural system.

The new computer technology allowed for amazingly quick numerical confirmation. An initial truss analysis that disregarded the diagonal members' bending stiffness and the essential fixed connections between diagonals and vertical columns caused momentary concern. But this issue and the few discrepancies between computer analyses were resolved, and member stresses were determined to be in close agreement. Through this rigorous examination, the system proved itself to be valid and efficient. The tying action of the primary spandrel beams at levels where diagonals met the corner columns was critical in forcing the cross-bracing diagonals to behave as column members and, with the transfer of axial load between diagonals at the building corners, established three-dimensional tubular action of the perimeter structure. The secondary spandrel beams, which spanned between intermediate intersections of diagonals and vertical columns, were also important to the system in forcing distribution of gravity and wind loads from the diagonal members to intermediate columns along each face. Because of this effect, the intermediate vertical columns acted together as an effective bearing wall, sharing applied loads according to their cross-sectional area instead of as independent load-carrying elements. In contrast to the columns in beam–column frames that experience large bending moments, the trussed tube's columns, vertical and diagonal, experienced minimal bending.

The efficiency of the trussed tube structural system was demonstrated by the final design:



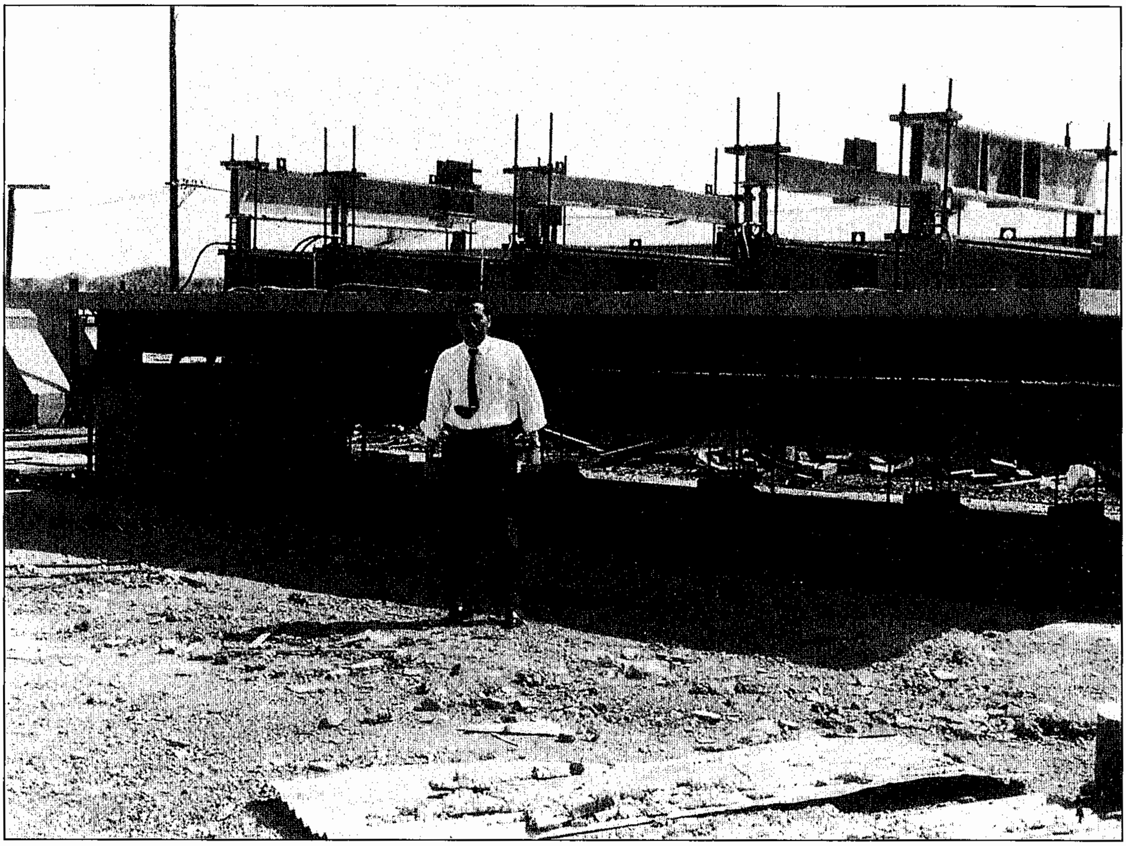
(a) Localized support of a concentrated load in a traditional beam–column frame versus (b) distribution of load for uniform support at the base in a bearing wall. The distributive action of the bearing wall can be simulated by (c) the system of closely spaced columns and stiff beams in a framed tube, or (d) the integration of columns, beams and diagonal columns in a trussed tube. (Drawing by David Fung.)

notwithstanding long interior floor spans of 30 to 58 feet, structural steel quantity averaged a low 30 pounds per square foot of floor area. This unit quantity of steel was equivalent to that required for an economical traditional building of 40 to 50 stories. Whereas the framed tube that Khan had developed for the Chestnut-DeWitt Apartments suffered from the inefficiency brought about by shear lag, caused primarily by the flexibility of spandrel beams, the distribution of stresses in the John Hancock Center columns under wind load was "very similar to that expected in a true cantilever tube structure" — a remarkable achievement.[10]

The 12- to 13-foot floor heights of the office levels allowed for a hung ceiling with space below the slab to run electrical conduits, mechanical ducts and plumbing pipes. Similarly, the 9- to 10-foot floor heights of the apartment levels could have accommodated hung ceilings — a necessity, if steel beams were to be fireproofed and located within room floorplans. But rather than assign primary importance to interior layout flexibility inside the individual apartments, the architects decided to create spaces with high ceilings and an associated sense of luxury. The need for hung ceilings was avoided by coordinating structural floor framing with the layout, so that steel beams coincided in plan with either partition walls or functional room separations.

To span between the floor beams, the engineers designed a lightweight concrete composite slab system, which could be employed on both the apartment and the office floors. To force composite action of the concrete slab and the steel beams, effectively creating T-beams, shear stud connectors were welded to the beams' top flanges. The bottom of the slab construction at the apartment levels served as the ceiling surface.

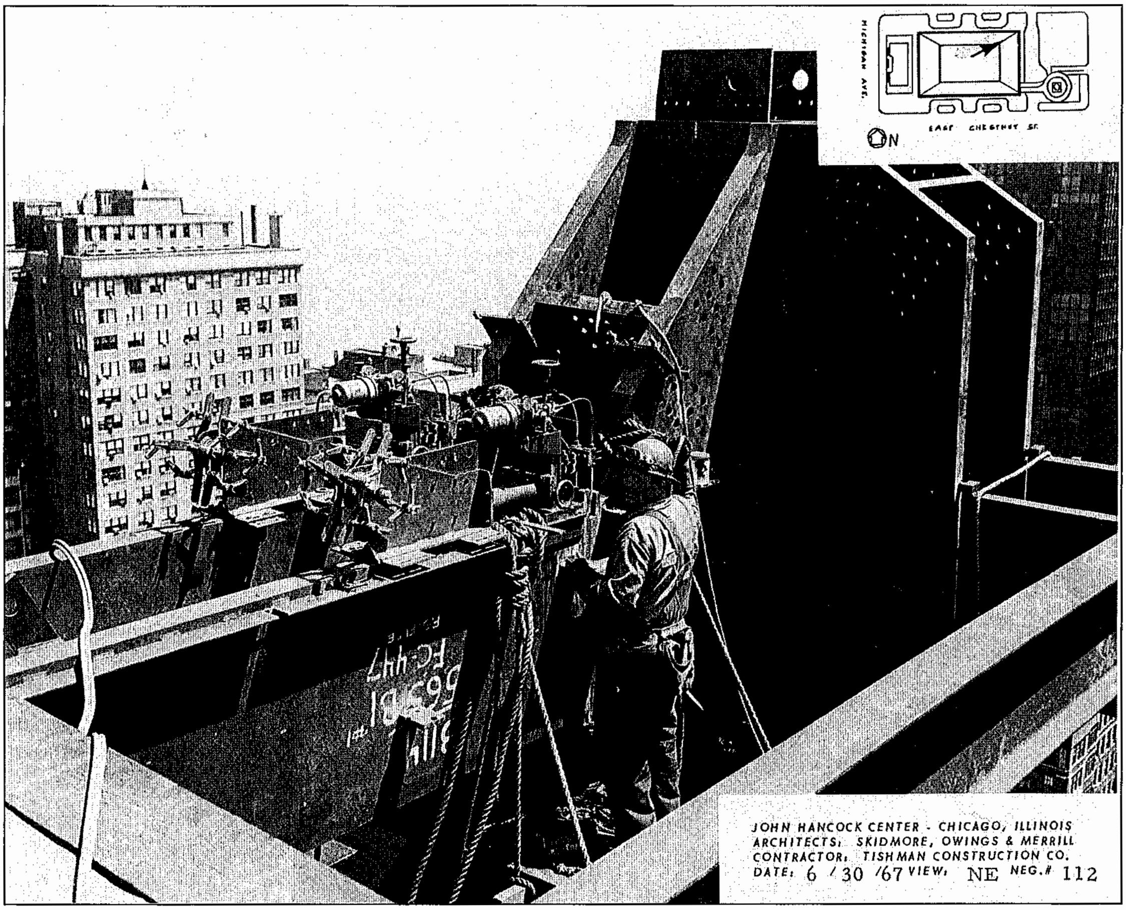
In another twenty years, designers would take for granted the application of composite action between the concrete slab and steel beam. But in the 1960s the practice of securing steel connectors to steel floor framing to



Khan during composite slab tests, April 1965.

engage a concrete slab in composite behavior was, though applied, still in the process of being refined. The 1963 American Institute of Steel Construction (AISC) "Specification for the Design, Fabrication and Erection of Structural Steel for Buildings" provided an early version of composite design recommendations that did not consider partial composite action, deflection, floor vibration or the distinct behavior of lightweight concrete.[11] Metal deck was initially considered a barrier to composite action between beam and concrete since the attachment of the deck to the top flanges of beams interfered with attachment of shear connectors. This difficulty was resolved first by cutting holes in the deck through which shear connectors could be placed and welded to the beam flange, and later by the introduction of shear studs that could be positioned on top of the metal deck and welded through the deck to the beam flange below. In the mid-1960s, engineers were permitted to design an economical composite floor framing system, but were expected to confirm the structural properties assumed in the design of that system. Khan pursued this path and planned a testing program of the proposed floor system.

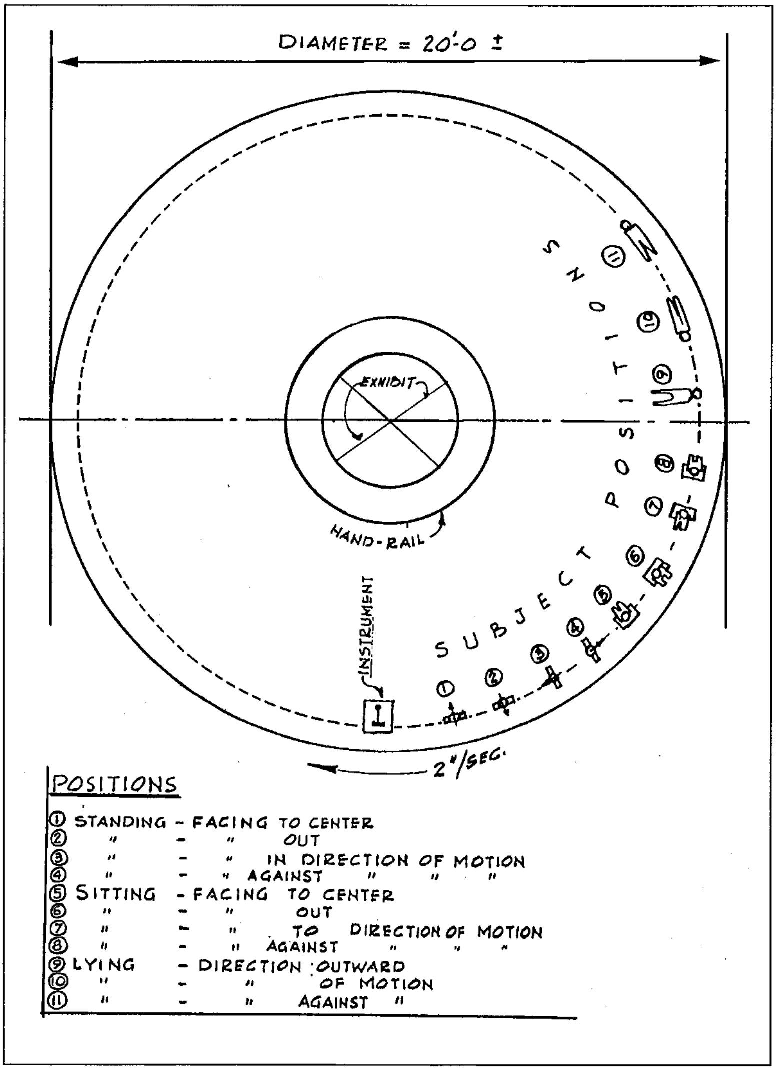
The corner joint detail — essential for integrating the diagonals, spandrel beams, and columns into a whole, tubular form — received much of the engineers' attention during design. Khan knew, when proposing the trussed tube system, that the joints transferring loads in the 100-story tower would not only require unusual analysis but also could become expensive and difficult to construct. He met with technical representatives from two steel fabricators early in the design process to discuss how the joints could be detailed to ease their fabrication as well as erection of the structural frame. To this end, the diagonal columns, vertical columns and spandrel beams were all made of built-up H-sections of ASTM A36 steel, and the major



This construction photo reveals the scale of the prefabricated main joints. (Courtesy of Skidmore, Owings & Merrill LLP.)

joints were fabricated in the shop. (ASTM A36 steel was introduced in 1960 and quickly replaced A7 steel because of its higher working stress and yield point and its weldability. Higher-strength steels were available as well during the John Hancock Center design, and Khan used A441 steel for some of the main joint gusset plates. But he hesitated to make use of higher-strength steel in high-rise member design, believing that it was inefficient to economize on material quantity if building vibration and sway became the governing design criteria.[12]) Prefabrication of the joints allowed welding of the thick steel plates to take place in the shop, thereby reducing overall steel costs and facilitating testing, and corrective measures, for residual stresses induced by welding. Field erection predominantly involved bolting, which contributed to the relative speed of erection of the steel frame.

SOM commissioned a steady-state wind tunnel testing program at the United Aircraft Corporation Research Laboratory to estimate wind pressure distribution around the building structure. Based on this information, on wind load data from meteorological observations and on computed natural frequencies of the structure for the first few modes under steady wind, the engineers were able to perform a pseudo-dynamic computer analysis. Considering the building as a single-degree of freedom system, they investigated the structure's response to wind load. Their computer analysis provided values for structural displacement, velocity, acceleration and rate of change of acceleration at prescribed time intervals.[13-15]



Khan demonstrated practical ingenuity with his use of The Tale of a Tub exhibit for motion perception investigation. This plan represents his placement of subjects on the exhibit's rotating platform, taking into account suspected variation in perception based on head and body position relative to motion. (Drawing by Fazlur Khan.)

Khan knew that, aside from structural strength considerations, design of this building required evaluation of the effect of movement under wind on the building occupants, particularly occupants of the apartment floors in the top portion of the tower. Assessing people's response to building sway, however, was difficult due to a lack of criteria regarding human perception and comfort. What motion of the building by wind gusts could be tolerated? As structural engineer William LeMessurier put it, "[a]lthough we are daily coming closer to being able to calculate deformations and vibrations under any loadings, we know less and less about what we want them to be.... No authoritative standard exists for the wind design of buildings which includes criteria for movement and vibration."[16] Not only was there no standard established, there were few studies of building motion in 1965, and none that evaluated building movement in terms of occupant perception and discomfort. Experimental psychologists believed that human perception of horizontal linear or rotatory motion was caused by the movement of fluid and pressure change in the inner ear and that pressure change was affected by the acceleration of motion and the rate of change of acceleration. Unfortunately, tests thus far had been directed to space-flight tolerance and high-frequency vibration, not to the type of motion that would be felt in a tall building. To evaluate anticipated motion of a tall building, correlation between motion and perception of motion first had to be established. Once a correlation was identified, then the anticipated structural behavior could be evaluated in terms of tolerance levels.

The study of the perception of motion belonged to a special field of psychology, and psychological testing was not an enterprise normally embarked upon by an architectural or engineering firm. The detailed study that was underway for New York's World Trade Center project was run by a research team of physiologists and expected to involve a large number of subjects.[5,17] This scale of investigation was not possible for the privately developed tower in Chicago.

For an initial evaluation of the John Hancock Center, the engineers compared its structural properties with those of other tall buildings. This limited basis for comparison indicated that it would perform at least as well as the majority of existing tall buildings. The project team, nevertheless, aimed to obtain a more direct means of confirming that the building's sway in wind would be acceptable to occupants.

As Khan pondered how the design group might devise a practical means of predicting motion discomfort so as to evaluate the building structure, a fortuitous Sunday family outing to Chicago's Museum of Science and Industry suggested a solution to the problem. One of the exhibits featured washing machines; in the middle of the room was a large tub (courtesy of a washing machine manufacturer). The clear-walled tub was elevated on a base and situated in the center of a 20-foot-diameter rotating section of floor. While standing on the platform and viewing the tub, Khan felt a slight jerk and perceived the rotating floor's potential as a motion simulator. Later that week, he inquired about the floor's controlling mechanism and determined that by operating the on/off switch, he could vary acceleration within the range that was of interest to him.

Khan developed a study of building motion utilizing the museum's exhibit. He obtained two accelerometers and recruited eight subjects, beside himself, for his experiments. The participants stood, sat and lay on the floor in various positions relative to the direction of rotation. Adjusting the platform's motion and recording each person's response, Khan charted each subject's level of motion perception with the corresponding component of linear acceleration. Perception began at maximum accelerations between 0.004 g and 0.0075 g. Tolerance to the motion, once perceived, varied greatly, but it was possible to determine a general threshold for discomfort.[18]

As a check on the results obtained from the experiments at the museum, he also measured the acceleration of an existing building. He had heard that the swaying motion of 860 North Lake Shore Drive, where a former student of his, Phyllis Lambert, lived, was apparent to occupants during strong windstorms. He asked Lambert whether she would be willing to participate in a study. She agreed, and he placed a monitoring instrument in her top-floor apartment. When she next perceived motion, she was to turn on the instrument, thereby registering her perception. The instrument would record the building's movement at that moment. A timely storm in August 1965 caused the 26-story structure to sway noticeably, providing Khan with a measurement of maximum acceleration corresponding to perceived building motion. This measurement agreed with the criteria that he had derived from the testing program undertaken in the museum.

Results from these rudimentary tests were qualitative in nature, and additional research in motion perception, as well as in wind engineering, would be needed to obtain definitive quantitative information. Khan's research nevertheless gave both the design team and the owner a level of confidence in the anticipated performance of the building.

Caisson Foundation

A gridded slab located beneath the basement slab, with the space between filled with compacted soil, was designed to transfer horizontal load from the tower to the clay soil. Below the gridded slab, 239 caissons were constructed to carry the vertical loads: the 57 caissons supporting the tower were founded in bedrock, another 182 were founded on hardpan. When the scale of construction and the impediments to caisson installation involved are considered, the task can be better appreciated. The lowest recorded elevation of bedrock in Chicago's greater downtown area in 1965 was approximately 145 feet below grade — a large distance for caisson construction. Preparatory exploration for the John Hancock Center indicated that bedrock at the project site was located around 120 feet below grade. Unexpected abrupt local variation,

One method used for repairing defective zones in caissons was to dig a 4-foot-diameter access shaft down to the level of defect. (Courtesy of Skidmore, Owings & Merrill LLP.)

however, required that one 6.5-foot-diameter caisson be extended a record 191 feet below ground level to reach sound bedrock. Caisson installation involved auger drilling through clay layers, hand mining of long distances of unsuitable rock layers, barrel cutting sockets into bedrock, dewatering inside the shafts and removing large steel casings during concrete placement.

Prior to the development of mechanical drilling equipment, caisson construction necessitated manual excavation and the manual installation of wood lagging with steel rings to provide the caisson form. Beginning in the early 1950s, large-scale drilling equipment offered an alternative method of constructing caissons of limited diameter, by excavating with an auger or bucket-type rig. To maintain the outline of the caisson hole, telescoping steel casing was inserted into the drilled shaft, and concrete was placed inside the steel casing. If the soil were considered stable, a portion of the steel casing could be removed before the concrete pour underwent initial set. Construction documents in the 1960s generally permitted recovery of the expensive steel casing for reuse since engineering practice did not account for the steel in caisson design, whether or not it was left in place. The timing of removal, though, was critical; if the concrete began to set, it might move upward with the shell. On the other hand, the casing could not be removed too quickly, because adequate concrete pressure head was needed to prevent soil and water from moving into the drilled opening. Construction of the John Hancock Center's deep foundations was accomplished by a combination of machine excavation and hand mining with jackhammers, and involved this procedure of steel casing placement and retrieval.

After foundation construction was complete, and as the first levels of structural steel framing were being placed, an unexpected halt was imposed on the project's fast-track schedule. In mid-summer 1966, SOM's field representative learned that the top of one 8-foot-diameter caisson had shifted under the light construction load of a steel column. This inexplicable occurrence was relayed to Khan, who immediately called a meeting at the site. Discovery of the inconceivable movement of a caisson raised heated argument since some of the project participants were convinced that the reading could only be a result of measurement error, not actual vertical displacement. Khan found himself under enormous pressure to believe any plausible explanation that would allow construction to continue. A delay and an examination of the foundation would be costly; besides, subsequent legal complications were inevitable. It was an unenviable dilemma for an engineer — the type that one hopes not to encounter during the course of a career.

He decided that SOM had no choice. In good conscience, he and the design firm had to insist on identifying and resolving the cause of the settlement. Though he did not relish confrontation, once he had made his determination, he held fast. That Friday in July, steel erection was stopped locally in the area of the building carried by the one caisson in question so that its shaft could be cored: concrete core samples would reveal irregularity in the concrete construction. Khan later recalled being somewhat uneasy about his decision to give heed to the one elevation measurement and to initiate an investigation. Yet that weekend the soundness of his judgment was confirmed.

To everyone's dismay, a 14-foot-long void, from elevation –57 to –71 feet, was identified in the exterior column caisson. It appeared that concrete, having begun to set, had clung to the steel casing when the casing was withdrawn from the upper portion of the shaft, leaving a portion of the caisson section without concrete.[19,20]

Once this void was discovered, the placement of concrete for all caissons became suspect. Steel erection was halted and an inspection program of tremendous scale was commenced in August and only completed in the spring of the following year. Approximately 20,000 lineal feet of 2-inch-minimum-diameter core drilling was tested; a supplementary investigatory method using sonic signals between core holes was also employed. A second void was found in a 6-foot-diameter caisson, and soil and water contamination was located in numerous others. The upper segments of the two caissons with major defects were removed and entirely replaced. In three caissons with less severe faults, temporary access shafts were excavated alongside the caisson shafts, from which defective sections could be manually cleaned and repaired. In all, 26 of the 57 caissons to bedrock received corrective work of varying degree. The program was costly and time-consuming; the return for it was full assurance of the foundation's structural integrity. Nevertheless, the scale of the investigation left Khan and some of the other designers feeling that the project had suffered from the snowballing demands of the multiple parties involved. The significant outlay occasioned by the investigative and repair program, plus the expense incurred by delays during initial caisson installation, contributed to the financial troubles of Jerry Wolman — the developer who had dared to go forward with the exceptional superstructure design — forcing him to sell his interest in the project to John Hancock Mutual Life in December 1966.

Colleagues later reminisced about the intensity of the dialogue during this period. Despite strong declarations during the initial days of uncertainty that extensive examination was inappropriate, Khan maintained a calm demeanor, thereby shifting the tone of the dialogue. The contractors, moreover, could never complain about proclamations made from a remote engineering office. Khan had visited the site regularly before the void was found, and he continued to do so, insisting on viewing the caisson repair work, although this required descending into deep and narrow access shafts. His initiative and spirit, combined with his practical understanding of the structural material, persuaded the contractors to accept his engineering judgment. Khan's decision to investigate the suspected structural weakness, his determination in the face of initial resistance and the discovery of serious problems that confirmed the wisdom of his actions, gained him great respect, as much from the contractors involved as from the design participants.[21,22]

The problem caused by the removal of steel casings had occurred on a number of other projects in Chicago and elsewhere (one void at La Guardia Airport in New York was reported to extend 31 feet in length), but it received heightened attention on account of this experience on the John Hancock Center.[23] Shortly after the project's completion, the Chicago building code was revised to encourage steel casing for caissons to rock to be left in place by distinguishing caissons with permanent steel casing from those without, and compensating for the material of a permanent steel shell in caisson design. Additional requirements for full-time inspection of caisson construction by the architect, the structural engineer or a representative of a soil and foundation engineering firm, and for detailed logs and approvals, were included in the Chicago building code of 1971.

Structural Aesthetics

The John Hancock Center design is surely rooted in constructional reality, in time and in place. Reflecting "clarity in thought and action," the soaring and resolute skyscraper embodies a distinct sense of focus and purpose.[24] In this respect, the designers had crafted a building "that will eloquently speak of our time," as Khan often interpreted one of modern architecture's ambitions.[25] Concurrently, the slim tower possesses the lasting relevance of mature design. The cross-bracing intimates solidity and the building's proportions give shape to a tower that, while elegant, satisfies an instinctive desire for respect of the laws of nature.

Khan did not shy away from philosophical notions of architecture and the arts — indeed, he pursued the attainment of architecture's potentialities through the integration of structural design. Only when architecture was founded in structural realities would "the resulting aesthetics . . . have a transcendental value and quality."[26] It was, for him, self-evident that engineers needed to share the responsibility of architectural design, guiding its course with the architects. Essential to his envisioned melding of creative spirit was a broadening of each designer's view beyond his or her own field of specialization.

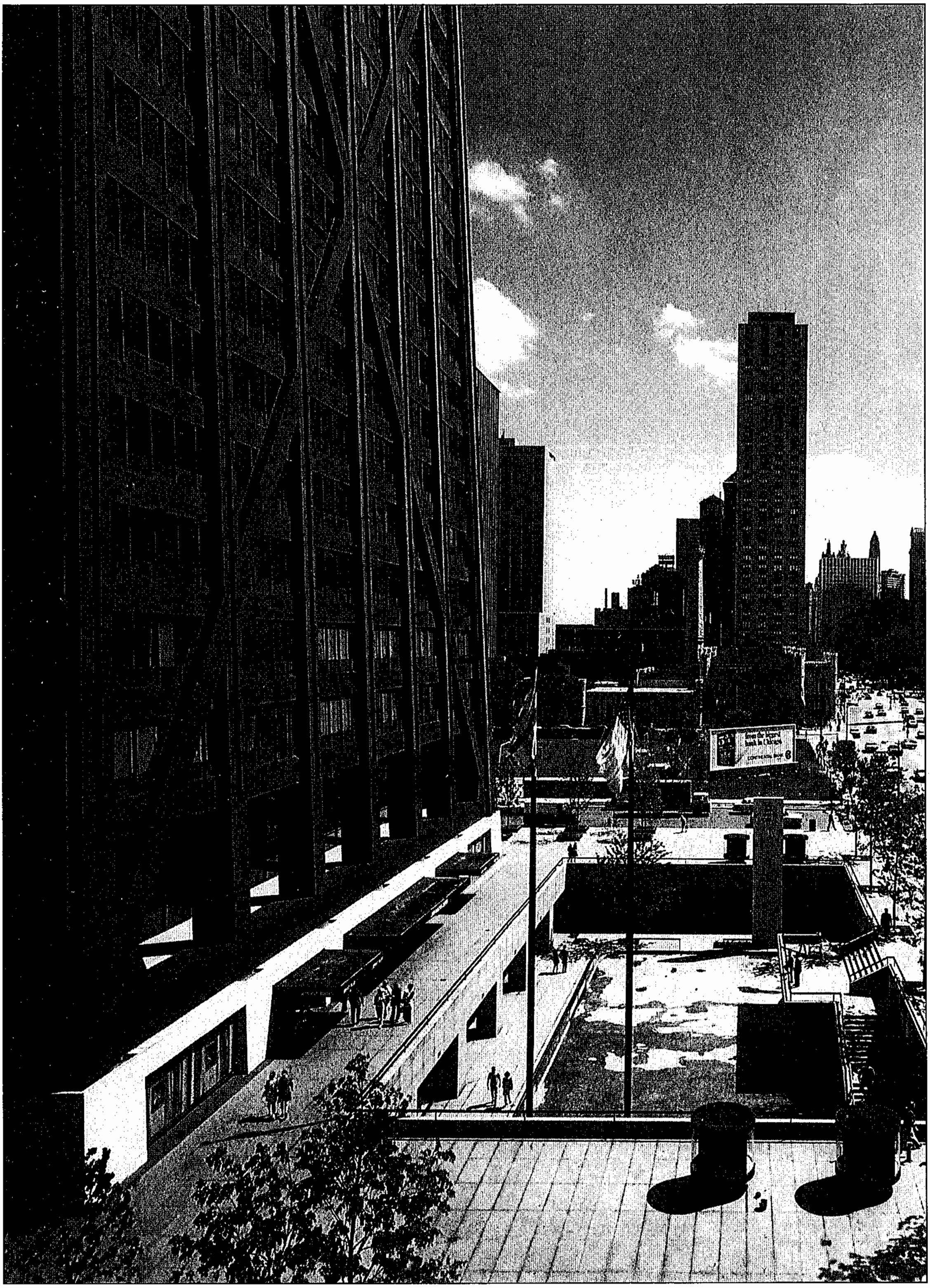
Concern that each discipline had resigned itself to a narrow view was voiced at the time by a number of prominent engineers. They urged the engineering profession to prescribe broader education and understanding, and Khan joined them in this effort. But he did not wait for a turnaround to occur in the profession before following his vision of the creative process. He could not understand why other, highly competent engineers condoned the creation of arbitrary form with illogical structural solutions. His personal interests, aside from his philosophical stance, would not have suited him well to such a role in design: he had developed definite opinions regarding structural and architectural aesthetics. His conviction of the importance of design integrity inspired him to influence design decisions — on occasion, treading beyond the accepted limits of his domain.

The meanderings of design along the path to construction comprise numerable memorable histories. One such history for Khan was the manner in which a particular design decision on the John Hancock Center Project was achieved. Writing about the events sixteen years later, he recalled the architects' and owner's concerns with perimeter diagonal members at the upper levels, where the highest apartments, the restaurants, the television studios and the observation deck would be located. During design development, the decision was made to furnish the topmost floors with unobstructed views. Spectacular lakefront and city views were, after all, tangible assets attributable to the building site's location and were needed to justify their high rents. There was a natural cutoff point for the bracing; the topmost X-brace could be the last diagonal element on the elevation, leaving the top floors without bracing.

The diagonals were extended to cap the elevation with a closed diamond form rather than the open X-figure initially considered. Viewing the model, left to right, are Fazlur Khan, Bruce Graham, Albert Lockett (partner in charge of management), Louis Bruner of U.S. Steel, and Richard Lenke (project manager). (Photograph by K&S Photographics, courtesy of Skidmore, Owings & Merrill LLP.)

Khan's sense of aesthetics and rationality was disturbed by the proposed false termination of the structural system. "[F]rom a philosophic point of view and from a structural-visual continuity of the system itself," he wrote in 1981, "it would have been a tragedy to terminate the diagonals abruptly."[26] Structurally, discontinuing the cross-bracing at approximately the ninetieth floor would have separated the structure into a tube system below and an unbraced beam–column frame above. Though not desirable, the design could have been accomplished; it was not literally a structural determinant. But he felt strongly that this early termination would diminish the clarity of the structural form. Believing that he could not dissuade the architects and the owner on the strength of his own sensibilities, he instead argued against this alternative by somewhat exaggerating its structural effect. He asserted that the efficiency of the system would be degraded, resulting in higher costs, and that the top floors of high importance might suffer from increased flexibility and motion. Subsequently, the decision swung back to full-height cross bracing.

Had the diagonals been terminated several floors below the top of the building, the upper section would have appeared visually incomplete and, perhaps more significantly, the diagonals themselves would have been interpreted differently. The X-figures of the building's dark elevations, rather than the diamond forms,



A depressed plaza originally contained a reflecting pool/skating rink. (Ezra Stoller © Esto.)

would have been accentuated visually. Though also of aesthetic interest, the authority communicated by the series of X-figures would have lacked the grace conveyed by the complete diamond shapes — so appropriate for the elongated surface areas of the slim building elevations. By extending the diagonal members to their intersecting points, the crowning visual form became the closed diagonal shape.

The "structural-visual continuity" that Khan had sought to articulate could be interpreted as a fluency in architectural narration. He was pleased that the architecture's expression of structure was generally well received by Chicagoans. He was equally pleased when observers, inspired by their emotional response to the building, sensed the designers' ambition for eloquence. A particular occurrence amused him: One day, while standing in the plaza of the John Hancock Center, he noticed two women gazing upward, one instructing the other on the building's creation. He came near to listen in on their conversation. The diagonals, the one woman confidently explained, were placed on the façade with artistic intent by the architect. This was indeed a wonderful tribute to structural vitality, Khan thought to himself. The admirer, it seemed, appreciated the articulate structure so much that she had no doubt that it was born of the architect's visualization of eloquent tall building form.

In contrast to the public's assessment of the project, some architects and critics found reason to fault the design. For one, the treatment of the first-story base was maligned. A travertine-clad story-high base, tailored for retail purposes with display windows and hidden structural diagonals, lifted the visual grounding of the structural system above the street level. In creating the base element of a tripartite division of the high-rise structure (the treatment of which had plagued architects since the origin of the skyscraper), the designers disrupted the clarity of its structural expression. The base, one reviewer complained, was "unworthy of the tower above."[27] *Chicago Tribune* architecture critic Blair Kamin observed that "the Hancock stumbles as it meets the street."[28]

In addition to specific aspects of design, the project also drew criticism for its scale and prominence. The 2.8-million-square-foot program housed in this skyscraping tower, urban planners rightly anticipated, would open the door to a change in scale of development on North Michigan Avenue. The architecture profession, many believe, chose to show its displeasure over the course of direction taken by development on Michigan Avenue consequent of the John Hancock Center, by declining to honor the building with an American Institute of Architects (AIA) award for over thirty years. Only in 1999 did the AIA recognize the John Hancock Center with its Twenty-Five Year Award, an award conferred to projects of enduring significance, commending its "structural achievements . . . combined with a simple, graceful design," which "earned the John Hancock Center and SOM much deserved respect over the years."[29] In the words of AIA member Carl J. Hunter, who, as a member of the AIA committee on design, nominated the building for the award, the tower "stands proudly as a remarkable collaborative achievement of architectural and structural engineering, befitting and elaborating upon the city's architectural legacy."[29]

Fazlur Khan did not live to hear the accolades on the occasion of the AIA award, but he had heard plenty in the years following the tower's completion. He had no doubt himself about the building's relevance: it was, in his view, a beautiful building as well as a fitting and efficient solution for its program and site. At street level, the open space around the tower offered a welcome relief from buildings extending out to the sidewalk; and to the skyline of Chicago the tower brought a powerful architectural identity. The John Hancock Center's dynamic expression at once embodied the spirit of an age when optimism kindled technical advancement, while carrying on the timeless tradition of vitality and practicality of its urban setting.

ACKNOWLEDGMENTS — *This article was adapted from Chapter 5 of* Engineering Architecture: The Vision of Fazlur R. Khan *by Yasmin S. Khan. Copyright © 2004 by Yasmin Sabina Khan. Used by permission of W. W. Norton & Company, Inc. Photos and illustrations courtesy of Skidmore, Owings & Merrill LLP as noted, except for pages*

14 and 26, which are courtesy of Esto, and page 17, which is courtesy of David Fung.

YASMIN SABINA KHAN *is the daughter of the late Dr. Fazlur R. Khan (1929–1982). As a licensed structural engineer herself, Ms. Khan has experience with the design of multistory buildings. Her biography about her father recounts Dr. Khan's central role in the significant engineering advances achieved in building design during the 1960s and 1970s, and explores his passion for integrating engineering and architectural design creativity*

REFERENCES

1. "Open Forum Discussion" with William LeMessurier and Paul Weidlinger, *Building Research,* Vol. 2, May/June 1965.

2. "Recollections of Fazlur R. Khan," part of an oral history project, Skidmore, Owings & Merrill, Fazlur Khan personal collection, June 1978.

3. Fazlur R. Khan to Bruce Graham, memorandum, SOM, Chicago Archive, 15 December 1964.

4. John B. Skilling to Albert Lockett, SOM, Chicago Archive, 4 March 1965.

5. Richard E. Lenke, memorandum for record, SOM, Chicago Archive, 9 February 1965.

6. Hal Iyengar, conversation with author, April 1999.

7. Cuscaden, R., "'Living in the Sky' Is Almost Heaven," *Chicago Sun-Times,* 14 January 1971.

8. Khan, F.R., "Creative Teaching and Its Influence on Innovative Concrete Structures," paper presented at the Annual Convention of the American Concrete Institute, November 1979.

9. Paul Weidlinger to SOM, SOM, Chicago Archive, 12 March 1965.

10. Khan, F.R., "The Bearing Wall," *Architectural & Engineering News,* Vol. 8, September 1966.

11. American Institute of Steel Construction, *Specification for the Design, Fabrication and Erection of Structural Steel for Buildings,* 1963.

12. Khan, F.R., "Design of High-Rise Buildings," paper presented at the Symposium on Steel Structures, American Inst. of Steel Construction, Fall 1965.

13. "X-Braces Trim Steel Tonnage," *Engineering News-Record,* Vol. 175, 23 September 1965.

14. Khan, F.R., Iyengar, S.H., & Colaco, J., "Computer Design of 100-Story John Hancock Center," *Journal of the Structural Division,* ASCE, Vol. 92, December 1966.

15. Khan, F.R., "The John Hancock Center," *Civil Engineering,* Vol. 37, October 1967.

16. LeMessurier, W., "New Directions in Structural Design," *Architectural & Engineering News,* Vol. 8, September 1966.

17. Chen, P.W., & Robertson, L.E., "Human Perception Thresholds of Horizontal Motion," *Journal of the Structural Division,* ASCE, Vol. 98, August 1972.

18. Khan, F.R., "John Hancock Center, Preliminary Report on Perception of Movement," Fazlur Khan personal collection, 1965.

19. Fazlur Khan, memorandum for record, SOM, Chicago Archive, 8 July 1966.

20. Fazlur Khan to Bruce Graham, memorandum, SOM, Chicago Archive, 3 August 1966.

21. Mike Oppenheim, conversation with author, July 1999.

22. Chandra K. Jha, conversation with author, Chicago, July 2002.

23. "Defective Piles Halt Airport Work," *Engineering News-Record,* Vol. 167, 9 November 1961.

24. Mies van der Rohe, L., "Where Do We Go From Here?" *Bauen + Wohnen,* Vol. 14, November 1960.

25. Khan, F.R., "Structural Theories and Their Architectural Expression: A Review of Possibilities," *Chicago Architectural Journal,* Vol. 1, 1981.

26. Khan, F.R., "100 Storey John Hancock, Chicago: A Case Study of the Design Process," *Engineering Structures,* Vol. 5, January 1983.

27. Winter, J., "John Hancock Center, Chicago," *Architectural Review,* Vol. 151, April 1952.

28. Kamin, B., "John Hancock Center," in *AIA Guide to Chicago,* Sinkevitch, A., editor, San Diego: Harcourt Brace, 1993.

29. Worden, M., "Big John Receives Twenty-Five Year Award," *AIArchitect,* Vol. 6, January 1999.