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Newer Structural Systems and Their Effect on the Changing Scale of Cities

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Dieser Vortrag den Dr. F. Kahn anlässlich der SIA-Studientagung über Hochhäuser vom 18. bis 20. Oktober 1973 an der ETH-Zürich gehalten hat, geben wir in zwei Folgen in englischer Sprache wieder. Wir können umso eher auf eine Übersetzung verzichten, als dipl. Ing. ETH, SIA, G. Wüstemann dieses Referat in einem Bericht ausführlich beleuchtet hat («Schweizerische Bauzeitung» 92 (1974), Heft 6 vom 7. Februar, S. 107–109).

Introduction

The world has seen major changes in architecture in the last 20 years. While urbanization by itself in the present day context is a result of growing industrialization, the high density construction of tall buildings in the center cities and even in isolated cases seem to be primarily the result of the need to optimize human interactions and other resource utilization. Industrialized urban density is distinctly different from overall population density of a country. A very large country like Australia with a very small population of only 13 million people, has developed urban centers with high density construction, whereas a densely populated country like China has not developed localized high density structures in the urban centers. Whether it is proper to build density structures in the urban centers, is in fact more of a political and economic question whose answer lies in the socio-political decisions. Undoubtedly, increasing industrialization at present means increasing high density construction in urban centers. It is because of this reason that cities with long historical heritage in Europe and Asia face a dilemma of sorts, while trying to respond to the socio-political attitude for increased industrial development. High density construction means tall buildings, and tall buildings designed in an insensitive manner without respect to the overall environment can certainly pose a threat to the scale and character of such historical cities of the world. The recent construction activities in Switzerland is undoubtedly trying to avoid this dilemma.

In the United States, the situation has been somewhat different although not necessarily for the better. There were very few older cities with long historical heritage, and therefore tearing down older structures and building newer ones as requires was seldom looked upon anything more than supporting progress. But the industrialization which required denser construction in the urban centers did not have the necessary technological support to consider alternative designs of such structures. Buildings were built only as tall as they had to be and not any taller. In simple arithmetic terms, density was achieved most of the time by building floor over floor from one end of the block to the other end of the block leaving hardly any open space on the ground and thereby creating the urban canyons of the 1930's and 1940's.

Increasing industrial growth required increasing density of the urban centers in the last 30 years, and this provided a challenge to the engineers and the architects to develop alternate economic ways of providing the same density of construction without totally disrupting the environment. Although concentration of population in the urban areas and particularly in the urban centers may not at first glance appear to be the solution for more office and residential space, efforts to the contrary in cities such as Los Angeles have only created a more unsolvable problem of traffic and congestion. With the present shortage of energy the idea of traveling long distances by car from the suburbs to the city becomes less attractive. It is therefore a reasonable conclusion that to cope with the changing socio-economic needs, more and more tall buildings will be built in the urban centers. From the economic point of view, however, new and improved methods of construction as well as new "total systems" for buildings must be developed by structural engineers, architects and builders. Innovations leading to more economic and efficient buildings can only be possible through a comprehensive understanding of the nature and behavior of various structural systems, the relationship of the structure with other disciplines such as the mechanical systems and the practical sense of construction problems.

The question is frequently raised as to what constitutes a tall building. Certain building departments define any building over two stories as a tall building. However, from the structural engineer's point of view perhaps the simplest definition of a high rise building is one whose structural elements (beams, columns, foundation, etc.) are directly or indirectly affected by wind, earthquake, or thermal load considerations. It is in fact quite possible that a moderately tall building (about 10 stories) may be strongly affected by the wind load criteria because of its particular structural system whereas a 50-story building may not be affected at all by wind load because of a new efficient structural system. Therefore, in this example as far as wind load is concerned, the 50-story buildings is not a tall building whereas the 10-story building is.

In the United States a new term called "ultra high rise" has been used recently to distinguish an extremely tall building, say over 50 stories, as opposed to buildings below 50 stories. Inasmuch as the challenge to engineers and architects is to find building systems that are not substantially affected by the height of a building, it is interesting to contemplate the beginning of a new era when high rise buildings of less than 50-stories will avoid paying any "premium" for its height and therefore could hardly be considered "high rise" from the structural point of view.

Without going too deeply into the analytical problems, this paper will discuss the significant recent structural systems in steel and concrete for tall buildings for some of which the author has been personally responsible.

Systems in Steel

The Chicago School of Architecture is probably the forerunner of the recent developments in steel construction for high rise buildings. The development of the cast iron column and beam sections led to the use of beam-column type frame construction by the Chicago School of Architecture in the late

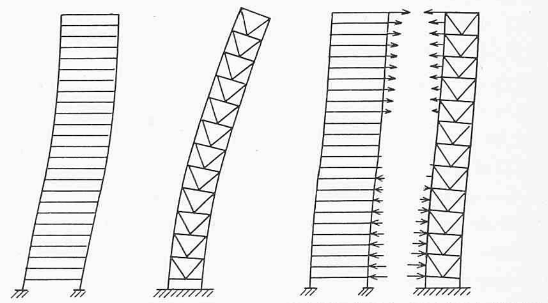


Figure 1. Primarily, the lateral wind shear is carried mostly by the frame system in the upper portions of the building and the majority of the wind shear is carried by the shear truss system in the lower portion of the building

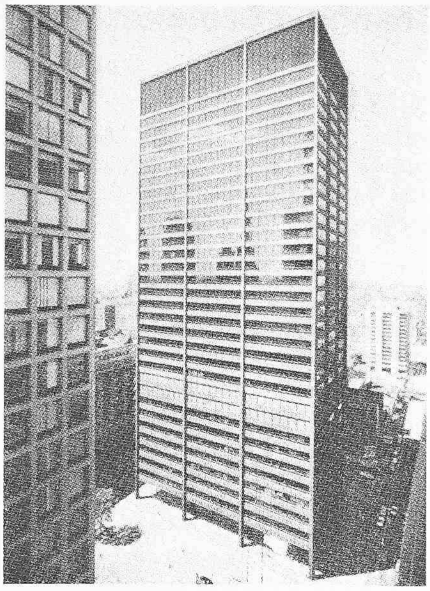


Figure 2 (left). Chicago Civic Center

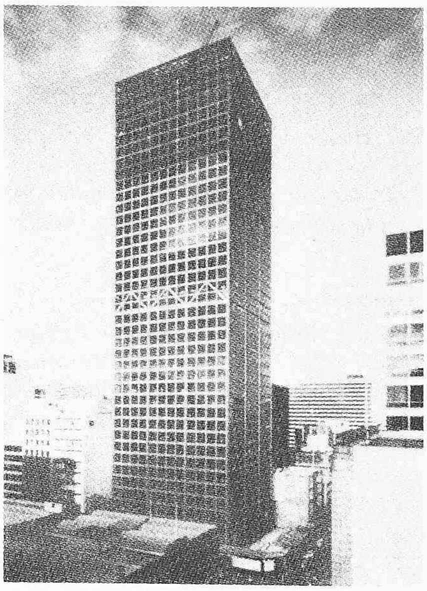


Figure 3 (right). Proposed BHP Headquatrers Building in Melbourne

19th century and its practice spread all over the United States and the world in quick succession. Around 1880, a number of significant high rise buildings in Chicago and elsewhere in the United States were built. The beam-column type structural frame, while becoming a strong innovation in the late 19th century, became a tradition for such construction until the middle of the 20th century although some innovations in structural steel properties were achieved during this time. The inertia of the beam-column type frame were not broken until the end of World War II, at which time new systems began to be developed. Inasmuch as the vertical shear truss in the central service core area can be considered an innovation, is origin was about the same time the beam-column system started being used and therefore cannot be considered a recent innovation. Only the new structural systems and innovations developed since 1950 are to be discussed in this paper.

Shear Truss Frame Interaction

While traditional vertical shear truss has been used for some time as well as the beam-column type rigid frame construction, the interaction of these two systems has not been taken to full advantage until very recently. The author in his studies published in the early 1960's pointed out that a rigid frame construction combined with shear trusses in the central service area can interact in a very beneficial way. Primarily, the lateral wind shear is carried mostly by the frame system in the upper portions of the building and the majority of the wind shear is carried by the shear truss system in the lower portion of the building as schematically shown in figure 1. The interacting system has two major advantages, namely lateral drift or sway is frequently reduced to less than 50% of what it would be otherwise if only shear truss was used, and the distortion of the floors due to lateral sway are less significant in view of the flat S-shape deflected curve. The shear truss frame interaction can be achieved simply by designing the main structural frame for gravity load disregarding the wind effects on the frame part of the structure and designing the vertical shear truss for the balance of the wind effect in addition to the gravity load. This system has been effectively used in buildings such as the Chicago Civic Center (figure 2) and the Chase Manhattan Building in New York.

Shear Truss Frame Interaction with Rigid Belt Trusses

The efficiency of the shear truss frame interaction can be further improved in terms of lateral strength and stiffness by connecting all exterior columns to the interior shear truss through horizontal belt trusses as schematically shown in figure 4. The addition of this belt truss normally will increase the stiffness of the entire structure by about 30%, thus resulting in considerable structural economy. Although "outrigger trusses" for purposes somewhat similar to this have been used in the Dominican National Bank Building in Toronto, Canapa, the full belt truss system at two levels of the building, one at mid-height and one at the top of the building, have been used first in the BHP Headquarters Building in Melbourne as proposed by the author. It should be noted that the belt truss system at midheight of the building also substantially contributes to the increased stiffness of the structural frame. An additional benefit derived from the belt truss system is the possibility of neutralizing the major portion of thermal movement effects on the fully or partially exposed exterior columns of the building (figure 3).

Framed Tube

It can be shown by simple mathematical derivation that the maximum efficiency of the total structure for lateral strength and stiffness can be achieved only by making all column elements connected to each other in such a way that the entire building acts as a hollow tube or rigid box cantilevering out of the ground. In such a case, the cverturning resistance as well as the overturning stresses in the columns would be direct tension or compression without any bending, and the column system can be espressed schematically as shown in figure 7. There are many practical planning and architectural difficulties in tyng all the columns of the building together. However, the exterior columns may be made to act together by various means. Within the architectural framework of rectangular windows the exterior column system may be tied together by spacing them as close as possible so that the column spandrel interaction results in optimum design of the column spandrels within realistic architectural limitations. This method of closely spaced column systems tied with deep spandrel beams at each floor level creates an equivalent rectangular or square hollow tube with perforated window openings as shown in figure 5. This particular structural system was probably used for the first time by the author in the 43-story De Witt Chestnut Apartment Building in Chicago, which was not in steel but in concrete. The most significant use of this system has since been made in the twin towers of the 110-story World Trade Center Building in New York.

The closey spaced columns creating the framed tube may loose some of its efficiency due to the shear lag effect caused by bending deflection in the two walls parallel to the direction of wind or earthquake forces. The resulting actual load distribution in the columns is schematically shown in figure 8. Here is a structural system that requires extreme studies for each project to establish the optimum criteria for combined advantages ot architecture and structure. The author can only point out at this time that extreme closeness of columns may lead to inefficiency just as far apart columns will do. The economic spacing of the columns can be established on the basis of an optimization approach.

The closely spaced column system in steel structure has one major disadvantage in that all connections must be fully rigid requiring mostly a welded construction. It is a well known fact that the unit cost of steel in a steel building increases in proportion to the number of joints to be made. Therefore, even though closely spaced column system is by itself a very efficient structural system, its application in tall steel structures can be justified only where buildings of extreme height are concerned. In the BHP Headquarters Building in Melbourne (figure 4), optimum structural-architectural spacing of 10 feet of the exterior columns was used for the reasons discussed above.

Column Diagonal Truss Tube

The exterior columns of a building can be spaced reasonably far apart and yet be made to work together as a tube by connecting them with diagonal members intersecting at the center line of these columns and spandrels. For extremely tall buildings, the diagonals should be approximately at a 45° angle resulting in large widely spaced crosses as was used for the John Hancock Center in Chicago (SBZ *92* (1974) H. 6, S. 108, Bild 3). This use of diagonal members to connect 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 of this dual function of these diagonals acting both as inclined columns as well as taking the major portion of wind shear, the efficiency of the structural system generally is very high for tall buildings. For instance, only 29.7 pounds of steel per square foot of floor area was used for the 100-story John Hancock Center which when compared to the traditional beam-column frame system would have been required for an average 35-story building.

The column diagonal truss tube system, however, can only be used for truly tall buildings where special solution of the curtain wall system can be economically justified.

Bundled Tube System

With the future need of larger and taller buildings the author feels that the use of the framed tube as well as the column diagonal truss tube may be used by bundling module tubes to create larger tube envelopes. In a tall building with extremely large floor areas, the exterior column system may comprise only a smaller percentage of the total number of columns. Therefore in such a building to use an exterior tube system would be to lose the advantage of possible participation

Figure 4. The efficiency of the shear truss frame interaction can be further improved in terms of lateral strengthand stiffness by connecting all exterior columns to the interior shear truss through horizontal belt trusses

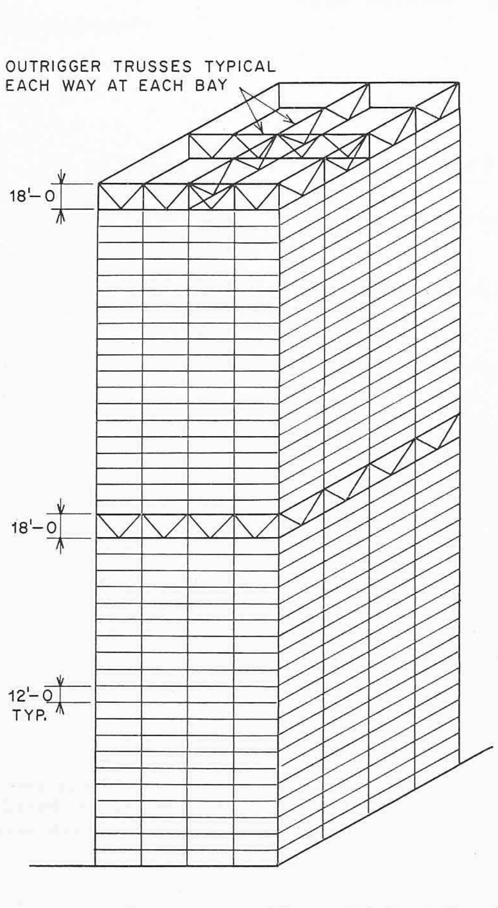


Figure 5. Closely spaced column systems tied with deep spandrel beams at each floor level creates an equivalent rectangular or square hollow tube with perforated window openings

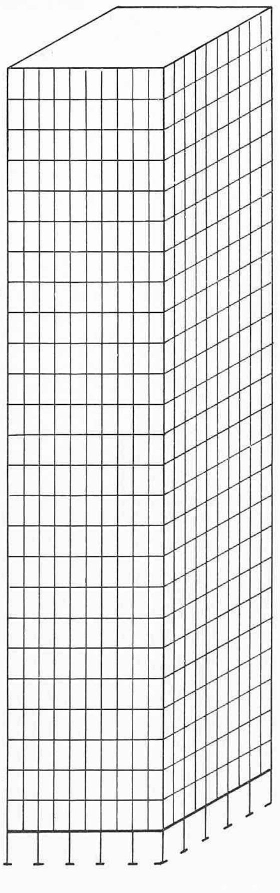
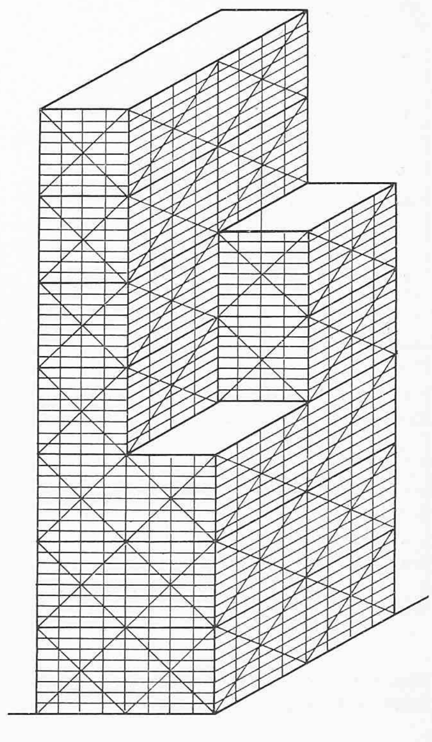


Figure 6. For large and extreme high buildings in the future, it is conceivable that megamodules of column diagonal truss tubes may be used to optimize the system



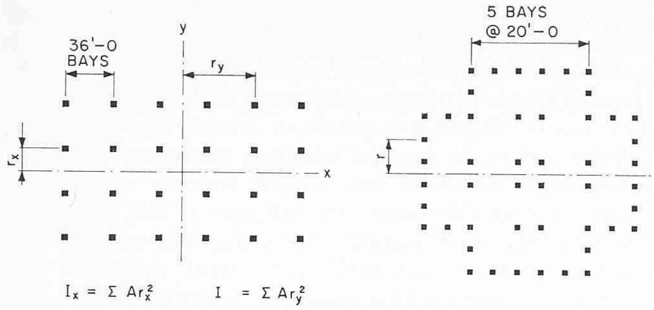


Figure 7. When all column elements are connected to each other in such a way that the entire building acts as a hollow tube or rigid box cantilevering out of the ground, the overturning resistence as well as the overturning stresses in the columns would be direct tension or compression without any bending, and the column system can be expressed as shown

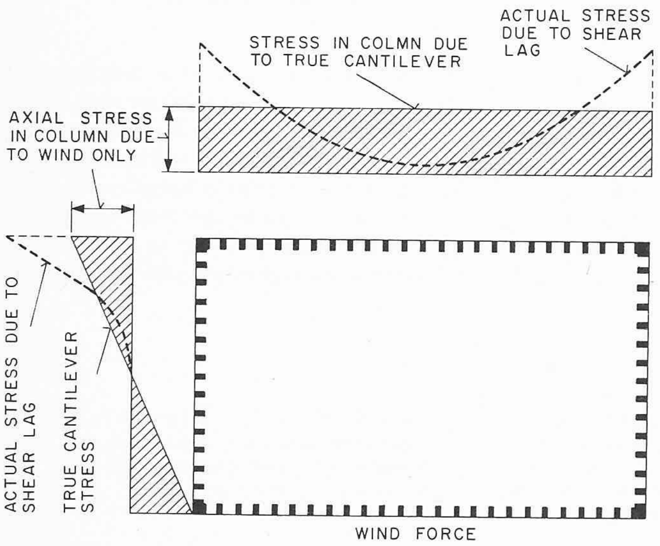


Figure 8. True cantilever vs. actual stress due to shear lag

of the interior columns. This can be overcome by arranging all columns of such a building into modular tubes as schematically shown in figure 9. For large buildings of extreme height in the future, it is conceivable that mega-modules of column diagonal truss tubes as schematically shown in figure 6 may be effecetively used to optimize the total structural system. Perhaps a somewhat less economical but architecturally more efficient bundled tube system can be made up of framed tubes arranged in modules similar to those shown in figure 9. Inasmuch as the author consideres these structural systems for the future, one building is already being planned by Skidmore, Owings & Merrill (SOM) with this type of structural system. The 110-story Sears Roebuck Headquarters Building in Chicago will have the mega-module framed tube of 75 feet square arranged in three rows both ways with column spacing 15 feet as shown in figure 10. An interesting side benefit of this system allowed termination of each module at different levels without any loss of structural integrity (Sears Roebuck Headquarters Building, SBZ *92* (1974) H. 6, S. 109, Bild 6).

Systems in Concrete

While tall buildings in steel had an early start in the late 1900's, present development of tall buildings in reinforced concrete is progessing at a fast rate providing competitive challenge to the structural steel systems both for office and apartment buildings. The first use of shear wall construction in this country in conjunction with flat plate slabs was probably first used by SOM on the Lake Meadows project in Chicago in 1949. The use of shear walls in conjunction with flat plates has virtually captured the entire apartment building market in the United States. Shear wall construction has been used with many modifications, one of which has been to combine such a shear wall with exterior simply supported steel structure framing. These innovations have already become traditional in the structural field. As the need for taller office and apartment buildings became great, newer structural systems had to be developed in reinforced concrete. Some of these recent developments are discussed below.

Fortsetzung folgt

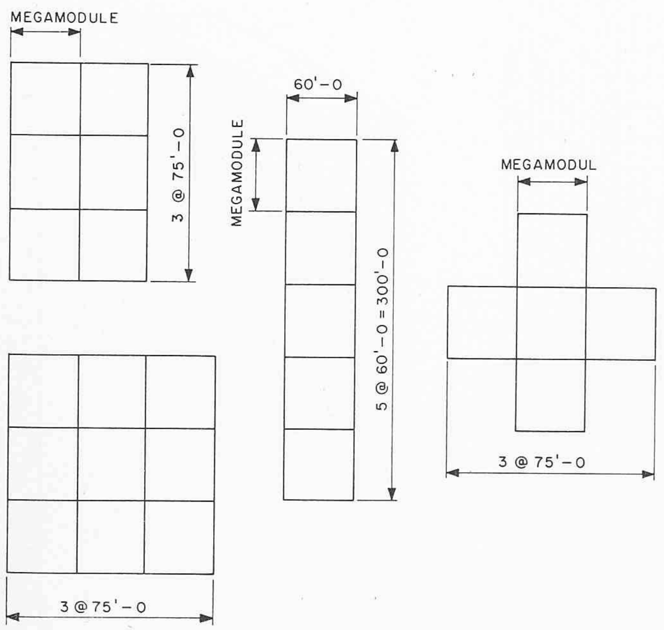


Figure 9. Bundled tube system by arranging all columns into modular tubes as schematically shown

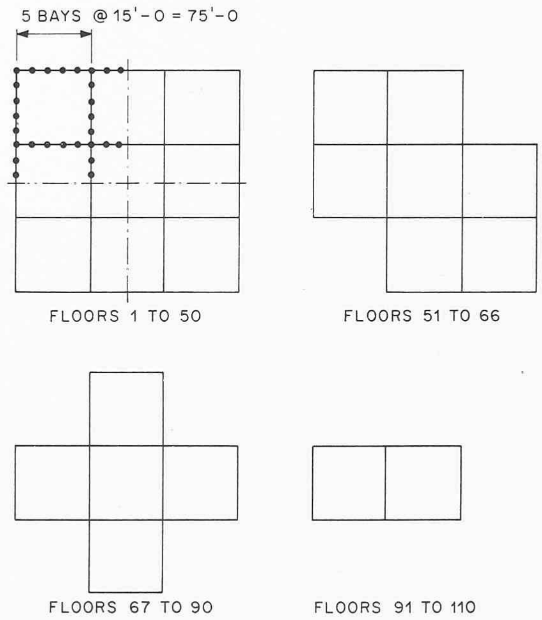


Figure 10. The 110-story Sears Reobuck Headquarters Building in Chicago will have the mega-module framed tube of 75 feet square arranged in three rows both ways with column spacing 15 feet