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Reflections on the Hancock Concept

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Abstract

This paper reviews the stages of conceptual design through the final design of the John Hancock Center in Chicago. Several unique features of the project considered during the design process are discussed. The structural system introduced the braced-tube concept for the first time. The collaborative effort among the architects, engineers, and fabricators that made the project successful is emphasized. The building has withstood the passage of time for the last 30 years. It remains as an icon of Chicago and a symbol of structural expression in architecture.

Introduction

The John Hancock Center of Chicago (Fig. 1) was awarded the 25-Year Architectural Excellence Award by The American Institute of Architects in February 1999. This award is given to a building whose architecture has withstood the test of time and, after 25 years, still represents the excellence it originally had. It is actually a testimonial to the enduring quality of the architecture. In the case of the John Hancock Center the structural expression of the diagonalized trussed-tube constitutes the essence of its architectural esthetic. In this sense, the structure itself has withstood the test of time in the context of its architecture.

The conceptual design of the Hancock Center was started in 1965 and the building was completed in 1970. Today the Hancock Tower, with its powerful diagonalized expression, represents a unique icon for the City of Chicago. This paper is written to commemorate the 25-year award with an examination of the conceptual development of the system and its enduring legacy in tall building systems technology. It is also relevant to note the evolution and impact of computers on the design process since 1965 when the Hancock Center was conceptually designed. It is particularly relevant as this paper is being developed for the Internet, a new computerized medium.

The Sears Tower of Chicago, which until recently was the tallest structure in the world, represents another break-



Fig. 1. John Hancock Center of Chicago

through in the systems methodology with respect to tall buildings. The Sears Tower was started in 1969 during the same time period as the Hancock Tower and involves a unique bundled-framed tube system. Hancock and Sears taken together represent a quantum jump in tall building structures in a short period of time. The comparatively rapid evolution from frame buildings to these unique high efficiency cantilever concepts will be examined here. The author was involved in the conceptual development and design of the Hancock Building. The paper contains the author's observations on this entire design process on the basis of this involvement.

System Evolution

Tall building systems as an organized structural system have a relatively recent history dating back to only the late nineteenth century. The Vierendeel form steel-tiered

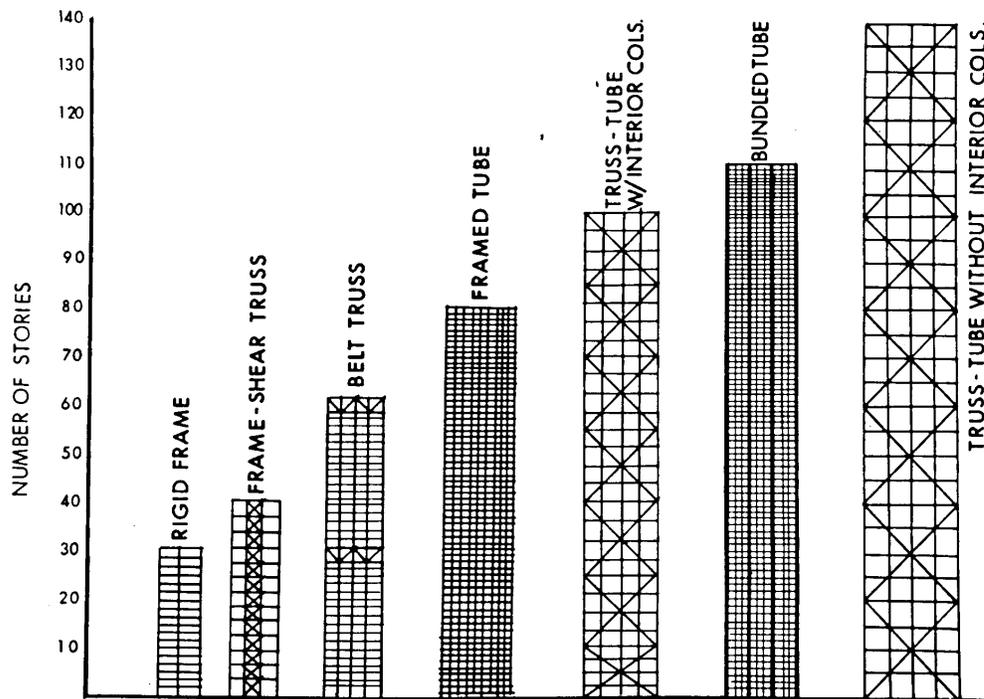


Fig. 2. Systems Chart

system has occupied the attention of tall building designers for nearly six decades until the early 1960s, with successive improvements in the same system without significant change in the form of the structure. However, during the decade of the 1960s, there was dramatic improvement in the technology of tall building structures. The system evolution had gone from the less efficient Vierendeel structural system to the more efficient cantilever systems represented by the Hancock Center, Sears Tower, and other tall buildings. It is interesting to note that a variety of systems in various combinations have been used since, but none exceed the efficiency of the cantilever.

In this sense, the cantilever concept represents the highest possible efficiency in a tall building system. The conventional Vierendeel steel-tiered system employed in many tall building structures, prior to the advent of cantilever systems, essentially consisted of beams and columns arranged in two directions to form a grid. Initially, connections between beams and columns were simple shear or semi-rigid moment connections at best. The developments in the early part of the twentieth century mainly consisted of enhancements in the quality of steel, steel shapes, and fasteners. Moment connections with in-

creased rigidity were developed with extensive riveting and knee-bracing. Outstanding examples of these early tall building structures include the 790 ft. tall Woolworth Building in New York (ca. 1913) and the Empire State Building (ca. 1930). In these cases it also appears that heavy masonry claddings and partitions contributed as much to the lateral stiffness as the steel frame itself.

After World War II, a dramatically different architecture based on principles of Modernism emerged. Technological advances conforming to International Style architecture included larger open spaces with longer spans, a well-organized core and column grid, glazed curtain walls, sprayed on fire protection, and lighter partitions, to name a few. Vierendeel frame systems were still the primary choice, which involved bolted and welded rigid joints. As building heights increased beyond 30 stories, however, considerably more steel was required to develop adequate lateral stiffness. A rule-of-thumb at this time was to allow one pound of steel per sq. ft. per story. This amounts to 100 lbs. per sq. ft. for a 100-story building, which is clearly uneconomical in any context.

The idea that steel members can be assembled to form a

three-dimensional resistive system began to emerge in the early 1960s. This was also coupled with the idea that different height ranges demand different system compositions to maintain a reasonable premium to resist lateral loads. The main proponent of this design trend was Fazlur Khan who systematically pursued a logical evolution of tall building systems that resulted in many innovative structural systems and recognizable built forms. Initially, Khan relation to building height (Khan, 1972; 1973). The least efficient system is the shear frame system that is economically suitable up to only 30 stories. This is followed by other structural systems culminating with an exterior diagonally-braced trussed-tube system as the most efficient. This development was extremely significant as it gave a logical platform against which the efficiency of newer systems can be measured. It also established a flexible design notion that system selection was the most important design event in the structural optimization process. This high-rise design chart has been extensively used and enhanced over time and is generally recognized as the greatest single contribution to high-rise building technology in the twentieth century. A systems chart proposed by Khan in 1972 is shown in Fig. 2 for steel buildings (Khan, 1972). He proposed a similar systems chart for concrete buildings.

It is in this context that the structural systems for the John Hancock Center and Sears Tower evolved. The realization of the systems approach to tall building design would not have been possible without the use of the computer as a design tool. Computer usage in practice was in its infancy in the early sixties and for the most part involved computerization of manual design calculations used in design offices. However, rapid development of analysis and design software for three-dimensional systems since then has helped to expedite the design and engineering processes.

The Program

The program for John Hancock Center includes multiple functions such as commercial space, parking, offices, apartments, and television transmission spaces yielding a total area of 2,800,000 sq. ft. The proposal to place all these functions in a single 100-story tower was based on the economies of possible structural systems. The single-tower concept was made possible as a result of the development of the trussed-tube at a unit structural steel quantity of 30 lbs. per sq. ft. The diagonalized form of the structural system had an equally radical impact on the architectural image of the building and, together with its revolutionary structure, constituted a daring leap by its designers – Bruce Graham and Fazlur Khan.

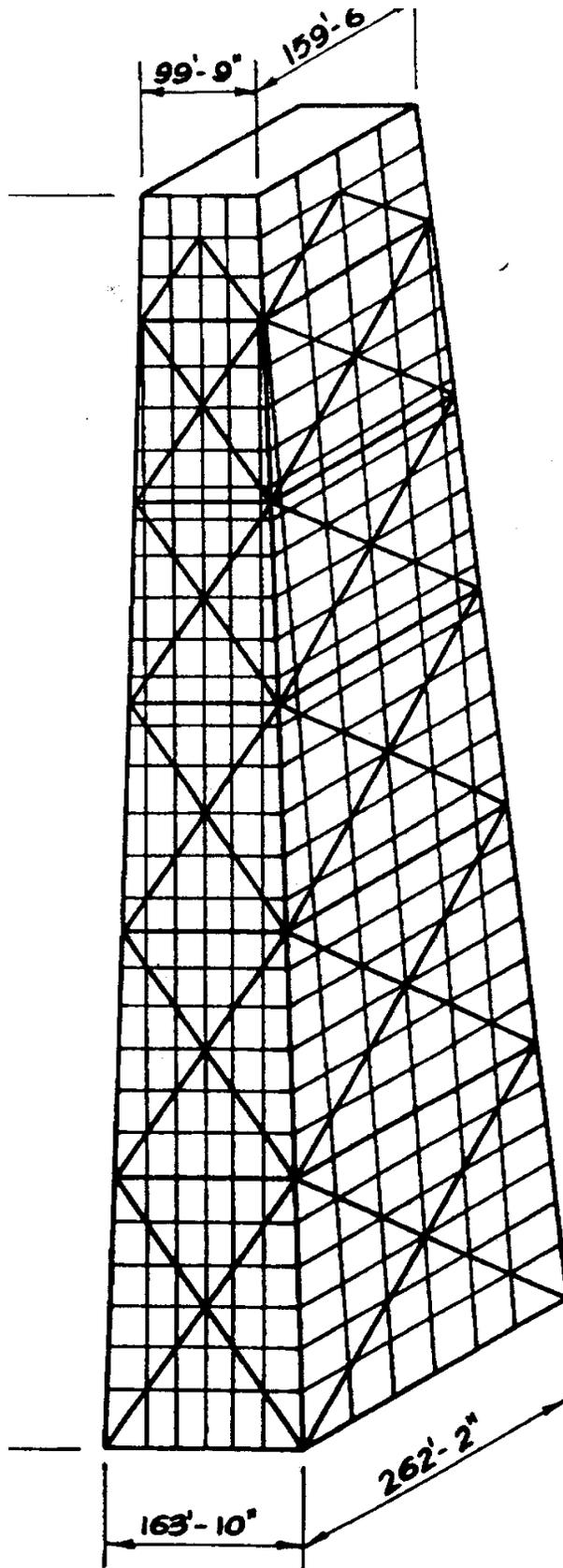


Fig. 3. Trussed-Tube Form.

The structure of the Hancock Center measures approximately 262 ft. x 164 ft. at the base and tapers to a topmost dimension of 160 ft. x 100 ft. at a height of about 1100 ft. above ground (Fig. 3). The commercial spaces and parking are placed at the bottom followed by 32 stories of offices, 50 stories of apartments, and spaces for television transmission, an observatory, and mechanical levels. The taper allows larger office floors with longer lease spans to be placed at the bottom and smaller apartment floor areas located toward the upper part. The overall impact of the tapered form allows for a continuous exterior structure. Additional benefits include reduced wind sail and improved shape-aspect with regard to wind dynamics.

The Concept and Behavior

The structural concept is based on an equivalent tubular system formed by a system of diagonal braces on the exterior, which ties all the exterior columns together and makes the whole system behave like a tapered rigid box (Fig. 3). The simplicity and straightforwardness of the structure and its impact on the architectural expression of the building can be readily observed. The essential character of the structure is created by the continuity of the exterior diagonal X-bracing on each face of the building. It is this three-dimensionality that makes it perform like a single tube structure in contrast to earlier systems that placed two-dimensional Vierendeel frames within the body of buildings in two directions. With the exterior trussed-tube assuming all the lateral load resistance, the interior gravity columns are required to carry only the gravity loads of floors in the most efficient manner. The absence of internal bracing or other internal resistive elements makes it possible to frame floors in a flexible manner for different functions, which is so essential for a multiple-use building.

Historically, diagonal bracing in truss form was introduced in bridge construction. The Eiffel Tower, built in 1860 in Paris, epitomizes the use of diagonals in towers. It also manifests the special characteristics of exposed steel construction: aesthetic lightness and taut delineation. The four trussed-legs of the Eiffel Tower express the optimum relationship of exterior form and function to resist structural overturning. The Hancock Center embodies the same principle of utilizing the exterior form to resist overturning. However, unlike the relatively massive legs of the Eiffel Tower, its structure is organized to create the equivalent of a thin-walled exterior tube for maximum space efficiency and rigidity.

Other tall building pioneers were also interested in thin-walled tube structures. Myron Goldsmith investigated the evolution of exterior fascia diagonals and their architectural expression in a thesis in 1953 while a student

at the Illinois Institute of Technology (IIT) in Chicago. The diagonal bracing was derived from diagrid type frames on each facade and by making the grid coarser, to a point of creating clear X shapes on each facade. Khan and Goldsmith also introduced this structural concept as a student thesis project at IIT in the early sixties, which involved a 60-story building outfitted with exterior diagonals. Simple manual calculations were performed together with a model load test to verify the lateral stiffness that indicated full box-like participation of fascia interior columns.

The possibilities of a diagonally braced structure are indicated in Fig. 4 – in which are shown a fine diagrid mesh in (a), the ultimate bracing with only corner columns in (b) and the tubular variety in (c). While the form noted in (b) is the most efficient, it poses certain practical fabrication problems relating to the size of the corner columns and diagonals. A distributed approach with some fascia interior columns as shown in (c) with a bay span of 30 ft. to 40 ft. is more practical and conventional. In order to channel loads into these columns secondary ties are necessary with the main tie restraining the horizontal spread of the X forms. Fig. 5 shows the load distribution characteristics of the fascia truss-frame and the effect of the ties (Khan, 1967). It is this type of load-flow that effectuates the behavior of an equivalent thin-walled tube. The geometric organization was followed rigorously in the Hancock Center structure, especially with respect to coordination of taper from each face with allocation of appropriate story heights for office and apartments.

The mega-truss form optimizes several parameters. The number of diagonals and, thereby, the window disruptions are minimized. Creating high 20-story tiers minimizes the number of column-diagonal connections. Normal column spacing of 40 ft. on the broad face and 25 ft. on the short face are used with conventional column and spandrel beam sizes. The diagonals act as inclined columns carrying their share of the gravity loads, which are always in compression even under extreme wind loads, thus simplifying the connection details using bearing type joints. 80% of the lateral sway under wind loads was determined from the cantilever component with the remainder from shear represented by axial deformation of the diagonals. Gravity forces generally controlled the system. The premium for wind loads was a factor of about 15% of the weight of the steel.

The Design

The design of the Hancock Center pushed the state-of-the-art in design at the time in many ways. The following is a brief retrospective discussion.

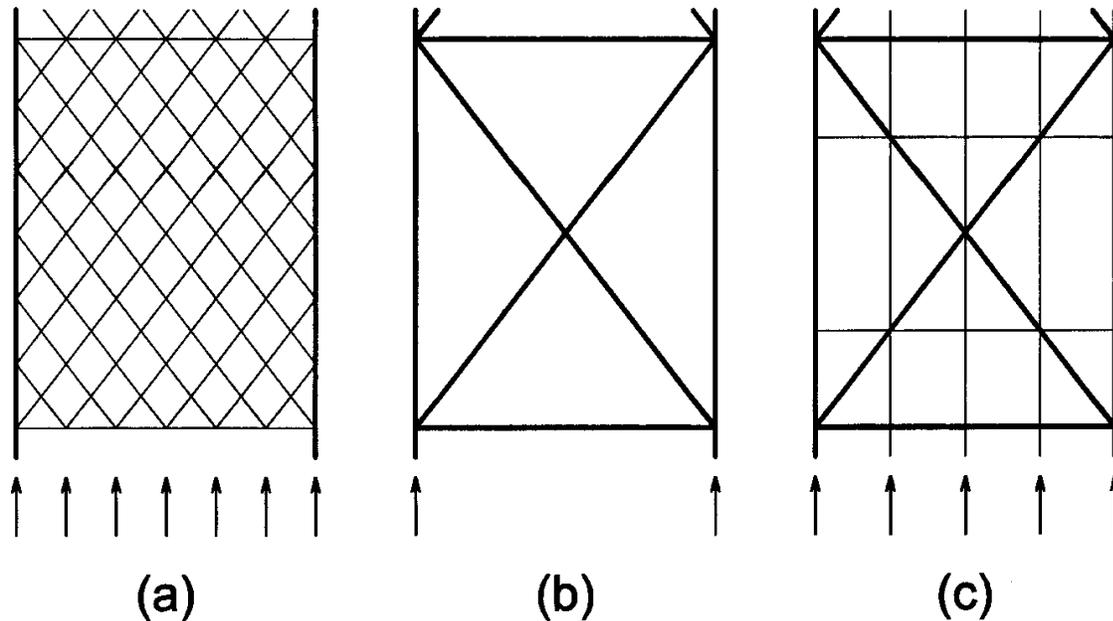


Fig. 4. Diagonal Possibilities

a. The Architecture. The architectural expression of the Hancock Center represents a radical departure from established aesthetics of the time. Initially critics labeled the building as too industrial, but over time it has come to symbolize the gutsy tradition of structural expression in Chicago. It is often characterized as super-rational, logical, and a representation of machine age architecture. It exhibits its true structure much in the tradition of bridge construction. Perhaps these are the qualities that are enduring over time.

The expressed diagonals of the façade have not adversely affected the quality of interior spaces. To the contrary, these elements are often coveted and decorated in a variety of ways, thus adding individual character to apartments. Furthermore, the multi-functional design fits very well with the commercial and residential character of the neighborhood. It has spawned a community of neighborhood tall buildings involving commercial/office and apartment mixes and, in this context, the collective mixed-use buildings constitute a unique neighborhood in the United States.

b. Computer-Aided Design. At the time that the Hancock Center was designed, computer-aided design in architectural and engineering practice was limited by the available memory capacity of hardware and the limitations of software. The largest structural problem that could be solved involved only 51 joints and three degrees of freedom and utilized an IBM 1620 computer

(Kahn, et. al., 1966). However, larger capacity analysis programs such as Stress and other custom space-frame programs were being developed at a variety of academic institutions. In order to maximize the use of computers, preliminary analysis including behavioral studies on parts of structure, geometry determination, and data preparation was done on a small computer platform while the final analysis of the entire structure was performed at several academic facilities on large mainframe computers. This type of coordination may seem primitive in light of current capabilities; however, it allowed for maximum use of available computer capacities at the time.

c. Load Distribution Study. Load-flow analysis studies were performed on a three-tier fascia truss with two degrees of freedom for each joint as shown in Fig. 6. Such truss modules were analyzed at various locations in the building (Kahn, et. al., 1966). The aim of these parametric analyses was to determine the optimum proportions of diagonals and primary and secondary ties to produce a relatively uniform compressive stress in the columns, as would be the case of a bearing wall or a tube. The assertion was that if it worked over parts of the structure, it certainly would over the entire structure. Final analysis was not attempted until satisfactory results were obtained on the substructure analysis. Such substructure analysis gives valuable insight into structural behavior that is generally missed in full model analysis.

d. Wind Loads. Determination of statically applied wind loads required consultations with meteorologists and other wind consultants about the highest recorded wind events. It was determined that a factor of 1.25 would be applied to the Chicago building code in use at the time in order to calculate wind loads for normal allowable stress design. A factor of 1.4 was used to limit the steel stresses to 30 ksi. Statistical analysis of wind records was not available at the time; however, recent studies confirm these factors.

e. Wind Tunnel Studies. Wind tunnel studies on pressure models were performed in a steady-state wind tunnel as contrasted to today's boundary-layer wind tunnel. The main objective was to determine the shape-drag coefficients at various heights in the taper, all directed towards determination of the static wind loads.

f. Dynamic Behavior. Dynamic behavior was assessed from consideration of resonance with the vortex-shedding frequency. The fundamental sway periods were computed at 7.6 and 5.00 seconds with respect to weak and strong axes, utilizing a seven-mass model. Recent analysis involving masses at each floor indicates values of 7.05 and 4.9, and field-measured values of 6.8 and 4.76. These figures represent a good correlation. It was assumed that vortex-shedding frequencies would vary with height because of taper and consequently cannot organize to produce an effective dynamic force. This analysis, combined with a relatively stiffer system for sway and torsion, produced an acceptable dynamic behavior. The evaluation was more qualitative than quantitative, however. The measured values of damping at very low amplitudes was of the order of 0.6 percent of critical, perhaps indicating the predominance of axially transmitted forces.

g. Motion Perception. Occupant motion perception was assessed on the basis of pioneering experimental motion studies on human subjects at various attitudes to determine the threshold of perception and comparing it to analytical results obtained from forced vibration analysis of the building subjected to simulated wind gusts. Several time-variant wind gusts were applied after consultations with meteorologists. The gusts were simulated to correspond to the building period. The measured threshold of perception was in the range of 0.4 to 0.8 percent of g and the analysis predicted low down-wind accelerations. However, this methodology could not assess cross-wind accelerations, which generally predominate. They can only be determined with reasonable accuracy with force-balance or aero-elastic wind tunnel studies, which were beyond the state of the art at that time. This aspect of wind tunnel technology has undergone considerable improvement since the construction of the Hancock building. However, the structure

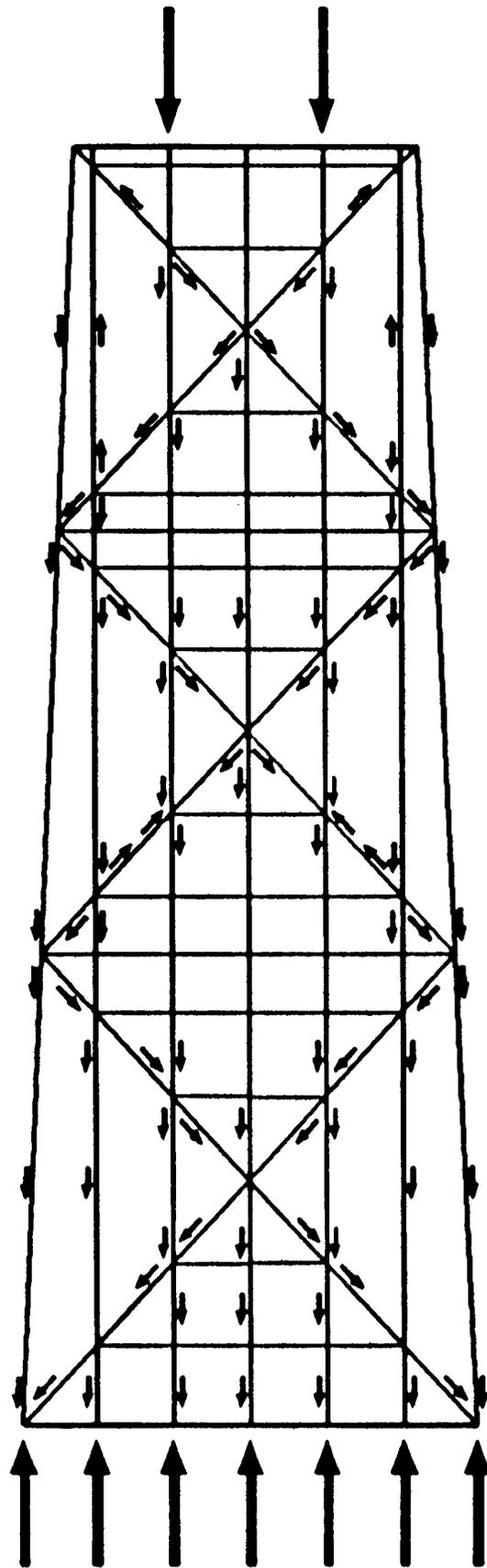
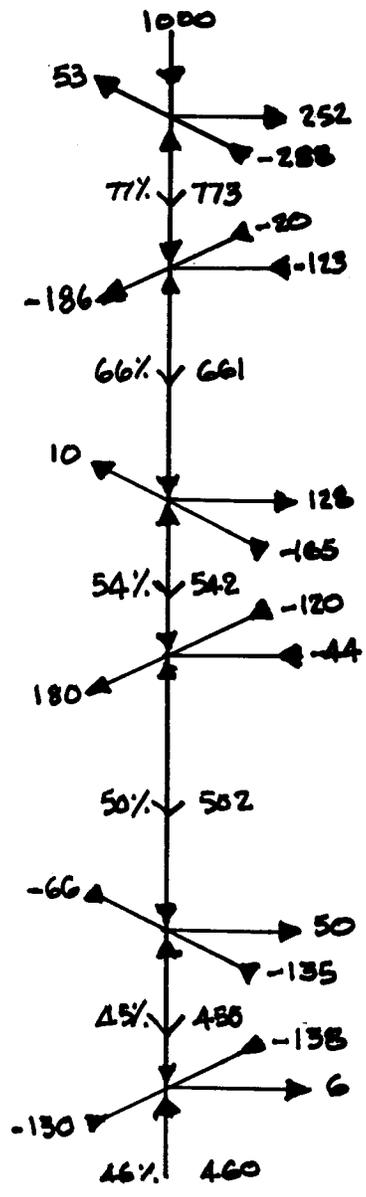
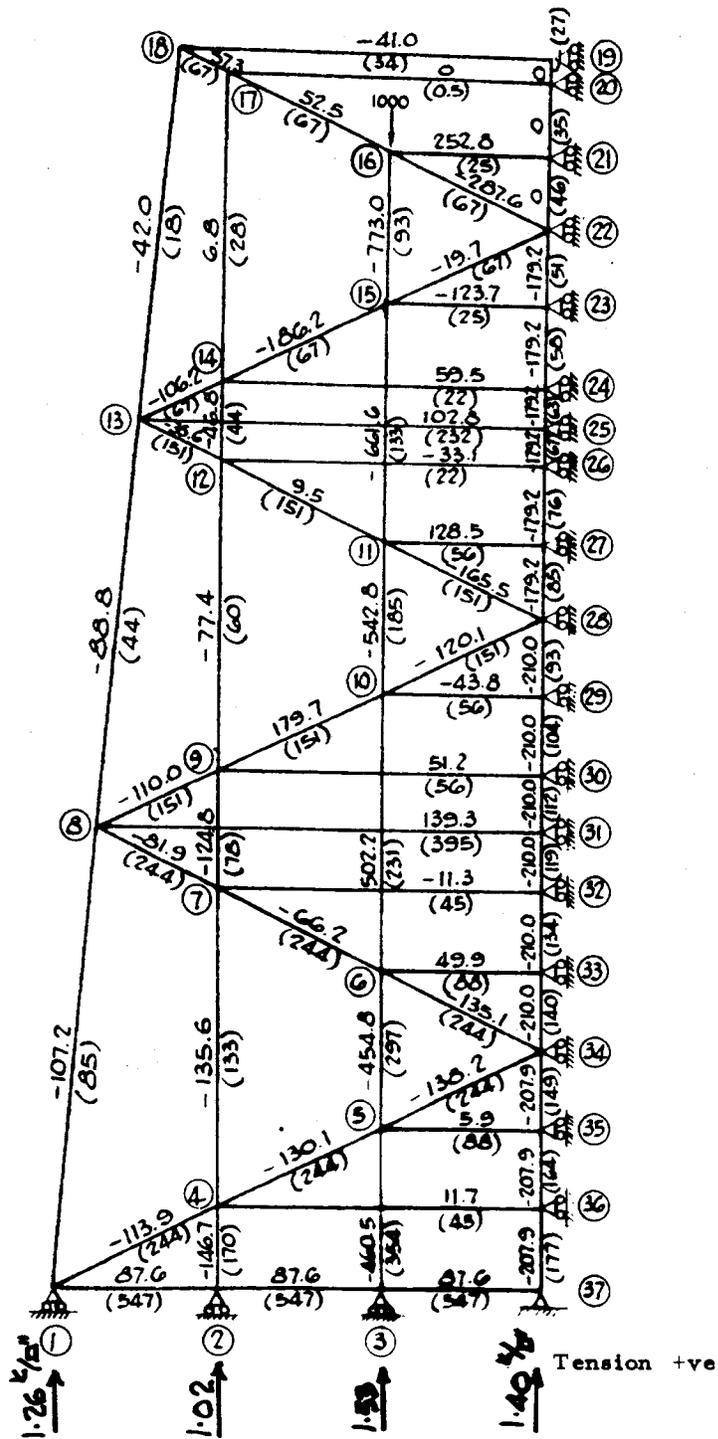


Fig. 5. Load Distribution



LOAD FLOW

Fig. 6. Truss Module Load Flow

has performed well for wind loading over the last 30 years with no complaints on motion perception.

h. Floor Vibration. As floor-framing members became lighter because of non-encased fire protection and composite design, there was concern about user perceptibility of floor vibrations. Furthermore, the evaluation criteria were in only the formative stages at the time. Available research results in studies conducted in the early 1960s at the University of Kansas generally related the natural frequency of beams to amplitude caused by human occupation with the assumption of a certain amount of damping for different degrees of perceptibility. A program was undertaken to measure the natural frequencies of many similar existing floor beams and the perceptibility chart was used on a comparative basis with these measured values to assess the acceptability of vibration transmitted through the floor beams of the John Hancock Center. Even though the criteria have been refined over the years with new theoretical and experimental results, comparative evaluations with existing buildings that have performed well are still being used. A recent verification of floor beam vibration using current criteria indicates acceptable results.

i. Thermal Foreshortening. Since the primary system of columns and diagonals are placed at a relatively small distance beyond the glass line, there had been concern about the temperature differential between exterior and interior columns. A maximum temperature differential of 5° F between the exterior and interior columns was sought, even with an extreme -10° F ambient temperature on the exterior. Cold-chamber experimental studies were undertaken to assure compliance with the criteria.

Joint Details

Primary system joint details among diagonals, columns, and ties involved the use of heavy gusset plates and weldments, especially at the corner joints. The member shapes (I-Section) and joint details were established with extensive discussions with steel suppliers and fabricators (i.e., American Bridge). This collaboration contributed to simplification and practicality in the concept and fabrication of the details. Generally, field welding was avoided between members and gusset-plated joints, but high strength bolted and butt-plated bearing joints were utilized. The gusset-plate assemblies were shop-fabricated. In each instance, the first corner-joint fabricated was measured for residual stresses due to welding. High levels of these stresses were noted and consequently all corner joint weldments were stress-relieved in gas-fired hot air ovens. Temperatures were raised to 1100° F in increments over time and gradually cooled to relieve the high stresses. Steel erection utilized exterior climbing-

derrick cranes, a first in tall building construction. Similarly, various new welding techniques were introduced including vertical electroslag welding. The efficient and orderly coordination of steel fabrication and erection testifies to the successful collaboration between engineers and fabricators – a relationship that has practically disappeared in the current market.

Conclusions

The unique and optimum structural concept of the Hancock Center was made possible due to the collaborative effort among architects, engineers, and fabricators. If the structural system used for the building were to be designed and constructed according to current standards, few, if any, structural changes would be made. Exhaustive analysis conducted recently indicates no significant variations in its structural performance. However, advances in wind tunnel technology may require verification of dynamic behavior and motion perceptibility in accordance with current methodology. When such studies are made, the acceptable dynamic performance over the 30-year history of this tallest dwelling occupancy may lead to further calibration of criteria regarding motion perceptions.

The lessons learned from studying the design process of the John Hancock Center indicates that the introduction of any new building systems concept requires comprehensive examination of all relevant parameters and influences, even if they are only approximate. As demonstrated in the case of the Hancock Center, this approach will eventually lead to technological advances in tall building systems. This is true also for the Sears Tower that has a bundled-tube system with a skeletal frame expression. Meanwhile, the classic, structurally expressive architecture of tall buildings such as the Hancock Center and Sears Tower will continue to endure as symbols for architectural daring and the power of conceptualization.

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