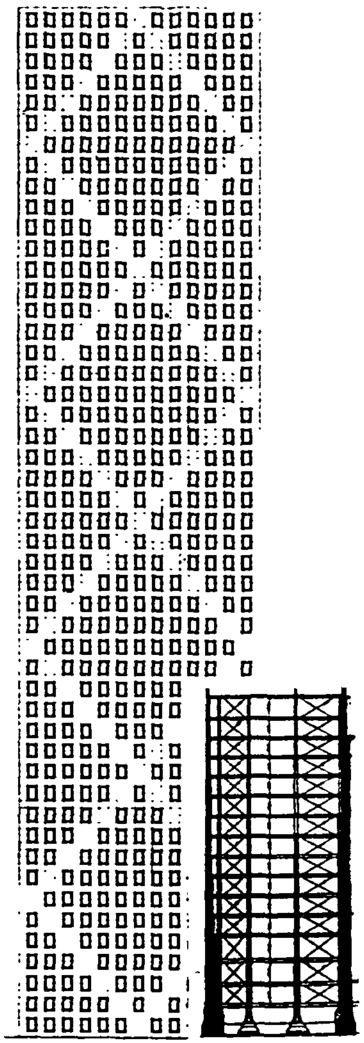


STRUCTURAL SYSTEMS FOR HIGHRISE BUILDINGS

WERNER SOBEK

This report was generously supported by the Skidmore, Owings and Merrill Foundation, Chicago

CONTENTS:

1 INTRODUCTION

1. INTRODUCTION

This is the second report the author is giving to the Fazlur R. Khan Foundation in Chicago.

The report was written in the United States under the first Fazlur R. Khan Fellowship in 1984 and it was completed in Germany afterwards.

"Highrise Buildings" was selected by the author as the draft-title for the activities during the fellowship. Under this theme the author studied the single aspects of highrise buildings as for example planning methods, architectural considerations, structural systems.... This was done by working at the offices of Skidmore, Owings and Merrill in Chicago and San Francisco, it was done by studying at the Illinois Institute of Technology, by visiting and discussing with different people and firms and by visiting lectures at different places.

The paper presented here is a condensed result of the studies done during the fellowship with a special view on structural systems.

It is necessary to mention the conviction of the author that a survey on highrise buildings structures cannot be a survey on structural systems exclusively. Architectural as well as urban planning considerations, the state of the art of engineering and material science, historical developments and so on have to be considered while discussing structural systems. In that sense, the following report was written to give a compact view on structural systems for highrise buildings by involving the discussion of some of these interdependencies.

The author is grateful to all the persons who supported him in his work and his studies. In particular he wants to express his gratitude to the firm of Skidmore, Owings & Merrill, Chicago and San Francisco.

Stuttgart, 1985 Werner W. Sobek

"One should perhaps remember that a new structural system is only as good as an equivalent architectural solution."

Fazlur R.Khan

2. ON THE DESIGN OF STRUCTURAL SYSTEMS FOR HIGHRISE BUILDINGS. SOME BASIC CONSIDERATIONS

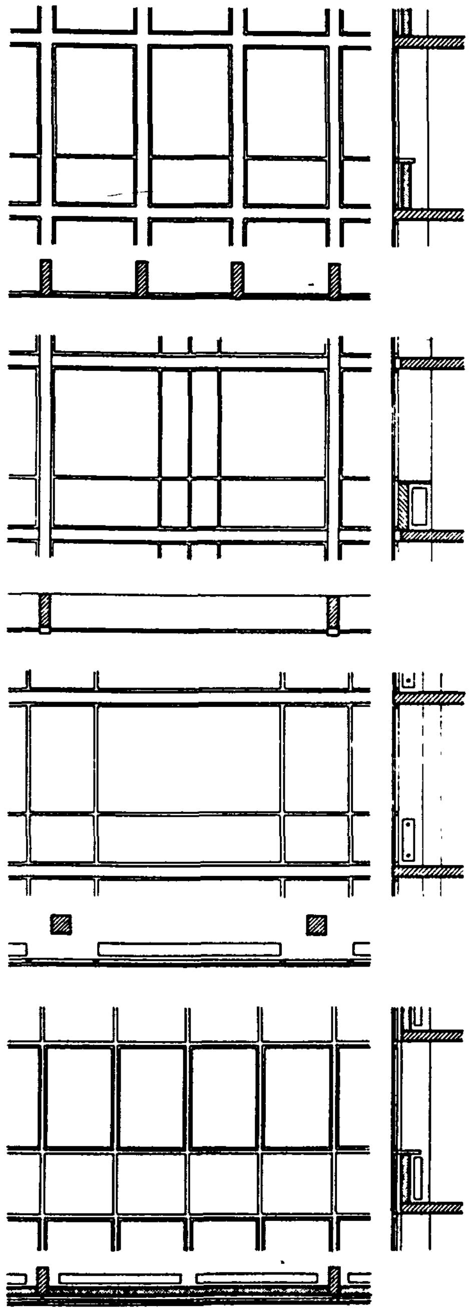
A highrise building as a whole may be considered as consisting out of five subsystems. These systems are the

- structural system
- architectural system
- mechanical system
- service system
- electrical system.

While designing the structural system of a tall building, the interaction of all these (sub)systems has to be considered. Therefore a short introduction into these systems is given on the following pages.

2.1 Structural Systems

The detailed discussion of the different structural systems is the topic of the chapters 3 - 9. Therefore only one remark is done here. It is concerning the design of the entire structure: Usually the structural design is governed by the necessary limitation of lateral sway caused by wind or earthquake loading. Maximum lateral swift under design-loads should not exceed the range of 1/600 to 1/1000 of the buildings height.
A height-to-width ratio of 8:1 seems to be the limit for the entire structure shape.
Necessary limitation of member-stress usually is not causing design problems.



2.2 Architectural Systems

Most important architectural systems to be considered here are the
- facade
- partition and wall

systems.

A. Facade System

Different groups of facade or cladding systems may be established depending from the classification purpose: Cladding materials, construction methods, size of cladding elements....

In this paper the facade systems are separated into 3 groups:
- curtain wall systems
- cladding system and exterior structural elements are within one plane
- relatively to the exterior structural elements the cladding system is set back

B. Partition and Wall Systems

"The primary function of the partition system in highrise buildings is the separation of large spaces into smaller ones for privacy, for the organization of work functions, and for fire protection"/2/. Partitions are nonloading elements. Movable and solid partitions may be distinguished.

2.3 Mechanical Systems

The major components of the mechanical system are:
- Heating
- Ventilating
- Air-Conditioning
- Plumbing

A Heating Systems:

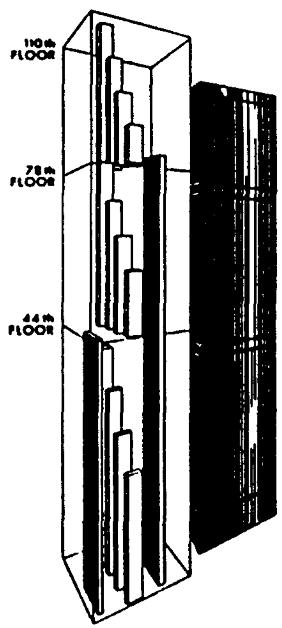
1 Forced Air Heating
2 Steam Heating
3 Water Heating
4 Electrical Heating

B Cooling Systems:

1 All-Air System
2 Air-Water System
3 All-Water System

C Plumbing Systems:

1 Pressure Boosting System
   - Gravity Tank System
   - Hydropneumatic Tank System
   - Booster Pump System
2 Hot Water Supply System
3 Chilled Water Supply System



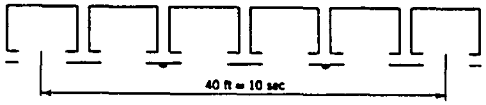
2.4 Service Systems

Main service systems are the
- horizontal
- vertical

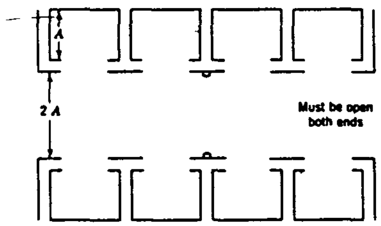
transportation system.

A. Horizontal Transportation Systems:
Special horizontal transportation systems are uncommon in highrise buildings.

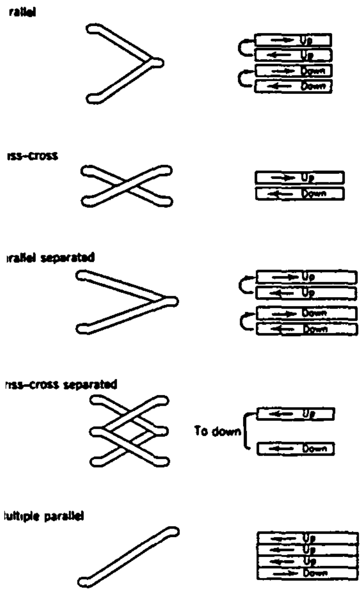
B. Vertical Transportation Systems:
A sophisticated vertical transportation system is very important because of the large quantity of people to be moved within a short time period at the beginning and the end of business hours.



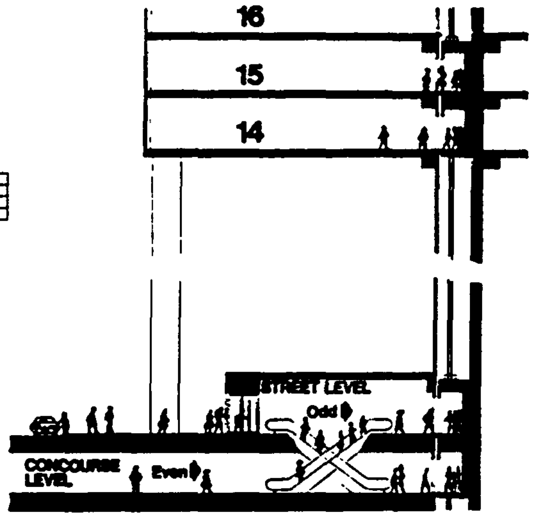
Unacceptable Six-car Arrangement



Eight-car Arrangement



Escalator or Moving Ramp Arrangements



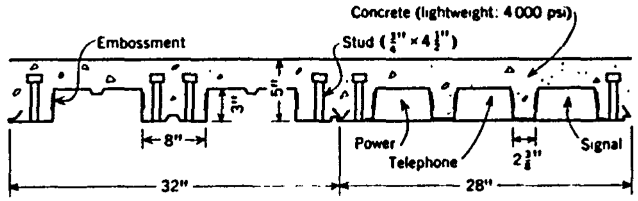
Vertical transportation systems may be divided into:

1 Elevators
2 Escalators
3 Material Movers

Elevators:
The first elevator with a safety-system was demonstrated by Elisha Graves Otis at the Crystal-Palace in New York in 1853. The first elevator with a safety-system was installed in a warehouse in New York in 1857.
Hydraulic elevators are not usually employed in highrise buildings.
While designing the elevator shaft arrangement a short access distance should be considered.
The sky-lobby concept allows a short access-time to the upper stories by providing shuttle elevators which are going non-stop from ground level to the sky-lobbies. These elevators may be designed as double-deck cars. In this case the design of the ground level and the sky-lobby areas has to ensure the equivalent loading of both car decks within the same time period.

2.5 Electrical Systems

Usually the arrangement of the electrical systems is not influencing the entire building design. The only important interaction of structural members and electrical system is the so called "electrified deck".



3 PURE WALL STRUCTURES

3. PURE WALL STRUCTURES

Since the beginning and especially at the beginning of all the trials to build as high as possible wall structures made out of masonry or clay have been used. Initially these high buildings were erected for defense or religious reasons only. But with the increase of the population within the cities sheltered by a city wall the necessity to build higher buildings arose. Some few examples may be shown to explain the historical development:

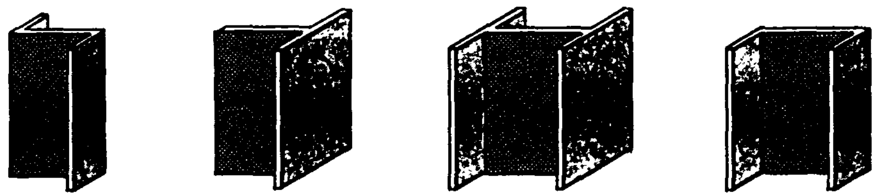
- Lighthouse in Pharos, 280 BC, 400ft.

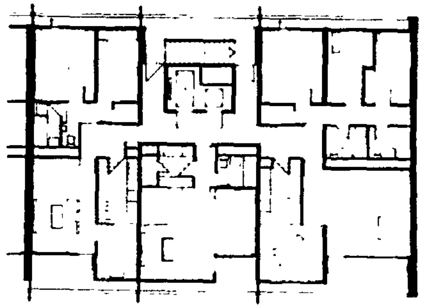
- Apartment complexes in Roman cities, 100ft.

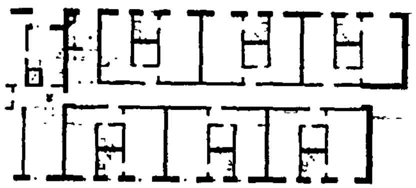
- Clay and brick buildings in Yemen since 1800, 15 stories.

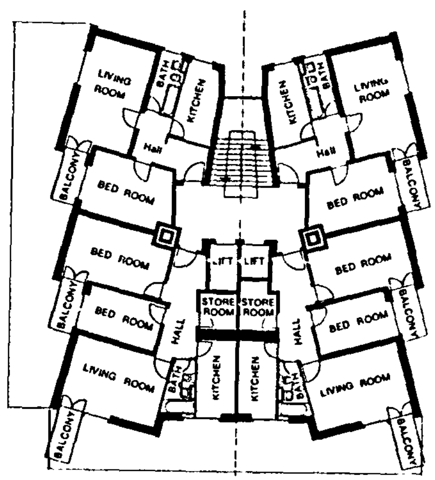
- Monadnock Building, Chicago, 1891, 16 stories.

The load bearing behavior of wall structures: All vertical loads are transferred to the walls by the floor structure. Loaded by these forces and by their own dead weight, the walls act as "bearing walls". Additionally horizontal forces caused by wind and earthquake have to be carried by the walls. These horizontal forces are distributed through the floor-structure to the walls. Because of their low rigidity against loading perpendicular to the wall, the walls must be loaded parallel to the walls plane. (They act as "shear walls".) This requires a certain arrangement of the walls within a building:









In combination with architectural requirements the principles just mentioned result in a number of typical wall-layouts which are used especially for residential buildings:

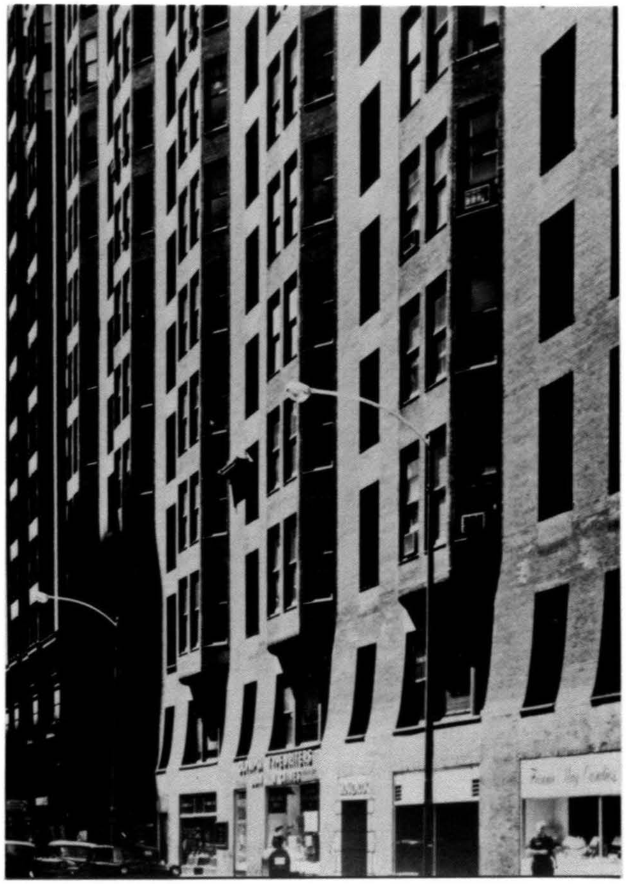
- cross wall system

- long wall system

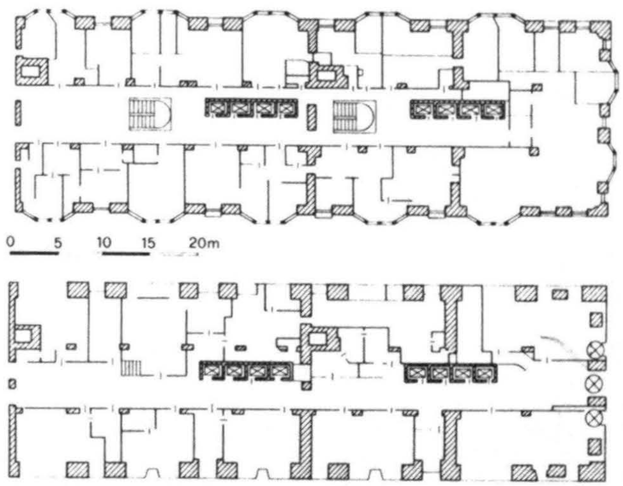
- two way system

Walls made out of unreinforced masonry or clay etc. are not able to carry tension forces caused e.g. by wind loading. Therefore these walls have to be prestressed, e.g. by dead weight. This and the low strength of the material results in a quickly increasing thickness of the wall with increasing height. The Monadnock Building (a: Burnham & Root, 17 stories, erected 1889-91 in Chicago) is a fine example to show this effect. The thickness of the exterior walls at the ground level is 2.0m. Even if this thickness was stipulated by building codes, the comparable 14-story Queen Anne Mansions in London shows a wall thickness of 0.9m at ground level.

The Monadnock Building is of interest because of some other circumstances: The tallest masonary building erected in the 19 th century seems to be designed and detailed very conservative. But the treatment of the facade was a big step forward as well as the interior iron frame of the Monadnock embodied the most advanced principles.



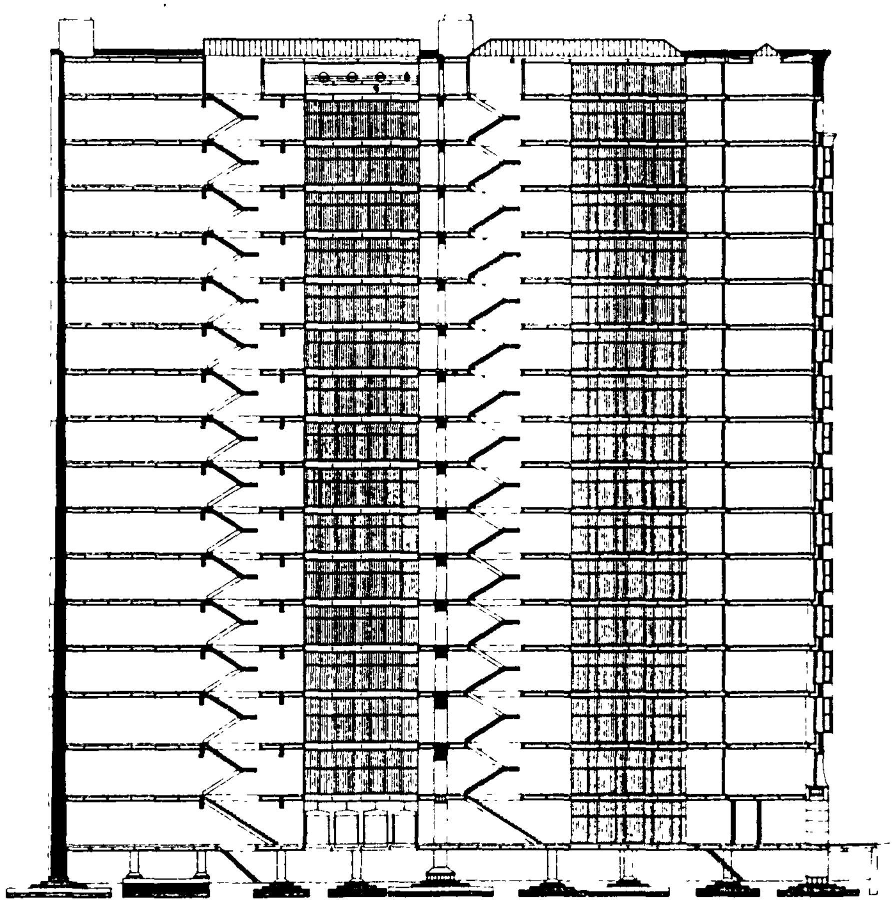
Chicago, Monadnock Building 1891



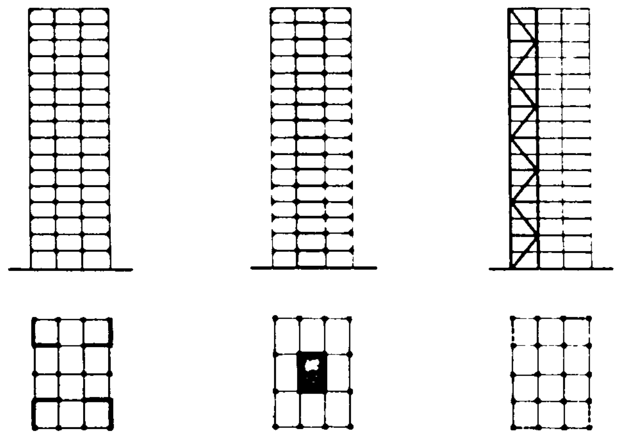
Structural masonry had a rebirth in northern Europe in the late 1940's:
Controlled by structural engineers, structures had been built up to the 20-story range.

By using high quality material, partial reinforcing and by designing the entire structure in a (from the standpoint of the structural engineer) proper way, structures up to 50 stories are possible, structures up to 25 stories seem to be economic./2/.

Monadnock Building Chicago Ill., 1889 91 Burnham and Root architects Longitudinal section



4 WALL AND COLUMN / FRAME AND SHEARWALL SYSTEMS



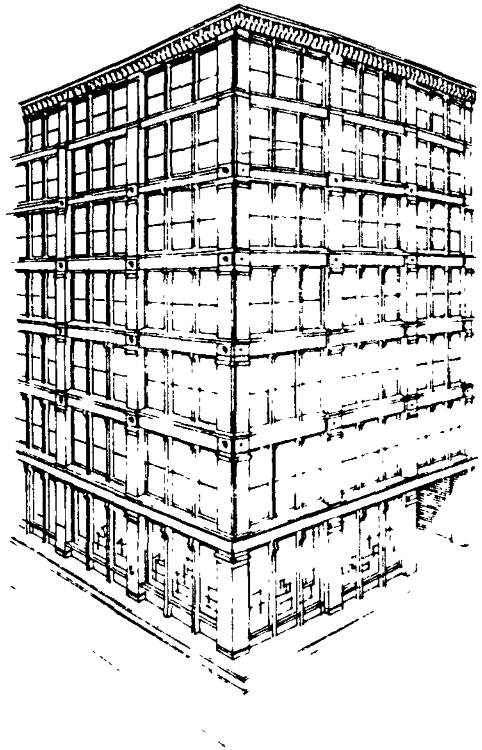
4. WALLS AND COLUMNS/FRAME AND SHEAR WALL SYSTEMS

The introduction of masonry, iron or steel columns into the pure wall structure system is forming the transition from the pure wall structure type to the wall and column type structure. Depending on the way the columns and girders/slabs are connected together, respectively the way the walls are loaded, very often some further structural classification of the wall and column type structural spectrum is done.

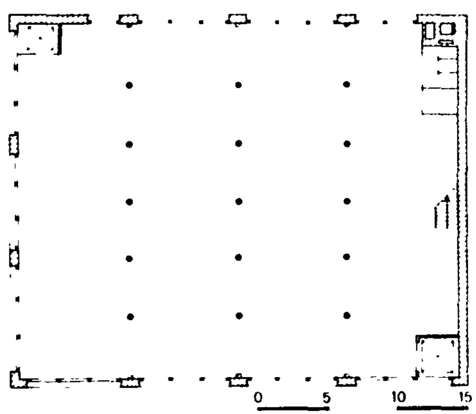
Because of the low efficiency of a bended structural member, the structural engineer usually will try to provide the columns with axial loading only. Horizontal forces therefore have to be taken by shearwalls. The arrangement of these shearwalls has to follow the aspects mentioned in chap.3.

However, the development of iron, later of steel members with special formed cross-sections as well as the possibilities of reinforced concrete made it possible to erect very light skeleton structures of limited height where the columns as well as some shearwalls or a core are equivalent members in carrying the horizontal loads.

An important example for the description of the development of the wall and column type structural system is the Nixon Building (Chicago) designed by Otto H. Matz. The building was in the process of construction when the great fire of 1871 struck. "It represented the most advanced structural techniques available at the time. The walls of the five-story building were divided into slender masonry piers that made it possible to open



Chicago, Leiter Building I 1879



the elevations into an area of glass nearly equal to that common among the cast-iron fronts. For the interior construction Matz aimed at complete fireproofing. The interior frame consisted of cast-iron columns and girders supporting wrought-iron joists and roof rafters. The upper surfaces of all framing members were covered with a one-inch layer of concrete, and the ceilings were plaster of Paris. Partly by design and partly by luck the structure of the Nixon survived the fire intact, and the building was opened to use a week after the catastrophe."/8/.

The First Leiter Building (compl. 1879, Chicago) designed by William Le Baron Jenney is another important example: Wrought iron girdes and wooden joists, cast iron columns at the interior, masonry piers and shear-walls in the facade-plane. The building is a break-through and a sensation because of it's large and open internal space.

The introduction of steel into the buildings frame was done 4 years later. William Le Baron Jenney designed the Home Insurance Building (1884-85, Chicago). "The frame of the Home Insurence included cast-iron cylindrical columns, built-up box columns of wrought iron, spandrel girdes and floor beams of wrought iron up to the sixth floor, and Bessemer steel beams and girdes above."/8/. The connections of the iron respectively steel frame were bolted. The Home Insurance Building had partially loaded brick party walls at the side, the exterior columns had a heavy masonry cladding.

The replacement of the massive masonry or concrete shearwall by a truss-type shearwall allows to save dead weight and allows to provide additional internal space or (in the case of an external shearwall) additional window area.

Home Insurance Building, Chicago, Ill., 1884-85 William Le Baron Jenney, architect. This celebrated building came closest to being the first true skyscraper, with fully developed skeletal construction.

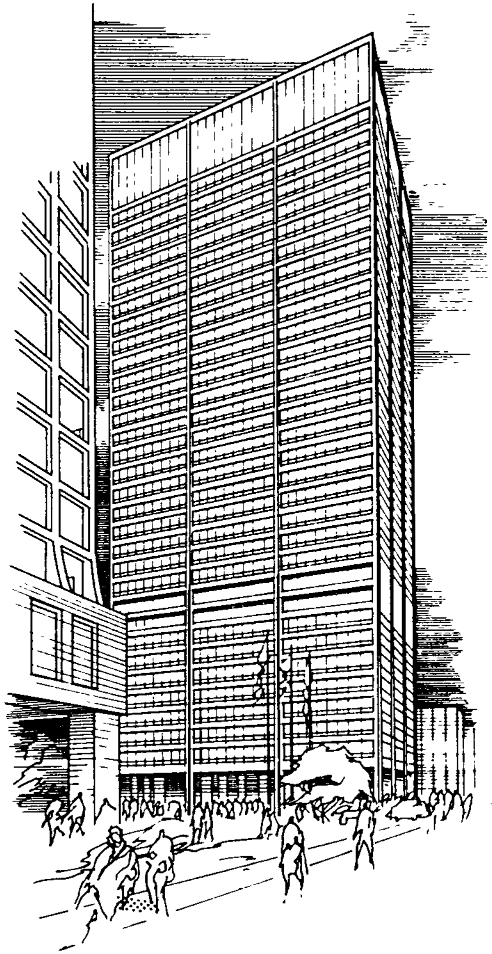
The first iron construction to use an external diagonal bracing was developed by Jules Saulnier for the Menier Chocolate Works at Noisiel Sur Marne in 1871. The 4-story building, situated near Paris, is still standing.

The 20-story Masonic Temple (a.: Burnham & Root, 1891, Chicago) was the first highrise building with a diagonal bracing./2/. Diagonal rods in the planes of the exterior walls were used to join beams and columns and to form this way "vertical trusses".

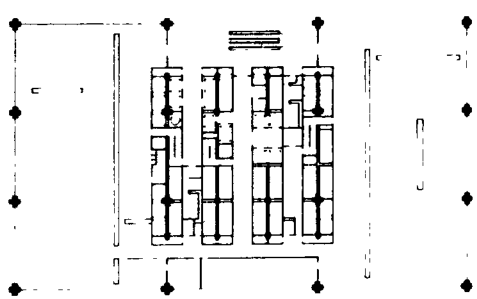
The same system, but now external located vertical trusses has been used at the St.Louis Mercantile Tower. The trusses here are forming very stiff regions at both ends of the building: End channel framing.

Reducing the height of the shearwalls or the core means that the columns of the upper stories have to carry all the horizontal loads acting in this height. Such a type structure is forming the transition to the pure frame systems.

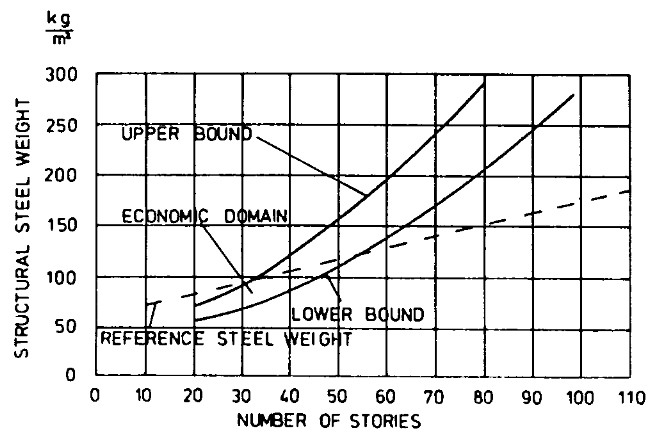
The Chicago Civic Center is an example for such a type of structure. "The huge building was erected between 1963 and 1965 from designs prepared by three associated firms of architects and engineers - C.F.Murphy Associates; Skidmore, Owings and Merrill; and Loebl, Schlossman and Bennett. The building has only thirty-one floors other than those reserved for mechanical and electrical equipment, but it rises to a full height of 648 feet because of the extremely high ceiling height required by court and hearing rooms, auditoriums, and other public enclosures. The primary bearing members are sixteen columns of cruciform section, set for a bay span of 48 feet on the short elevations and 87 feet on the long - unheard-of dimensions that revolutionized the scale of building elements. The long span required floor girders in the form of the Warren truss 5 feet 4 inches



Chicago, Civic Center 1963/66



deep; in this depth it held uniform for the entire floor framing system, regardless of span, so that ducts and conduits can pass through the triangular openings between the web members of the truss. The welded connections between the trusses and columns make the primary frame a system of portal bracing, which is supplemented by K-truss bracing in the 29 foot bays of the elevator shafts. This apparently marks the first of the K-truss in steel-frame buildings, although it was revived for the main trusses and lateral frames of bridges shortly after the turn of the century, nearly eighty years after Stephen Long invented it.
The external covering of the framing members in the Civic Center is a special kind of high-strenght corrosion-resistant steel manufactured under the trade name Cor-ten." /8/.

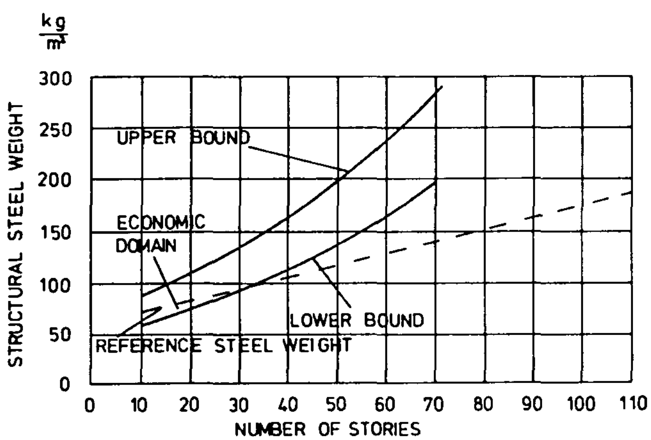


FRAME WITH SHEAR TRUSSES

BY IYENGAR


Dancing UNDER PICASSO AUG 13-17
TO THE BIG BANDS/TIME 12:00 NOON

5 RIGID FRAME SYSTEMS



FRAME BUILDINGS

BY IYENGAR

5 RIGID FRAME SYSTEMS

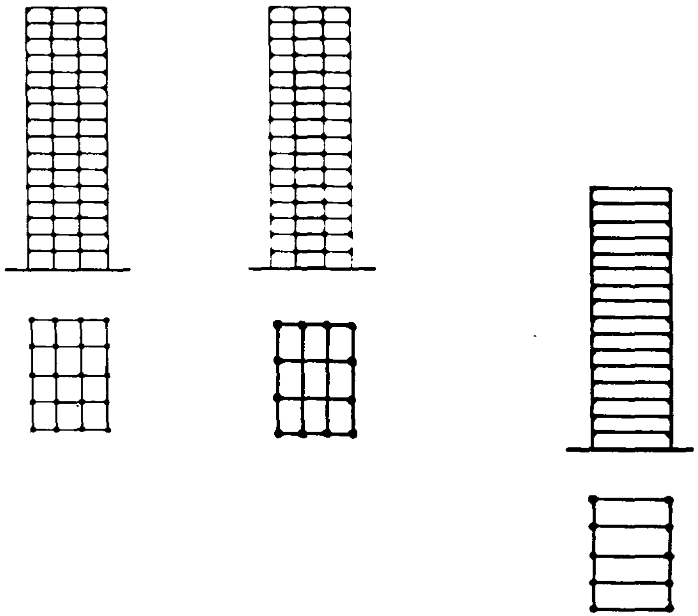
Omitting the shearwalls (shear trusses) in the type of structures just discussed forms the transition to the pure rigid frame systems.

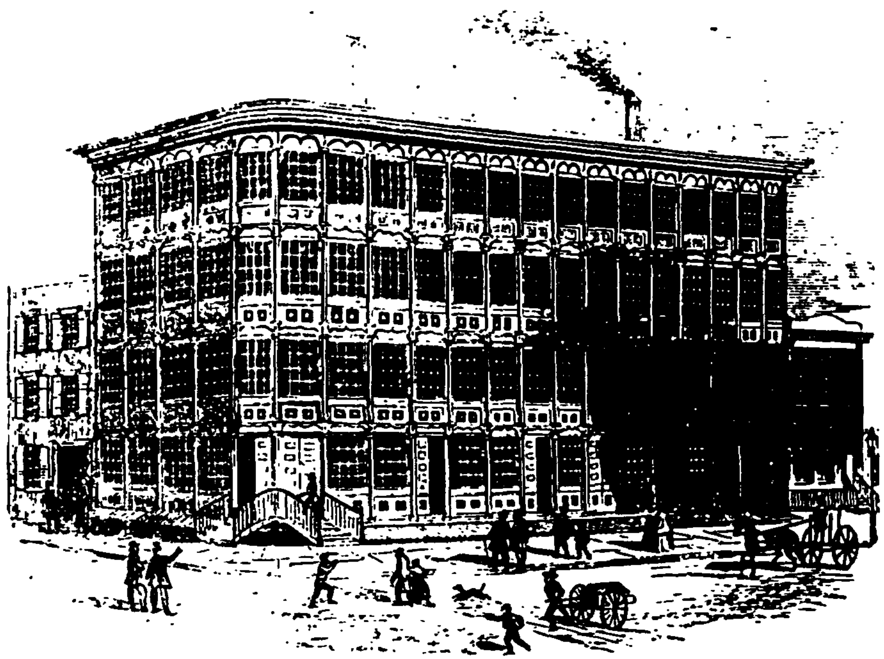
In a rigid frame structure all vertical loads are transferred by the floor structure either to the horizontal beams which are linking the columns or directly to the columns. The arrangement of columns and beams within the structure has to provide stiffness against lateral loading from all directions. Lateral forces are transferred to the foundation by bending of the beams and columns in addition to axial loading. The lateral sway of a multi-story rigid frame structure under horizontal loading is caused primarily by this bending of the columns and beams which "constitute about 90 % of the total sway. The remaining portion (10 %) of the total sway is caused by the cantilever action of the entire frame causing tension and compression in the columns which is generally known as the "column shortening effect"."/28/.

To reduce lateral drift means to increase lateral stiffness. This usually is done by increasing girder and column size, by modifying column spacing and by increasing the efficiency of the girders connection to the columns. The figures on the left page show some of the common types of such modifications.

The rigid frame principle seems to be economic up to about 20 stories for concrete and about 30 stories for steel framing.

A large number of frame-layouts is possible, the





following basic types may be distinguished:

- spatial frames, all column-beam connections are rigid
- exterior framing, interior columns are gravity loaded only
- exterior framing without interior columns

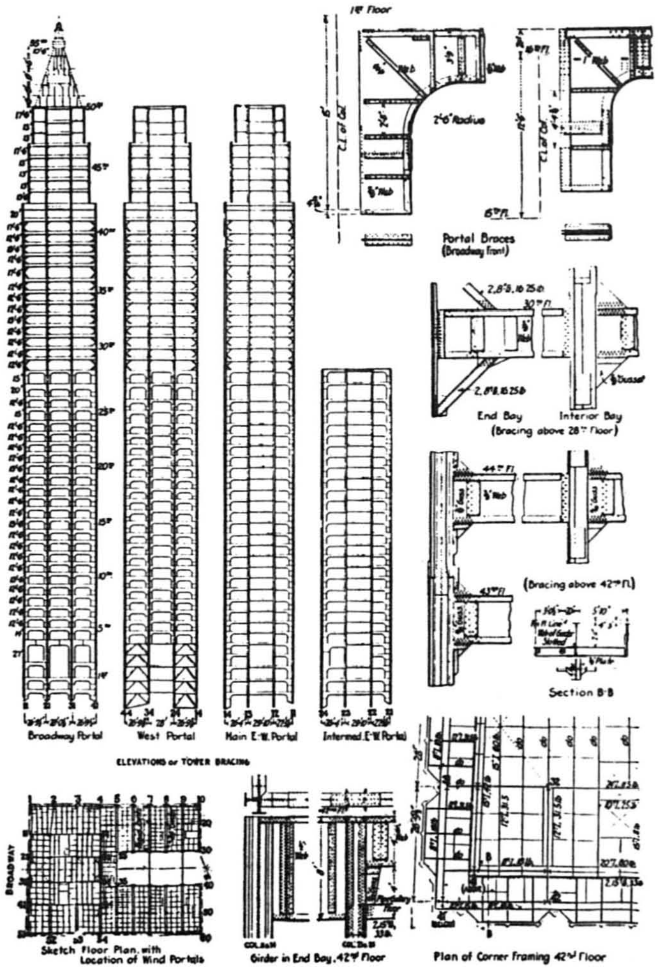
One of the first buildings incorporating the possibilities of the framing of iron or steel members was the James Bogardus Foundry established at Centre and Duane streets in New York. The building was designed by James Bogardus and it was erected in 1848-49. " The extreme simplicity of the foundry construction brought it as close to the mechanization of building techniques as was possible at the time. At the base was a continuous footing of stone extending around the periphery of the building and supporting a cast-iron sill planed to smooth surface and uniform thickness. Hollow cylindrical columns turned on the lathe, with flanged ends machined smooth, were bolted to the sills through the column flanges at the sill joints. Spandrel girders in the form of channels were bolted to the top flanges of the columns. Another set of sills, columns, and channels was added for each succeeding story. The outer members of the iron frame took the place of a bearing wall, which than had no function and was omitted. The floors of the factory were carried on timber beams, but in all other respects the structure was simply a cast-iron cage. Bogardus designed it that it could be disassembled by drawing the bolts and re-erected on another site. The disassembly was accomplished in 1859, but there is no evidence that the that the factory was ever rebuilt." /8/. The hand-bolted, unbraced frame system of the Bogardus factory was nor able to be used for buildings higher than the four story factory building because of its low rigidity against lateral loading: The development of the riveted and braced frame as well as the replacement of the cast iron by wrought iron and/or steel members became a necessity. This was done by Chicago builders in the period of 1880-1890.

The first use of riveting in a major building happened at the 13-story Tacoma Building (a: Holabird & Roche, 1889, Chicago).

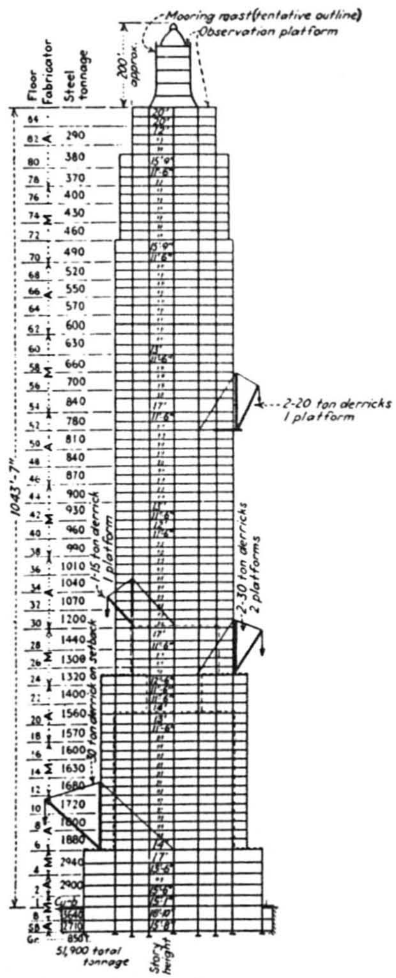
The Second Rand Mc Nally Building in Chicago was the world's first sky scraper with an all-steel frame, totally freed from all masonry adjuncts. The building was erected between 1889 and 1900. Burnham & Root were the architects, Wady & Purdy the structural engineers. Surely, the introduction of steel into the buildings frame was done by William Le Baron Jenney at the Home Insurance Building for the first time probably, and: The first highrise buildings with a column-girder connection stiff enough to act as a frame where the Monadnock Building designed by Burnham & Root and Jenney's Manhatten Building. But all these three buildings didn't act as pure frame structures.

The portal bracing (stacked portals) introduced at the Old Colony Building (a: Holabird & Roche, e: Purdy, compl. 1894, Chicago) and also used for the Monadnock and the Manhatten Building was the framing method mostly used for highrise buildings until 1930. Hereby portal

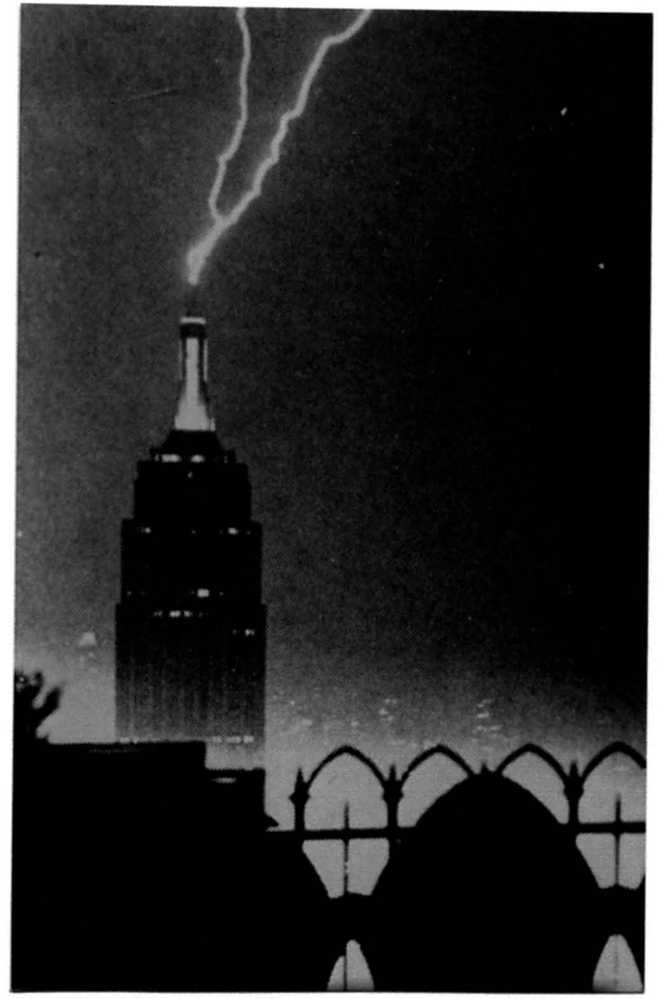
Woolworth Building, New York City, 1911–13. Cass Gilbert, architect; Gunvald Aus Co., engineers. Elevations and details of the steel frame. The Woolworth was the highest building in the world at the time of its construction and was supported on the most elaborately braced steel frame.



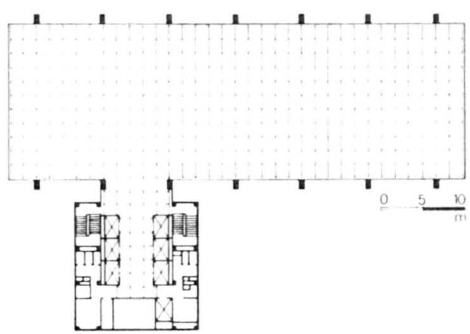
Empire State Building, New York City, 1929–31. Shreve, Lamb and Harmon, architects; H. G. Balcom, engineer. Elevation of the steel frame. The highest of all American skyscrapers until the World Trade Center is completed, the Empire State is carried on a traditional portal-braced steel frame.



bracing is a kind of wind bracing where rigidity is secured by riveting the girders web throughout its depth to the column. The Woolworth Building (a: Cass Gilbert, e: Gunvald Aus & Co, erected 1911-13, New York City) and the Empire State Building (a: Shreve, Lamb & Hammon, e: Balcon, compl. 1931, New York City) are two of the most famous buildings carried on portal braced steel frames.



Chicago, Inland Steel Building

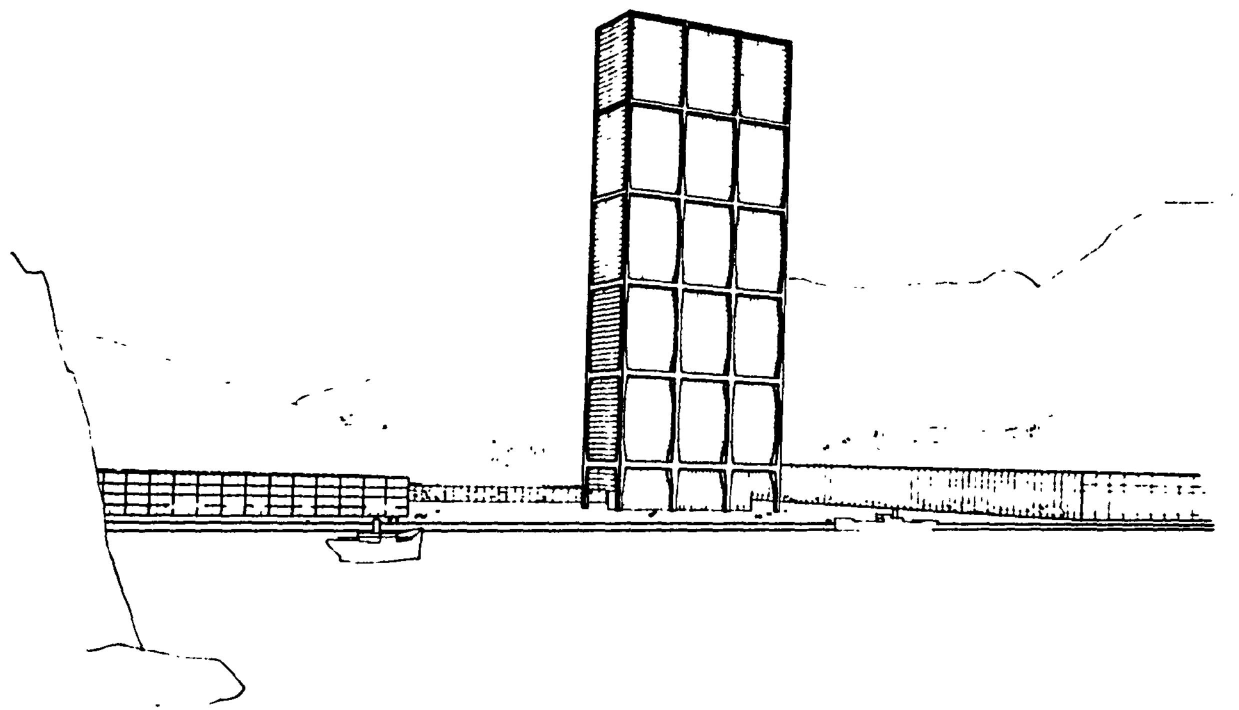


"The first skyscraper of reinforced concrete came at the beginning of the century with the sixteen-story Ingalls (Transit) Building in Cincinatti (1902-03). The architects were Elzer and Anderson, and the designers and builders of its column-and-girder-frame were the staff of the Ferro-Concrete Construction Company. The reinforcing system was based on Ransome's patents for fully develloped reinforcing against tension and shear."/8/.

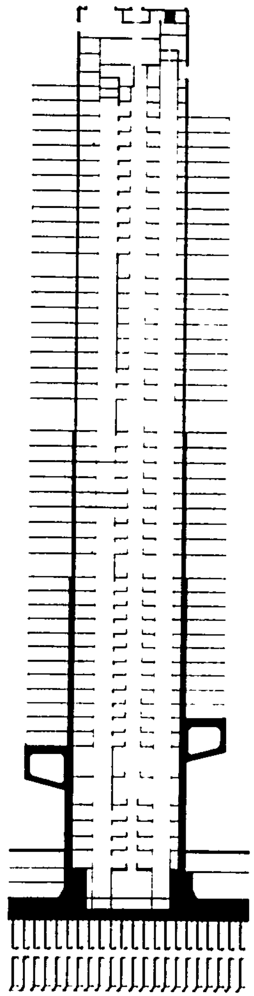
After the "long hiatus in building caused by the depression of the thirties and the war that followed"/8/ it was the Inland Steel Building (a/e: SOM, 1955-1957, Chicago) which brought the leadership (in having the most advanced highrise building) back to Chicago. The 19-story office building is designed on the imperative of separating elevators, stairs and service areas from the office space, that means the servant and the served areas are distinguished explicitely. The structural system for the office building is a serie of 7 parallel portal frames: 58-ft transverse girders are loading the columns located outside the perimeter wall. The column girder connections are fully welded. Reinforced concrete floors are acting as horizontal diaphragms. The elevators and utilities shaft is located outside the office building. It is a steel structure braced with full-length diagonals. The whole tower is sheated in stainless steel.

The Business Men's Assurance Co. (BMA) Building (a/e: SOM, compl. 1964, Kansas City) is another building which must be mentioned here. The rigid frame's spandrel beams span 36ft. They are made out of high strength steel and they are fully welded to the columns.

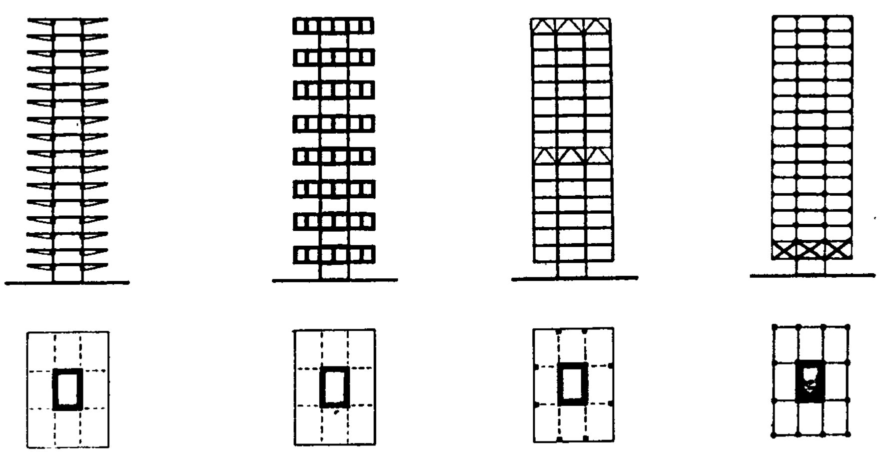
With the proposals he published in his thesis /10/, Myron Goldsmith enlarged the spectrum of structures by the so called multistory frames or megaframes, the ultimate application of framing.



6 PURE CORE STRUCTURES



National Westminster Bank. Section.



6 PURE CORE STRUCTURES

Elevator shafts, stairs, installation etc. as well as all service rooms usually are combined within a so called service core. This service core may be designed as a vertical hollow-tube structural element as described in chapter 4. Because of its small internal lever-arm compared to the entire structures plan dimensions, the stiffness against lateral loading of such a (structural) core is relatively small. Therefore the pure core structures are an exception within the variety of the different structural systems for highrise buildings. Buildings with a single core as the only load-bearing element for vertical as well as for horizontal loading have a limitation of the buildings height of about 40 stories.

The 52-story National Westminster Bank (a:Seifert & Partner e:Pell, Frischmann & Partner, 1970-1979, London) is mentioned here as an example. And as an exception too. Because of the large size of the core, the building is at the transition to the exterior tube type structures.

Typical structural systems are the

- core and cantilevering slabs system

- suspended system

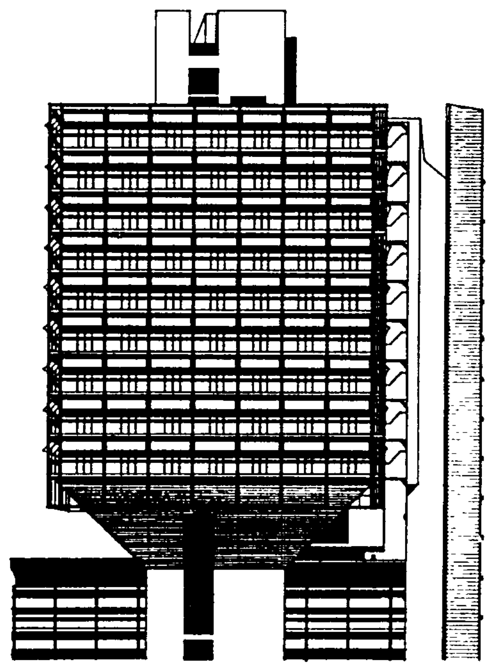
- supported system

(see left side).

Again, the core should be centered in the buildings plan to minimize torsion of the cores shaft caused by horizontal loading. Also the center of gravity of the single floors should be at the vertical axis of the core.

The ability to create a structure-free architectural solution at the base of the building is an advantage of the pure core structure type.

By connecting a number of cores together, e.g. with stiff girders and/or diagonal elements, the transition is formed to the multicore structures and to the megastructures as described in chap.4 and chap. 9.



Frankfurt a. M , Verwaltungszentrum Olivetti

7 CORE AND COLUMN STRUCTURES

7 CORE AND COLUMN STRUCTURES

In chap.6 it was described that a service core may be used as a structural element. In such a case the core usually is designed as a tubular type structure cantilevering out of the ground. Tubular action hereby is achieved by designing the core either as a cellular, framed tube or as a trussed tube.

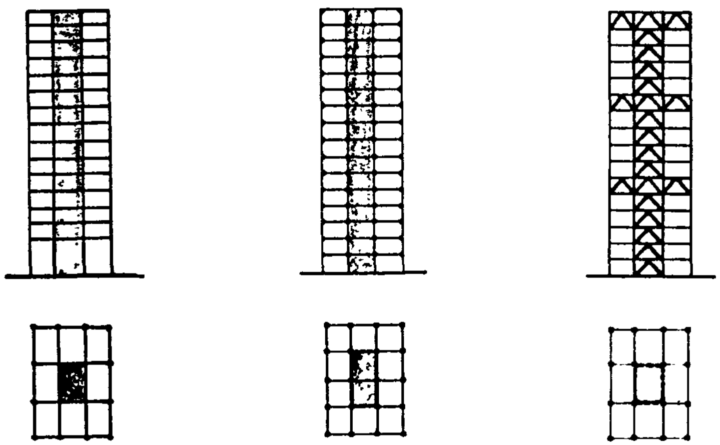
In combination with a floor and column system the limits for the application of the pure core type of structures are enlarged.

There are three main types of structural systems to be distinguished:

- the core combined with hinged slabs and columns

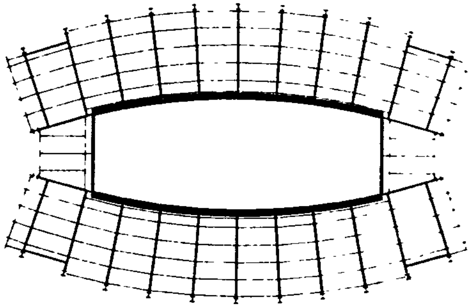
- the core combined with a floor-column-frame

- the core combined with an outrigger /belt truss structure in addition to the usual floor and column arrangements.

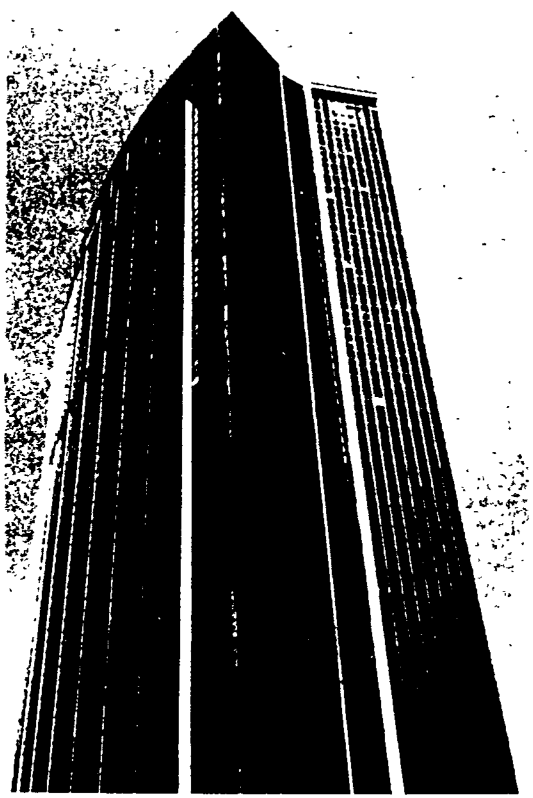


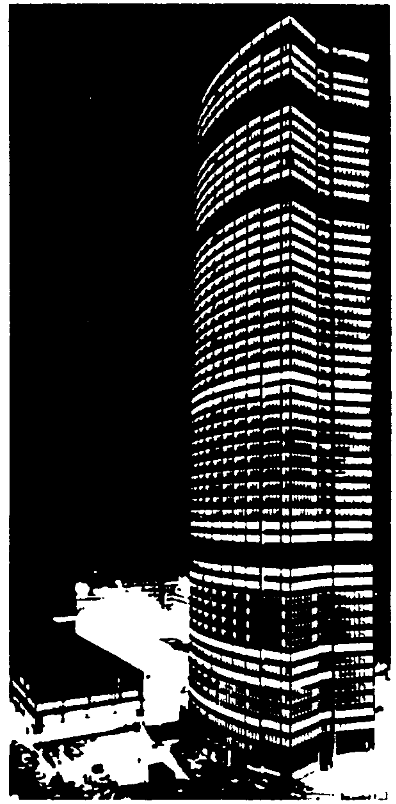
The most simple system is the combination of a core connected with the columns by hinged slabs. Here the columns are carrying vertical loads only. Compared to the pure core type structure the area of the single floor may be enlarged but total structural height is also limited to about 40 stories because stiffness against horizontal loading is not increased.

A lot of buildings has been designed using this structural principle. Especially a huge number of buildings up to the 30-story range.



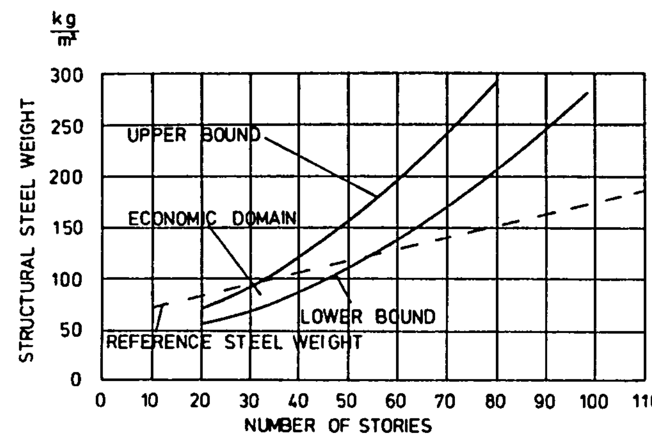
Tour Montparnasse





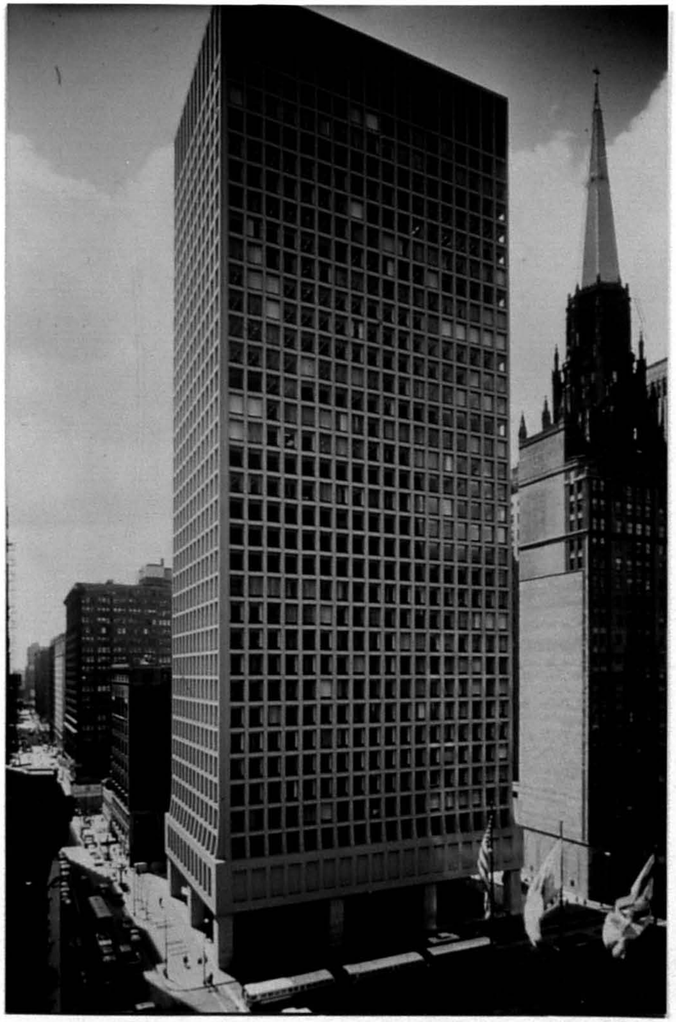
The 59-story Tour Montparnasse (a: Beaudoin, Cassan, De Marien, Sabout e: Epstein & Sons, 1971-1973, Paris) is mentioned here as an example. The building has an interior concrete core, perimeter steel columns and steel girders connecting the core and the columns. The floor structure is a lightweight steel decking with poured-in-place reinforced concrete. Structural steel is 60.3 kg/m^2, reinf.steel is 25.9 kg/m^2, concrete is 385 kg/m^2

Combining the core and a rigid frame structure is a more powerful instrument to increase structural efficiency. 55 stories seem to be possible and economic. Hereby the plan size of the core as well as frame stiffness are the determining factors: There is a smooth transition to the tube-in-tube type structure if frame rigidity is increased.

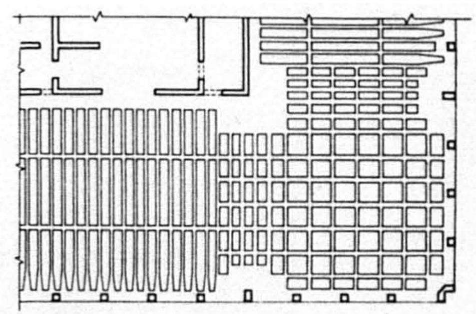


FRAME WITH SHEAR TRUSSES

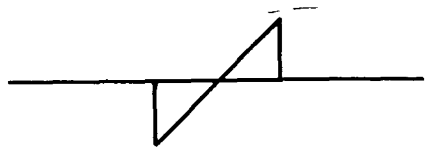
BY IYENGAR



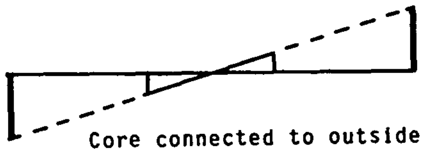
A very well known example for a core/external frame structure is the Brunswick Building.
The 38-story Brunswick Building (a/e: SOM, finished 1962, Chicago) was the first major-sized building in Chicago to be built after the Prudential Building. An exterior frame with columns 9ft 4in centers is linked by the floor structure to the core's shear walls thereby reducing the buildings drift from 13 inches for the pure core system to only 3 inches for the coupled core/exterior frame structure. (Under maximum wind loading)./13/.
The floor framing is a one-way joist system (38 ft free span) except for the corner areas of the floor which are a two-way waffle slab. It is easy to see that the columns at the transition between the two floor systems are loaded more, therfore they were made deeper. This structural peculiarity is not expressed on the outside of the building.



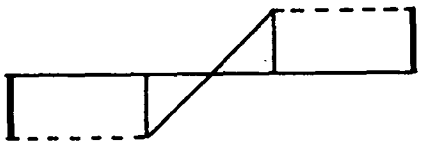
Stress distribution in core and exterior columns due to wind loading



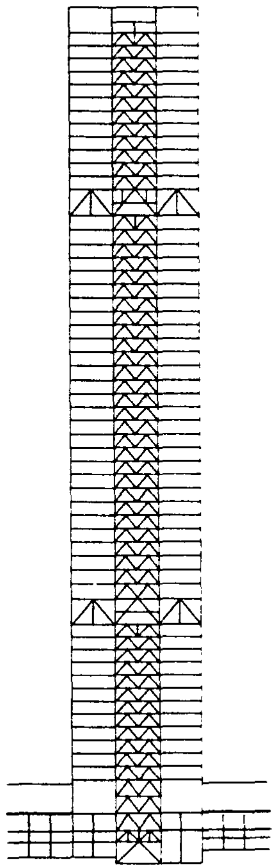
Core alone



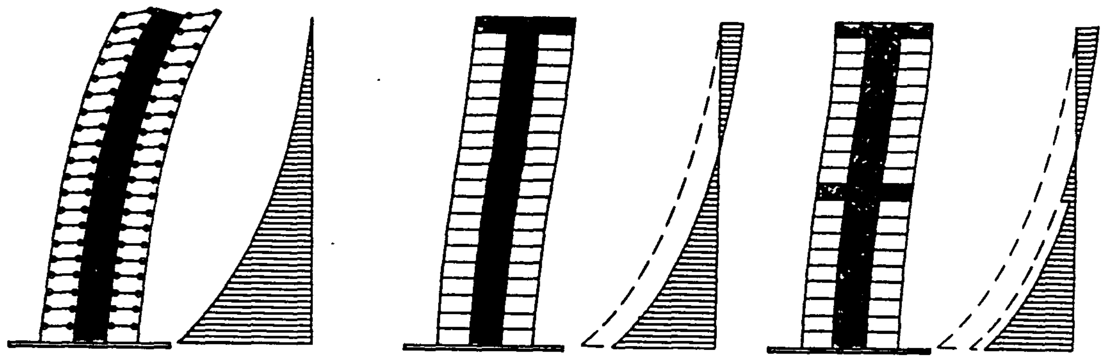
Core connected to outside columns by rigid arms

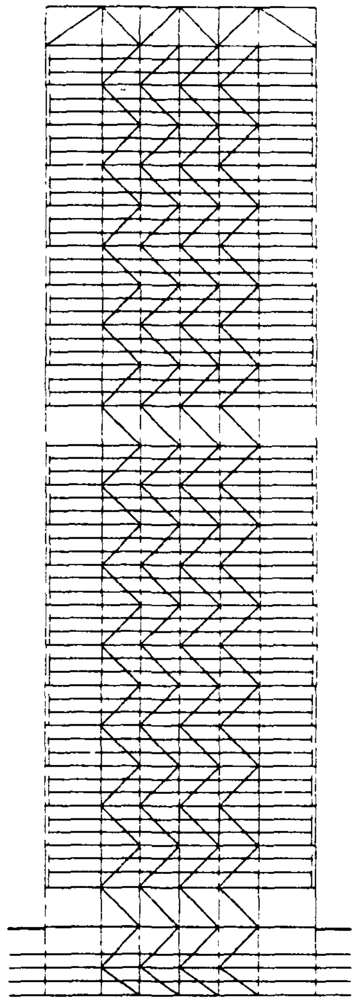


Core connected to outside columns by elastic arms



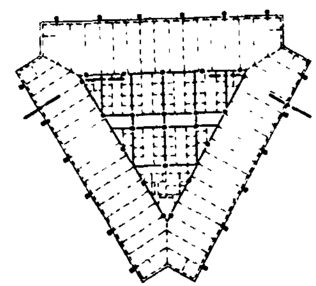
For buildings higher than 50 stories the core/ rigid frame combination becomes inefficient because of the increasing amount of steel necessary to limit lateral drift caused by wind loading. Effectivity may be obtained for structures up to the 65 story range by tying the core to the exterior columns with belt trusses. "The belt trusses, working as lever arms, throw direct axial stresses into the exterior columns. When the shear truss tries to bend, the exterior rows of columns act as struts to resist this movement. These belt trusses can be used not only at the top of the building, but midsection as well, increasing the stiffness of the building by 30 per cent."/13/. The loading of the core and the column is defined by the stiffness of the belt truss as it can be seen using the figures on the left side.

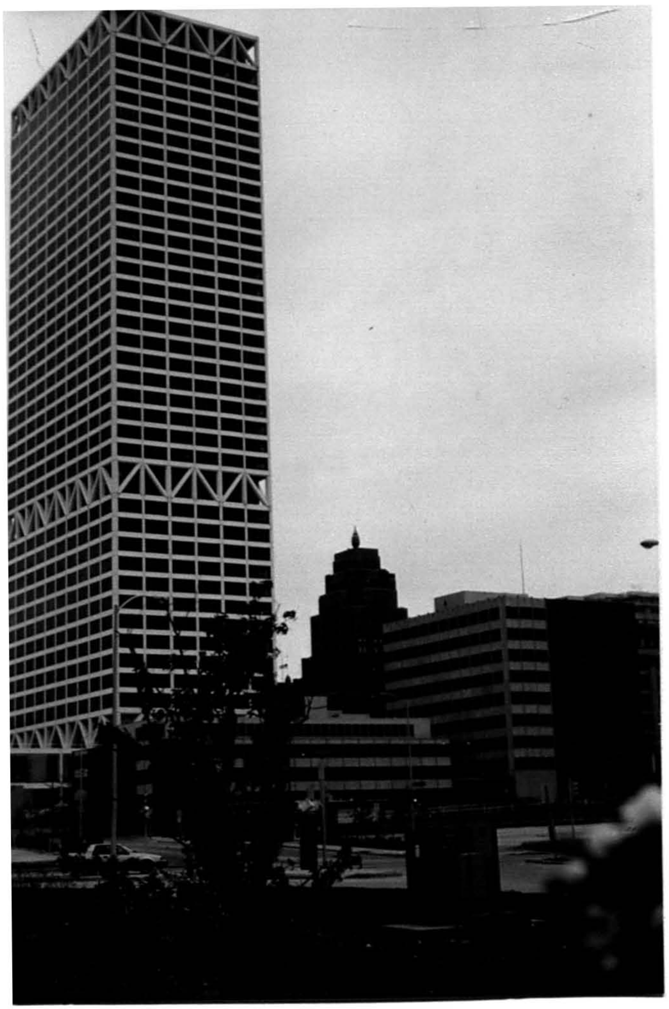


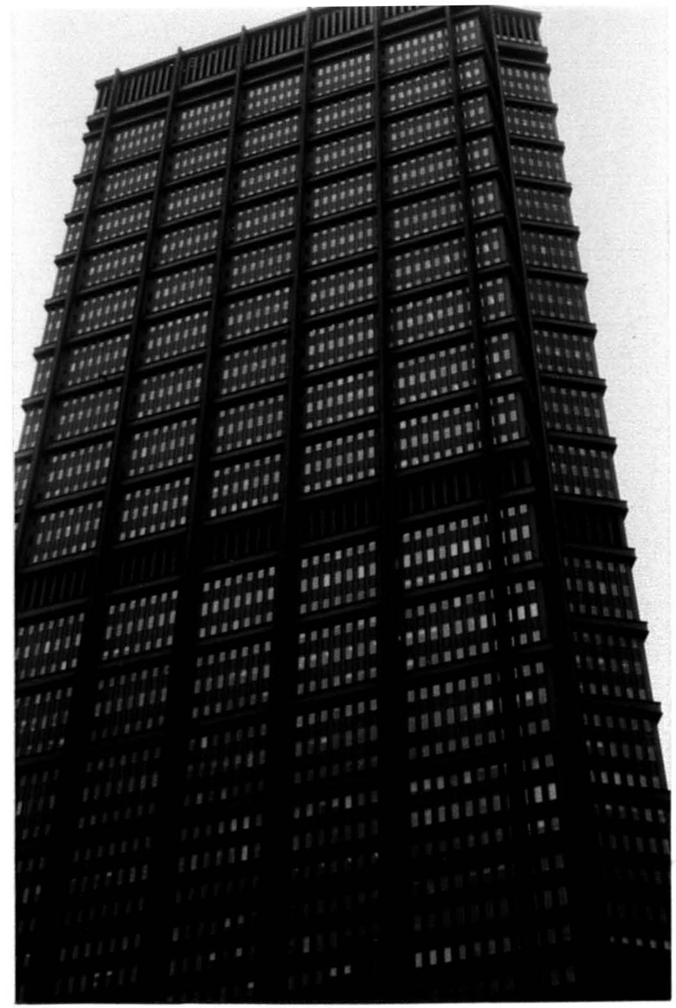


Using the structural system mentioned above, the 51-story I.D.S. Tower (a: Johnson/Burgee, e: Severud, Perone, Coulin, Bandel, Minneapolis) could be built with remarkable 17 lb per sqft structural steel /25/. Another core/outrigger-belt-truss structure is the 42-story First Wisconsin Center (a/e: SOM, Milwaukee). Here not only belt trusses are "used at mid-height and at the top, but a truss at the bottom is used as a transition member to collect column loads" /13/ because of the doubled column spacing at the ground level.

Last not least the U.S. Steel Building (a: Harrison, Abramowitz,Abbe, Pittsburgh) should be mentioned. Here the triangular core is designed as a steel truss cantilevering out of the ground with a height of 256 m. The U.S. Steel Building has an outrigger truss at the top of the building, tying the core and the exterior columns together. The exterior hollow box columns are filled with water, a part of the fire safety system of the building. /32/.



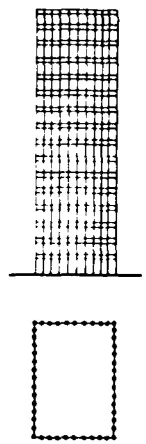




8 FRAMED TUBES

8. FRAMED TUBES

The highest efficiency of a slender structure cantilevering out of the ground is obtained by designing the structure as a hollow box with additional horizontal stiffeners. Looking at the history of highrise buildings it took a long time to remember this basic principle of the theorie of structures and to develop a solution satisfying structural as well as architectural aspects.

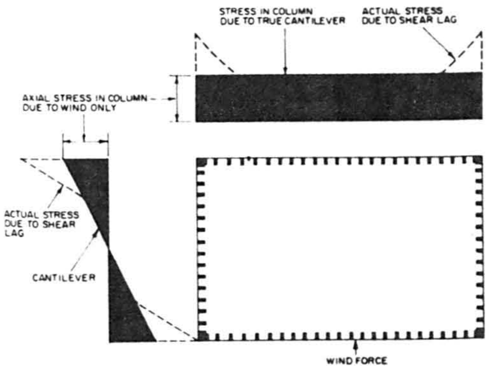


Materializing the facades plane, providing the necessary window area and using the floor structures as the stiffening elements led to the perforated or punched tube concept at first. Further development of the idea and the wish to keep up the rectangular window size ended in a type of structural system called "Framed Tube":

The behavior of a tube is simulated by very closely spaced exterior columns connected together by deep perimeter spandrel beams at each floor.
Column spacing is generally from 4 to 10 ft. Depending on the overall system of the building column spacing can be increased up to 15 ft. The spandrel beams usually vary from 2 to 4 ft depth.

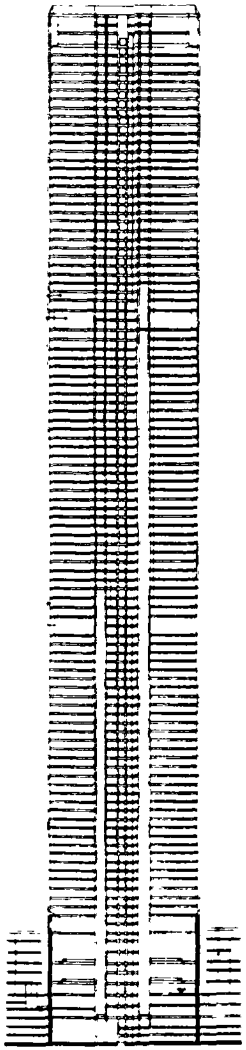
Because of the rectangular column-beam-net rectangular window shapes are possible. Hereby the opening size in a frame tube structure usually is up to 50% of the wall surface.

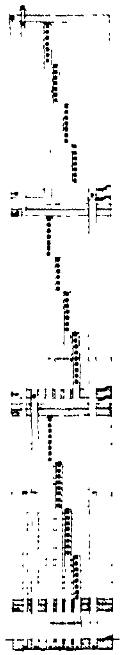
The 43-story Chestnut-De Witt appartment building (a/e: SOM, finished 1963, Chicago) was the first highrise building designed by using the framed tube concept. The concrete structure has closly spaced columns with 5 ft 6 in centers all around the perimeter which are connected at each floor by continuous 2 ft deep perimeter spandrel girdes.



The efficiency of framed tube structures drops off in buildings taller than about 50 stories in concrete and about 80 stories in steel because of the so called shear lag phenomenom: under horizontal loading, the faces parallel to the load direction tend to act as multi-bay rigid frames. As a result, the columns in the corner areas take much more load than expected under the assumption of pure cantilever action and: they take much more load than the columns in the middle of the "flanges". Bending moments in the columns and edge beams this way become the controlling factor in structures higher than the mentioned limits. /13/.

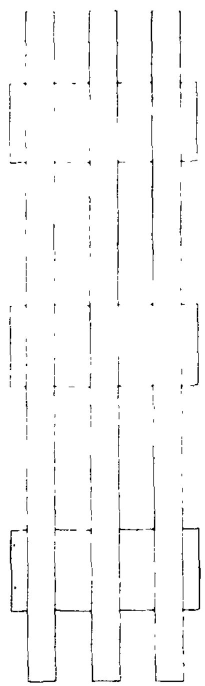
If tube efficiency is defined as the ratio of the cantilever portion of the deflection (due to column shortening only) to the total lateral deflection of a building, today it is possible to design structures with a tube efficiency in the range of 60% to 80% /53/.

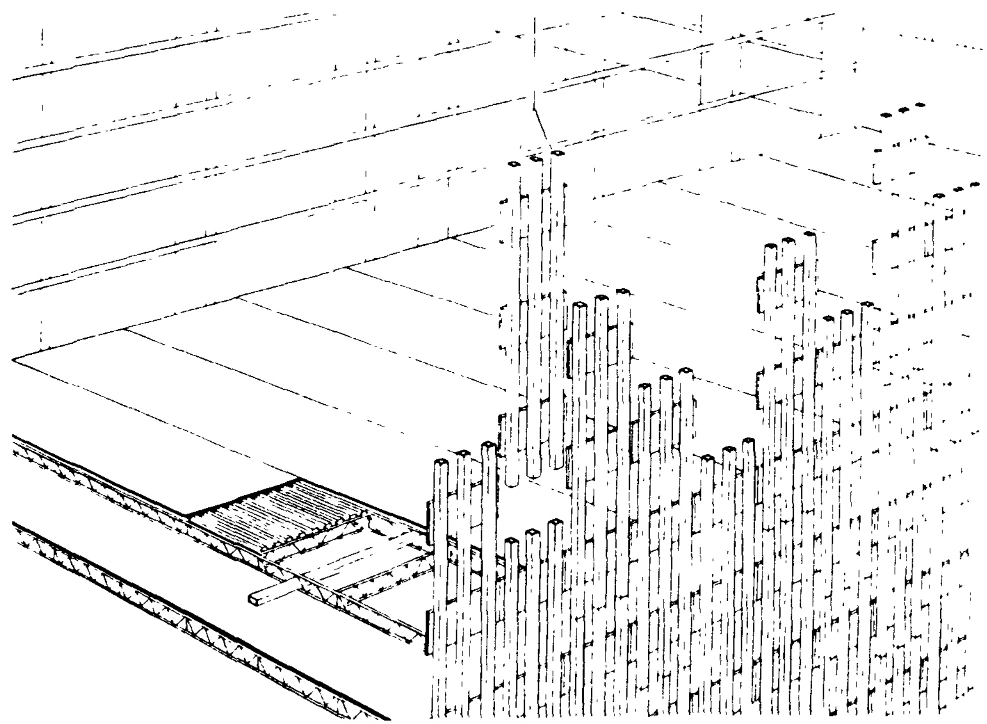


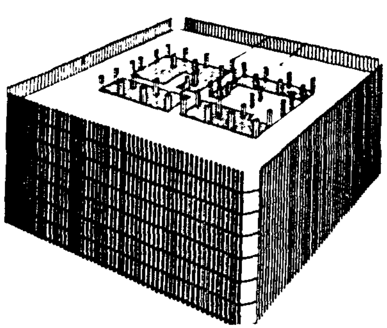


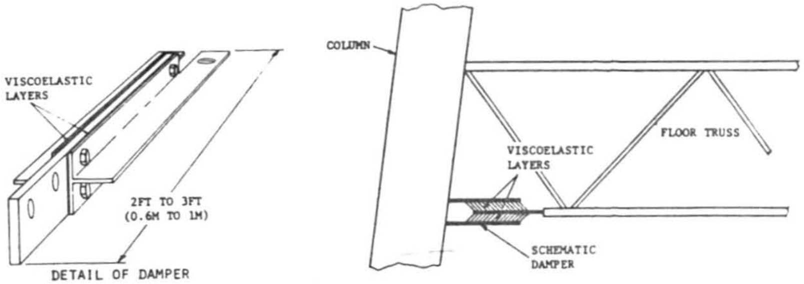
The 110-story World Trade Center (a: Yamasaki & Ass., e: Skilling, Helle, Christiansen, Robertson, 1966-1973, New York City) is the highest single cell perforated tube structure built up to now. The perimeter is designed as a Vierendeel-Truss-Net. Exterior hollow box columns are 1.02 m centers. With a height-to-with ratio of 7:1 the limits of structral possibilities have been reached, also because the simple geometrical shape of the two towers was not ideal from the standpoint of the windload problem. To avoid that buildings motions caused by windloading would exceed a limit acceptable by the occupants, approximately 10 000 dampers were installed in each 110-story tower. /41/.

These dampers are "composed of three steel elements, two 4-by 4-in. tees and one 1/2 in. by 4-in. bar between







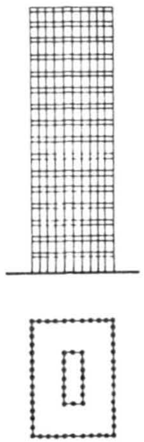


VISCOELASTIC DAMPER AS USED IN THE WORLD TRADE CENTER

which are sandwiched two viscoelastic layers - 0.05 in thick by 4 in. by 10 in.. These layers are epoxy bonded to the steel. One end of the bar extends beyond the bonded area for attachments to the bottom chord of the truss while the coped ends of the two tees extend in the opposite direction for bolting to a seat on the column"./41/.

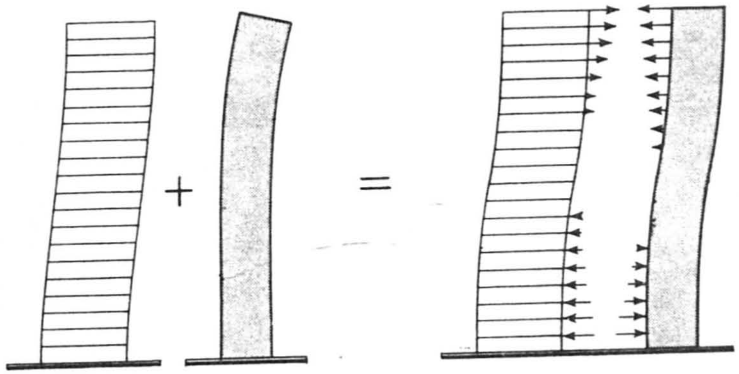
Structural steel for the World Trade Center is 186,6kg/m.

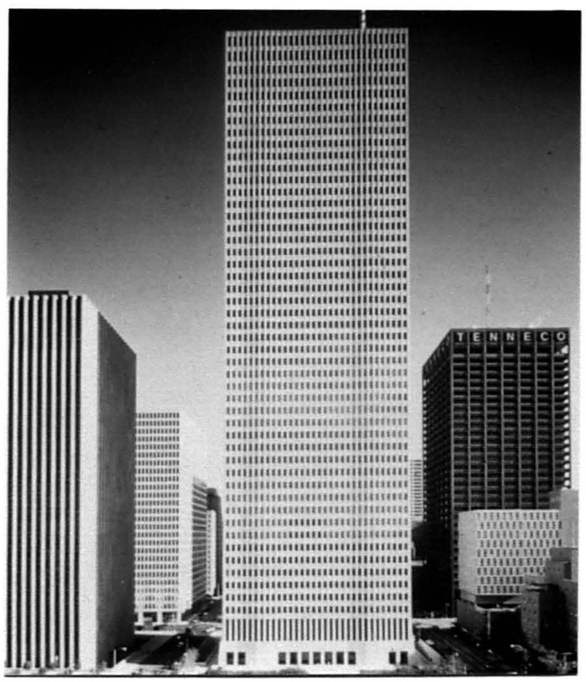
Basic principles of structures show that for a highrise building structure it is not necessary to provide the same high level of stiffness against lateral loading in the upper stories like in the lower ones: Spandrel beams as well as column size may be decreased in the upper stories and the stiffness of the beam-column connection may be reduced. Additionally the size of the "column-spandrel beam-net" may be increased. These facts may yield in an architectural expression, as for example in the Olympia Center (a/e SOM, compl. 1985, Chicago).



TUBE IN TUBE

Structural efficiency of a single-cell framed tube system may be increased by designing the service core as a structural element, as well. Especially in tall office buildings the dimension in plan of the service core usually is large enough to allow the design of the core as an efficient tubular structure itself. The resulting structural system, an exterior and an added interior tube, is called a "Tube-in-Tube" system.

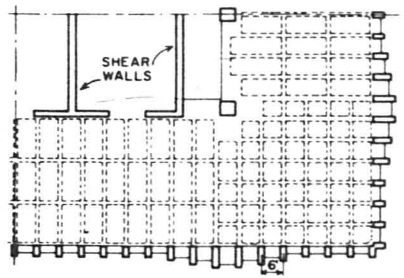




The floor structure ties both tubes together, they respond as a unit to lateral loading: While the exterior tube is usually acting like a very stiff frame, the interior tube usually shows the behavior of a shearwall or core. Therefore "the exterior tube resists most of the wind in the upper portion of the building, where as the core carries most of the loads in the lower portion"./3/. By tying them together structural efficiency is considerably increased. The tube-in-tube system seems to be economic up to the range of 80 stories for steel and 60 stories for concrete structures. One of the advantages of this type of structures is that shear lag of the exterior tube is considerably reduced. Another advantage is the possibility of creating a large, column free office space by carrying all vertical loads through the floor structure to the exterior and the interior tube. Column-free span or the distance between interior and exterior tube hereby is in the range of about 35 to 40 ft..

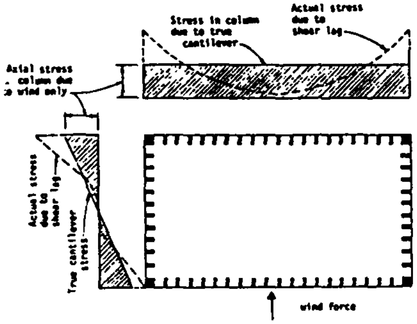
While designing a tube-in-tube system it should be considered that the inner tube should be placed at the centerlines of the outer one. Torsion loading of the structure caused by wind loading than is effectivly reduced.

One of the first structures designed as a tube-in-tube system was the 52-story One Shell Plaza Building (a/e: SOM, compl. 1969, Houston). Until the completion of Water Tower Place in Chicago in 1977, One Shell Plaza was the tallest concrete building in the world. Today it remains the tallest light-weight concrete building. In the One Shell Plaza, "as with Brunswick, one-way joist system was used, in this case spanning 40 ft. from exterior to core; columns were placed 6 ft. apart. The corners are a two-way waffle slab, and again, as in Brunswick, exterior columns near the corner of the waffle are more heavily loaded by gravity than the other columns.

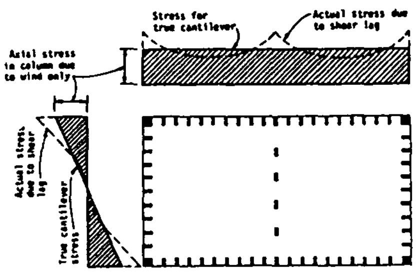


But, in contrast to Brunswick, these columns get gradually deeper, the additional depth is allowed to project out from the face in the building, and this gravity-load-carrying picture is expressed "plastically" in the building's exterior. In further contrast to Brunswick, the base of the building is pierced by much smaller openings, and the bold, massive base itself gathers up the columnar loads."/13/.

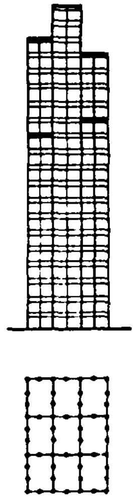
Plan shape of One Shell Plaza is 192 ft. by 132 ft, height is 715 ft. Width to height ratio is 1:5.4.



SHEAR LAG IN FRAMED PERIMETER TUBE



SHEAR LAG IN BUNDLED TUBE



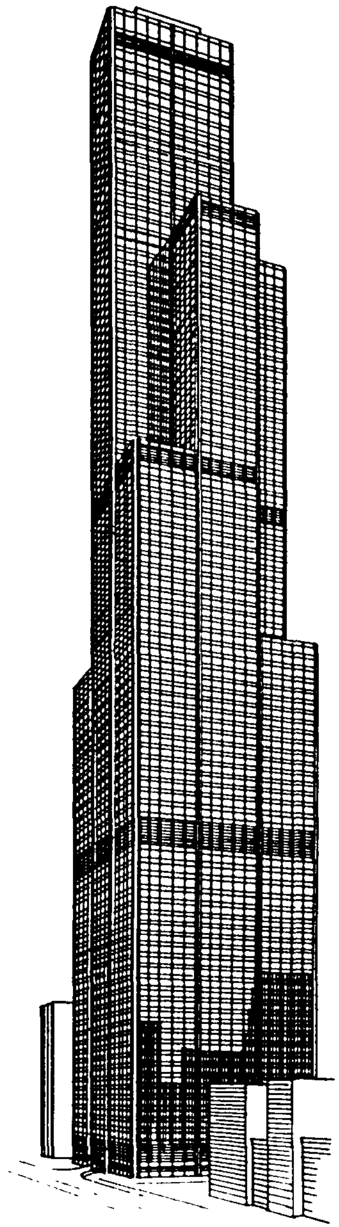
BUNDLED TUBE

Besides the tube-in-tube principle, the introduction of vertical diaphragms is a possibility to increase tubular efficiency:

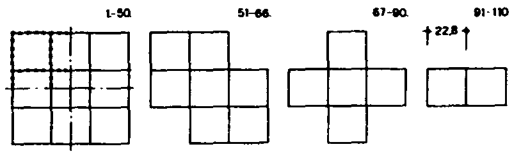
By adding additional webs, usually designed as a column-beam-net, shear lag may be decreased efficiently and stiffness against lateral loading is increased. Structures designed this way look like an assemblage of single framed tubes and are called "bundled-tube" structures therefore.

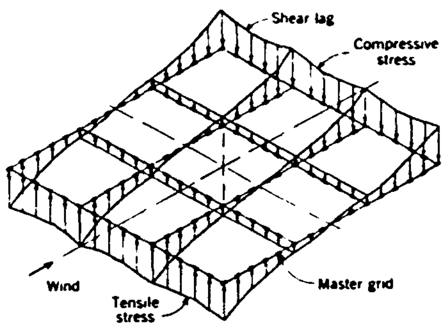
The figure on the left side shows a stress distribution diagram of a 2-cell tube under wind loading. It is easy to see that the added diaphragm parallel to the wind (web) is transferring forces into the intersection area with the perpendicular wall (flange), thereby creating peak stresses at the intersection line with the flange. Compared to the stress distribution of a (single-cell) framed tube, one can see how the introduced diaphragm minimizes the shear lag of the exterior tube and how it also contributes strenght against bending. The deviation of such a multicellular structure from ideal tubular behaviour, indicated by the broken lines, does not seem to be very significant.

The bundled tube principle used for steel buildings makes it possible to erect buildings up to the range of 110 stories./15/. Using concrete, about 75 stories seem to be possible and economic./3/. To create an optimal structure, a column spacing in the range of 15 feet is not to be exceeded and also a certain relationship between column and spandrel stiffness is necessary. See /15//27/ for details. Structural steel quantity is in the range of 160 to 200kg/m.



Chicago, Sears Building 1972/74





Drawing shows tension and compression in columns due to wind forces. In this building not only exterior frame but also interior columns work together to resist wind forces. Full-width rows of interior columns reduce "shear lag."

The Sears Tower (a/e:SOM, complet.1974, Chicago) was the first highrise building designed as a bundled (framed-) tube structure. Sears Tower is the worlds tallest building and a good example for the high efficiency of the bundled tube principle. The 109-story, 442m high building contains a floor area of 409 000 m^2 and involves a daily user population of 16 500 people /22/. The basic shape is composed of nine single tubes. The tubes have a different height as a direct result of space requirement. The height of the single tubes is 50, 66, 90 and 109 stories. Each tube is composed of columns at 4.58m centers and deep beams at each floor. Columns and spandrel beams act together as a perforated/framed tube. All beam to column connections are fully welded. Horizontal load distribution is done by floors. "Floor areas are typically framed by one-way trusses of 75 ft. span at 15 ft. centers. Each truss frames directly to a column by means of high strenght friction bolts designed for shear only. The span direction of these floors is alternated every six floors to equalize the gravity loading on the columns. The trusses are 1.02m deep and utilize all the available depth in the space between ceiling and floor slabs above."/22/.

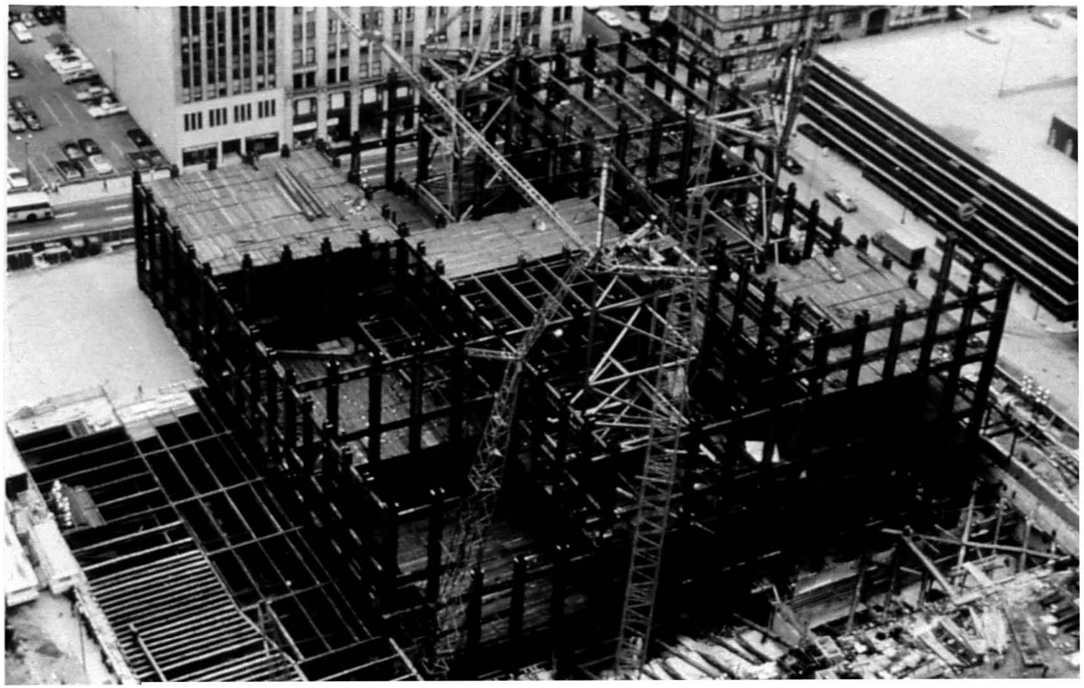
"Trussed levels, consisting of diagonal members between columns, are provided at the intermediate mechanical levels - two immediately below the setbacks at the 66th and 90th floors, the third at the 29th-31st floor mechanical level. The trussed level serve three purposes:

1. The large gravity force concentrations that occured in the members at the setbacks were relieved.

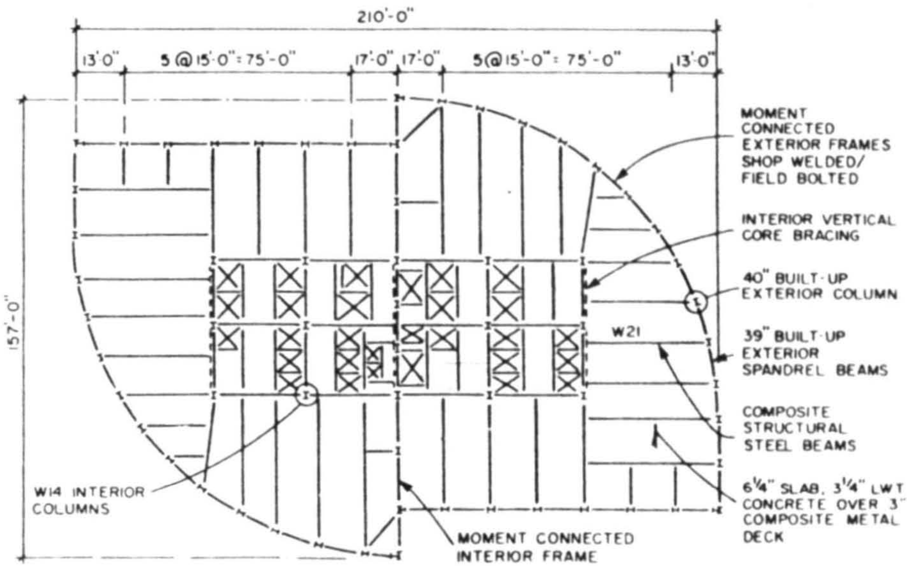
2. The differential column shortening, due to gravity and wind forces, was reduced especially at the setbacks.

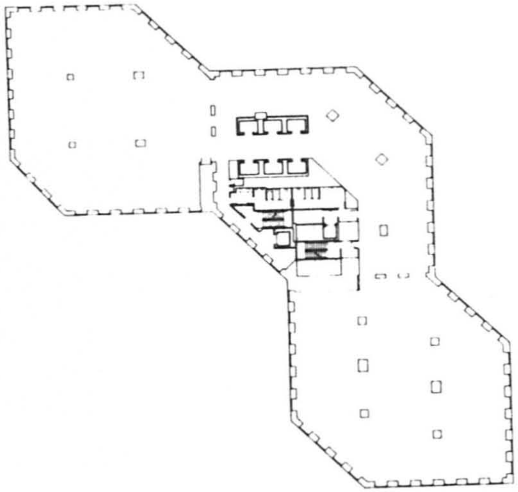
3. The overall lateral stiffness of the framed tube was increased by approximately 15%"./22/.

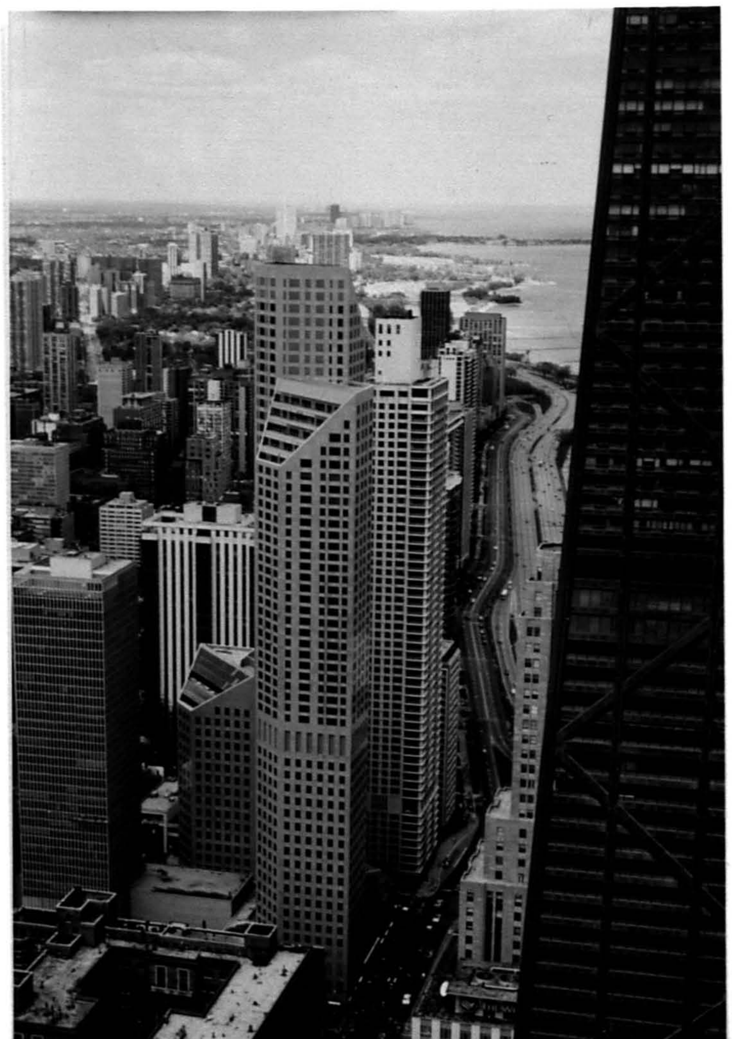
Structural steel quantity is 161 kg/m . Wind sway is about 7.62mm per story for the design wind pressure /12//22/. Fundamental natural period is 7.6 seconds./22/.



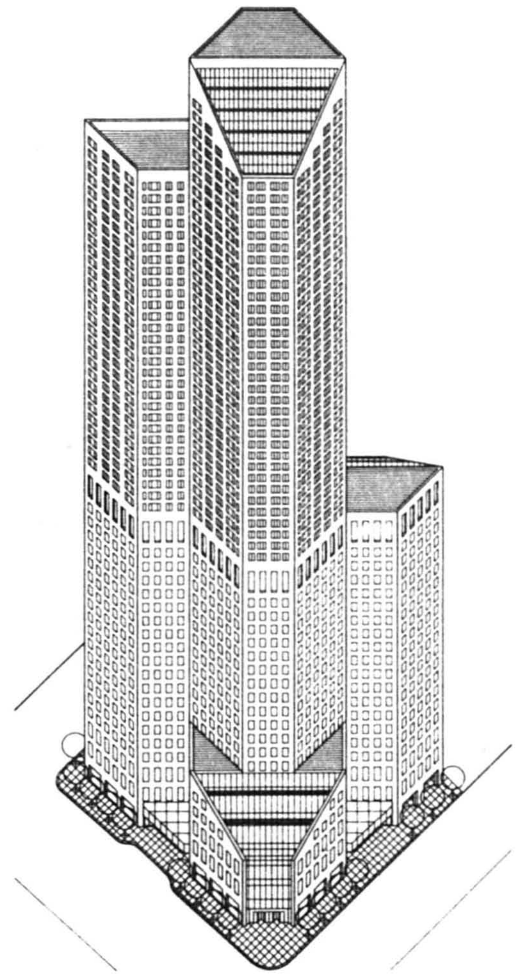
The 71-story Allied Bank Plaza Building (a/e: SOM, compl. 1984, Houston) is one of the most sophisticated structural systems using the bundled tube principle. Each of the two tubes is a quarter circle in plan. The two tubes are joined by an integral wall on the flat side of each quarter circle. A belt truss circles the entire perimeter between levels 34 and 36. Two outrigger trusses, running parallel to the integral wall, join the belt trusses and the rectangular core together. Linked this way, tubes and core act together to resist lateral loading. The structural steel quantity for the Allied Bank Plaza Building is 128kg/m.

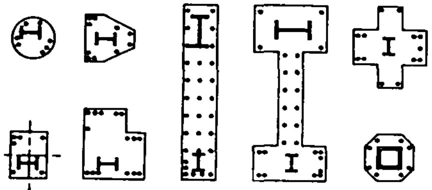




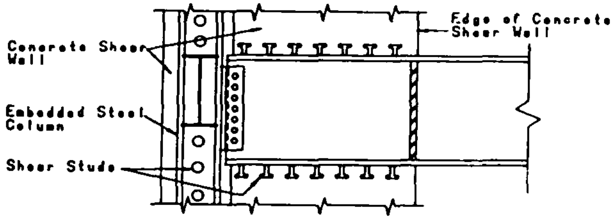


One Magnificent Mile (a/e: SOM, compl. 1974, Chicago) is an example for a bundled tube type structure realized in reinforced concrete.





Composite Column Sections



Steel Link Beam Embedded in Concrete Shear Wall

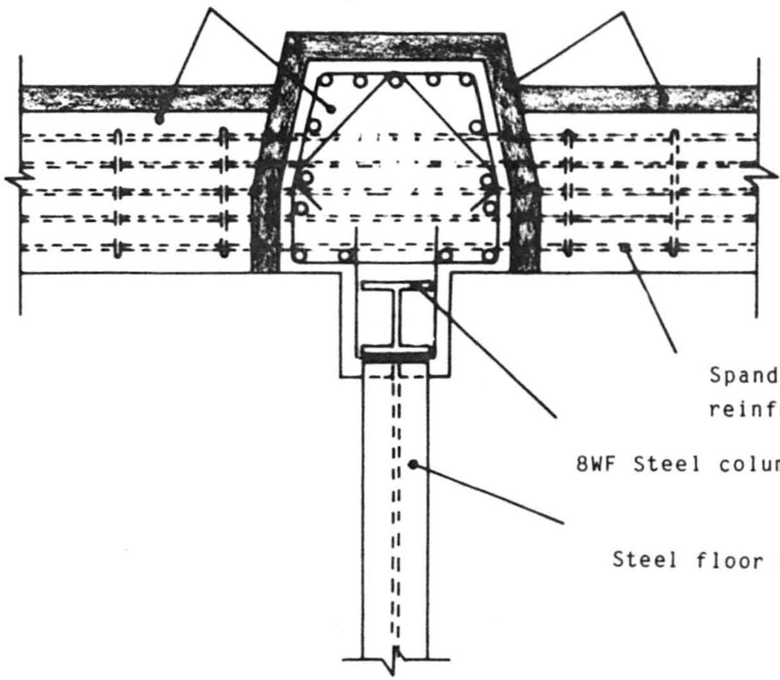
A very interesting evolution of the tubular structure type was caused by the introduction of the so called "composite system".

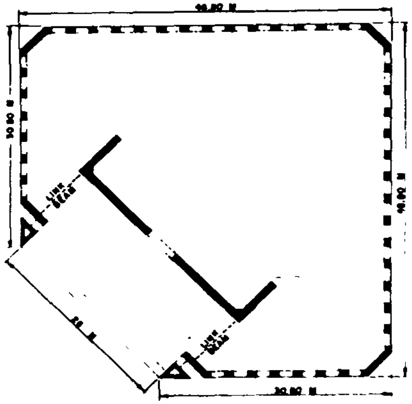
Composite system means the replacement of an all-steel or an all-concrete structure by a system using the advantages of both: At first a steel frame is erected. The exterior columns of this steel frame are much more smaller than if the frame would be constructed entirely of steel. Using this steel structure allows a very high construction speed, thereby providing rapid working-level platforms at each floor for other trades, such as HVAC, electrical and plumbing. Construction of the slabs in the upper stories is going on while in the lower stories the concrete frame is erected. Load transfering between structural steel frame and concrete frame normally is done by using standard shear studs.

Other advantages of the composite system are: Rigidity of steel is 5-7 times than rigidity of concrete per unit volume, but costs are 20-30 times than costs of formed-in-place reinforced concrete. Using composite systems therefore helps keeping the costs of the structure down. Concrete structures and therefore composite structures too are more rigid than pure steel structures. "A steel building tends to move under wind loads a lot more. In tall buildings, a key design problem is to reduce the amount of building deflection due to wind load, so that cracking of ceilings, windows, etc. doesn't become a problem and so inhabitants don't become seasick"./14/.

However, two main problems have to be solved when using composite structures: The first is the increasing of the building's dead-load. "The dead load of a concrete building is at least double that of a steel building (but the overall weight, including liveloads, would be only 30 to 40% more than the weight of a steel building)"./14/. This effect requires higher foundation costs. The second problem to be solved is the problem of construction time. Composite structures are only competitive when able to be erected nearly as fast as an all-steel building. For example, a proposed composite structure for the Dallas Main Center which costs 10 Mill. $ less than the chosen one had no change for application because of 7 month more of construction time./21/.

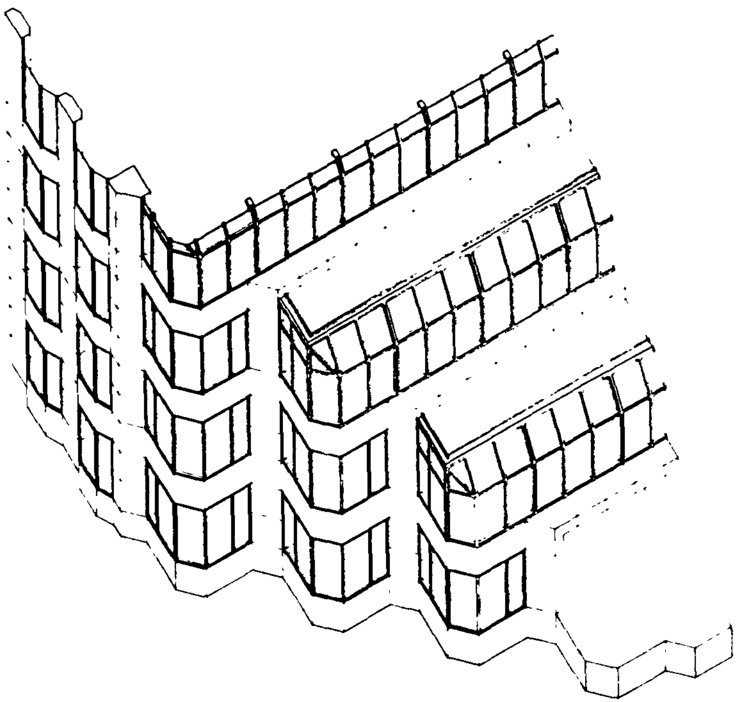
In the meantime, very fast going formwork has been developed and a number of buildings using the composite system had been erected:
The first building in the United States to mix concrete and steel in its frame was the 2o-story Control Data Building (a/e: SOM, compl. 1969, Houston).
Here a precast skin was used as a left-in-place formwork.

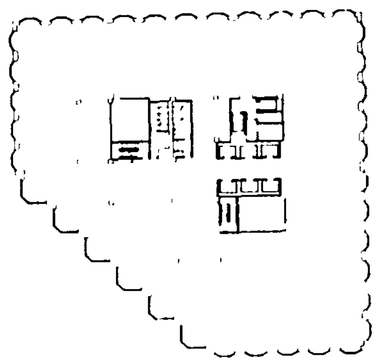




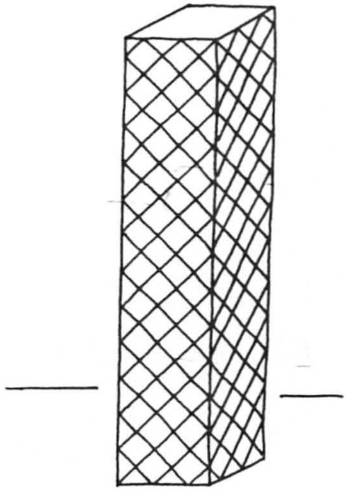
The Texas Commerce Tower in Houston (a: Pei, e: Colaco, compl. 1982, Houston) is the worlds tallest exterior composite building. The 75-story building's structure is an exterior tube with an interruption on one side of the building. Therefore a concrete core was introduced.

The Three First National Plaza Building (a/e: SOM, compl. 1981, Chicago) is another example for an exterior framed tube using the composite method. The columns of the 57-story building are spaced at 4.53m centers. During construction, the steel frame was erected 12 stories in advance of the exterior concrete frame. "The structural steel frame was stabilized during erection by a temporary system of diagonal bracing. The typical sequence of construction had the erected steel frame four floors in advance of the metal deck placement which was four floors in advance of the completed composite concrete floor slab, which was four floors in advance of the completed exterior reinforced concrete frame. To keep pace with the steel erection,the formwork for the exterior concrete frame utilized steel gang forms with a semi-automated hydraulic form handling system."/20/.





9 DIAGONAL TRUSS TUBES

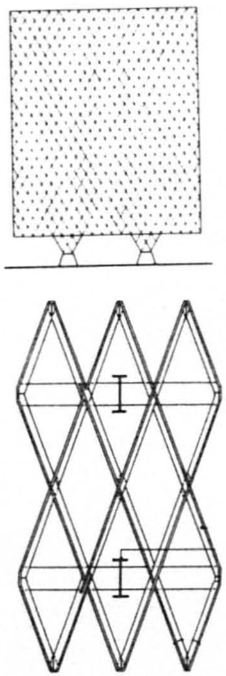


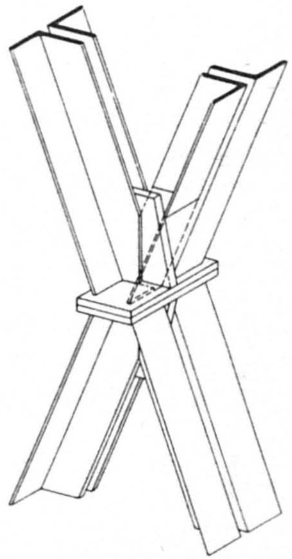
9 TRUSS TUBES

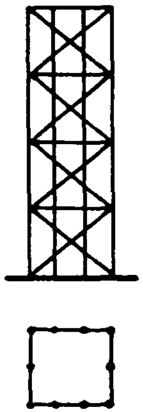
It was mentioned that a single-cell framed tube structure becomes inefficient if the building's height is more than 80 or 90 stories. The inefficiency is caused by the shear lag phenomenon. The methods discussed up to now to avoid or to minimize the problem were the introduction of the tube-in-tube, the bundled - tube and the partially-stiffened framed-tube principles.

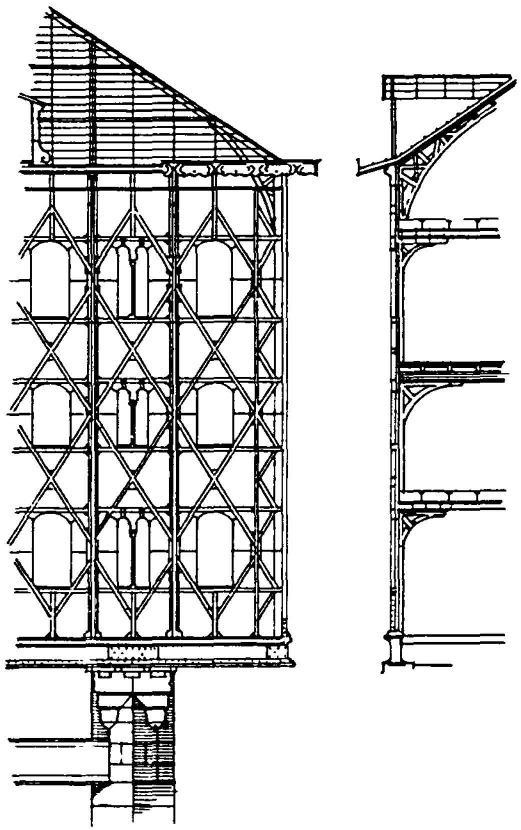
Obviously the highest efficiency under lateral loading is obtained by designing the exterior tube as a network of closely spaced diagonals. This type of stucture is called a "diagonal-truss-tube".

The somewhat not to high 13-story IBM Building (a: Curtis and Davis, e: Worthington, Skilling, Helle and Jackson, 1962-63, Pittsburgh) is an example, especially for the resulting architectural expression.







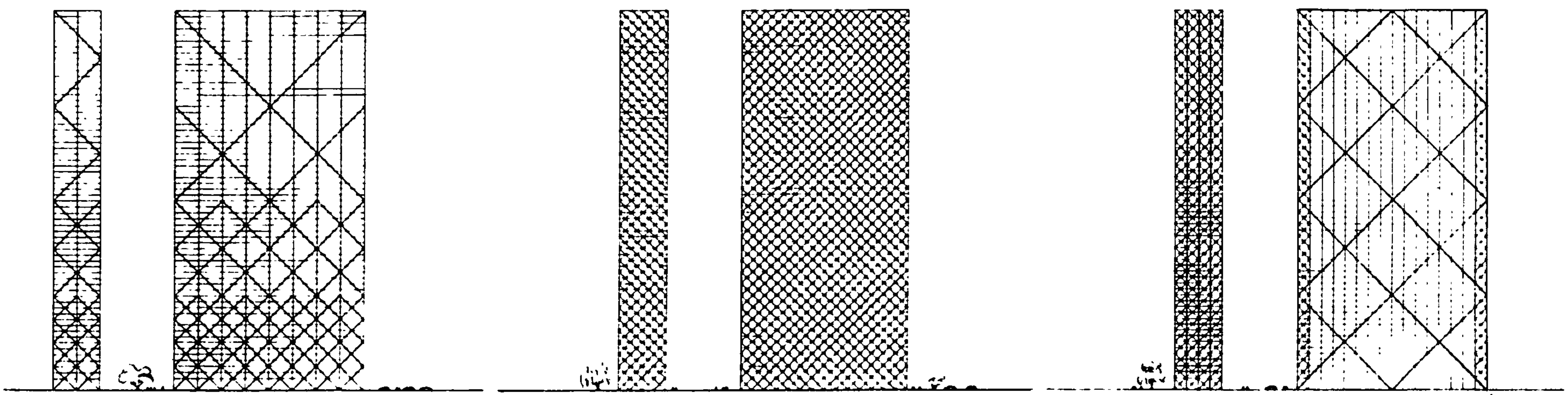


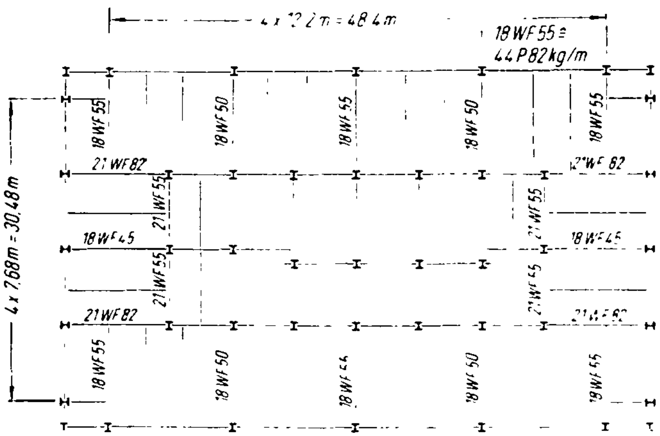
Architecturally, application of the diagonal truss tube principle "means re-arranging the entire concept of window wall details. But an even more important factor which may substantially increase the overall costs of this system is that the perimeter mechanical supply is considerable more complicated. Also, from a construction point of view, large number of joints must be handled as in the "framed tube" system but because the diagonals system is much more rigid in the plane of the wall, adjustments during construction become extremly difficult."/28/

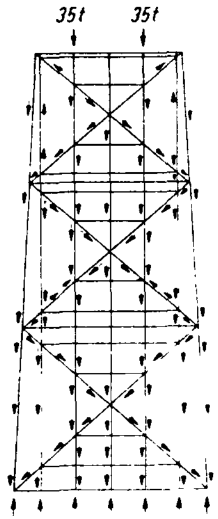
Due to these problems, a combination of the framed tube principle with the diagonal truss concept seems to be the optimum: Excessive number of joints as well as shear lag are reduced. The result is a structure with widely spaced columns, the usual type of spandrel/beams and a few diagonals: "Column-Diagonal-Truss-Tube". Hereby, at the levels where the diagonals intersect at the corners, it is necessary to provide a large tie-spandrel to limit horizontal stretching /28/.

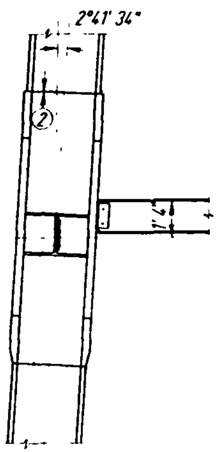
The 4-story Chocolate Factory Menier (a/e: Saulnier, 1871/72, Noisiel sur Marne) is one of the first buildings with an exterior frame stiffened by a net of diagonal elements.

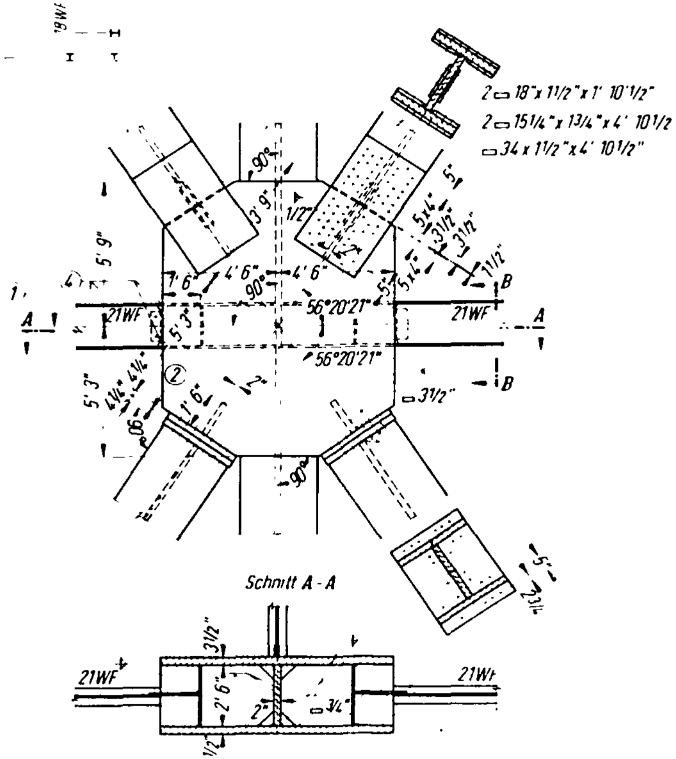
In 1953 Myron Goldsmith of SOM /10/ developed the structural principles of the exterior diagonalizing of tall buildings in general. He also was the first to study the architectural impact of this type of structures.







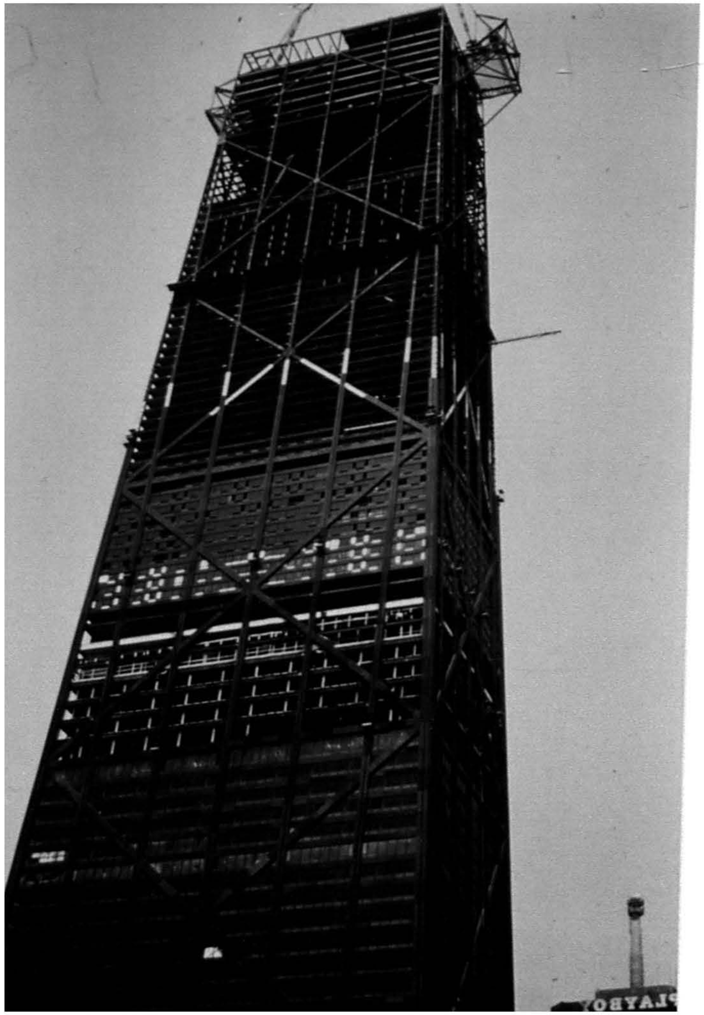


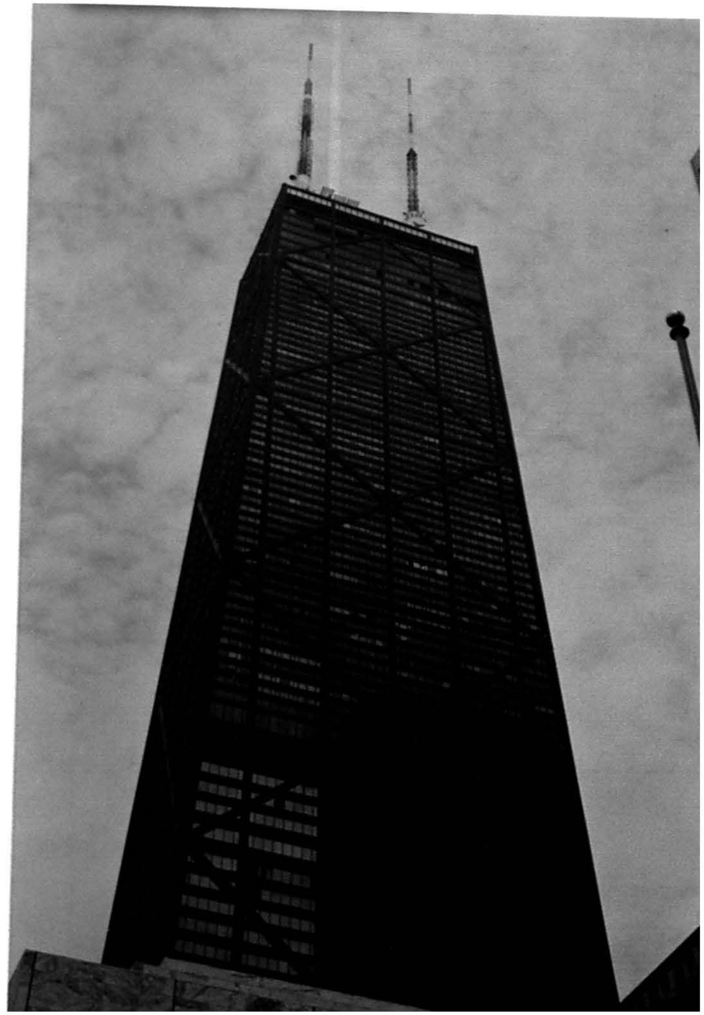


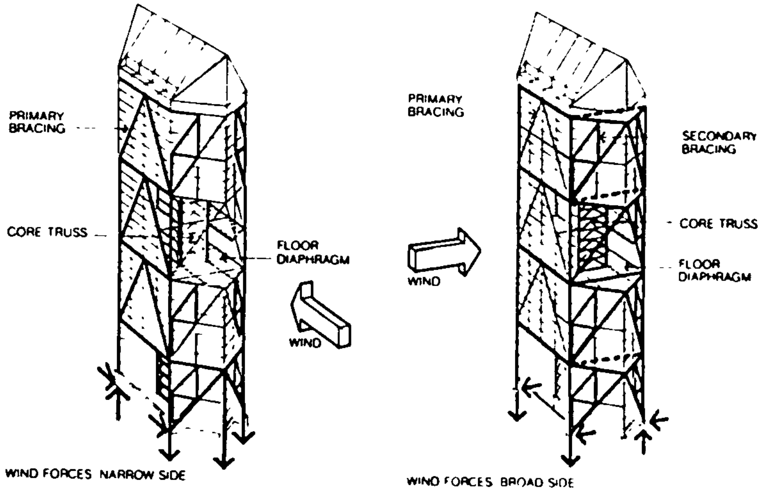
It was F. Khan together with B.Graham of SOM who developed and designed the breakthrough:

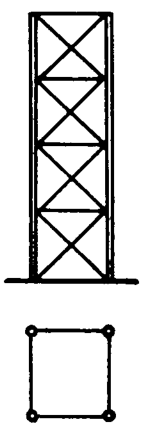
The 100-story John Hancock Center (a/e: SOM, 1970, Chicago) is an excellent example of a column-diagonal-truss-tube structure: Interior columns are designed for gravity loading only. The exterior columns, the diagonals, the main and the secondary ties (not very efficient!/30/) are forming a tubular structure. The structure is acting like a spatial truss. Therefore shear lag is efficiently reduced.
The remaining spandrel beams at each floor, which were not used as horizontal ties, were designed to satisfy the floor load requirements only.
The structural system, the floor layout and a typical intersection point of two diagonals is shown on the left.

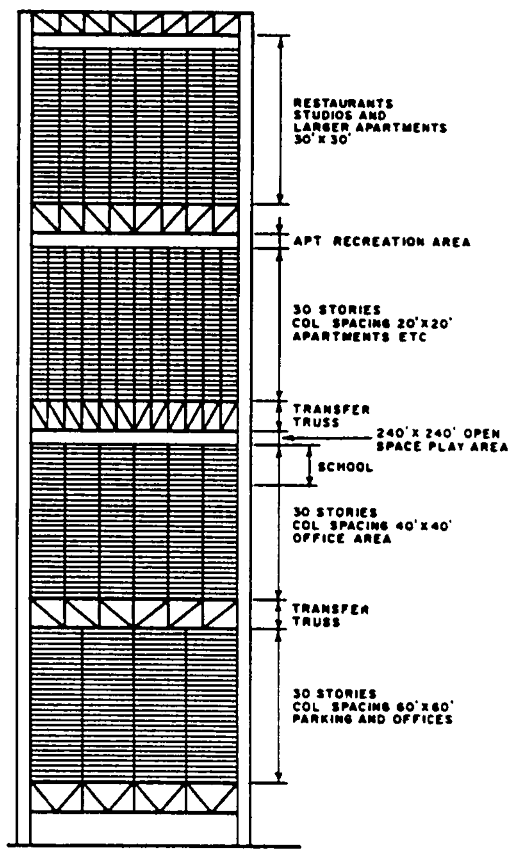
Structural steel is 145 kg/m .
The John Hancock Center is a multi-use building. From bottom to the top:
6 stories of shopping area, 6 stories parking area, 29 stories office space, 2 stories machinery and service, 48 stories appartments, TV studio, restaurant, observation deck and machine equipment at the very top of the building.





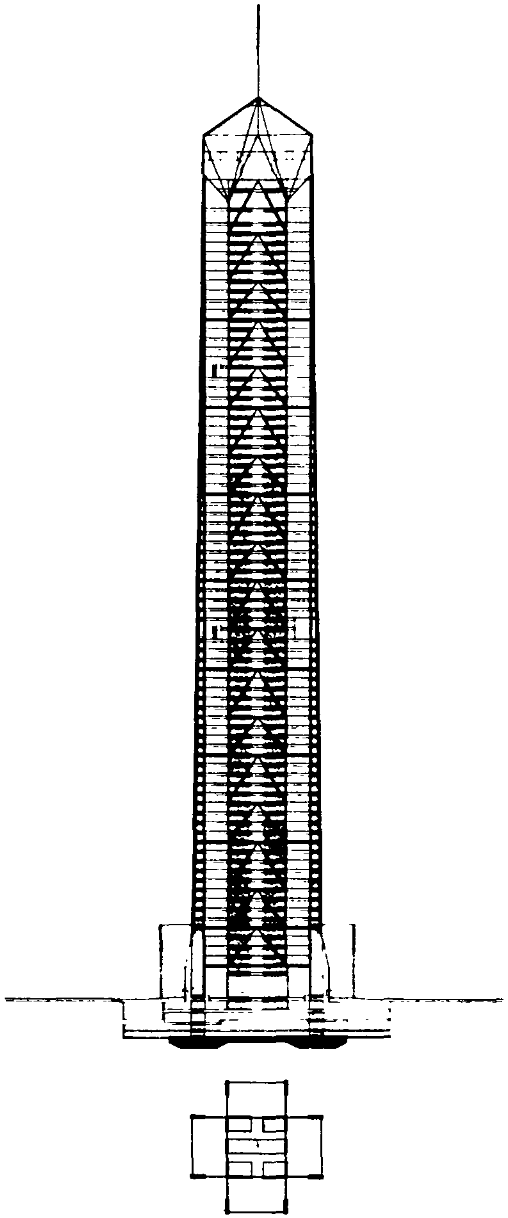






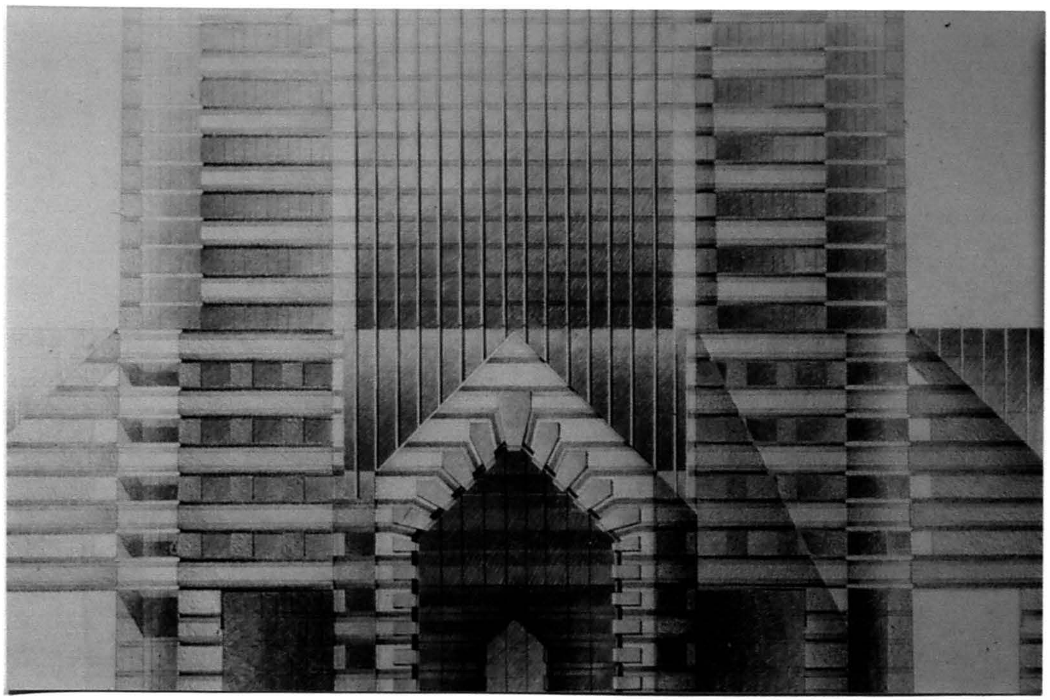
The Medical Mutual of Cleveland (a: H. Stubbins, e: Le Messurier, Cleveland) is an example for the combination of an exterior diagonalized (not visible from the outside) framed structure with a core structure at the center of the exterior tube. "The wind forces on the faces of the building are picked up through the floors at every level by the structure's trussed core. This core than acts like a continuous vertical beam spanning four floors. At every eight floor (one support of the beam), the floor diaphragm links the core directly to the major exterior truss. At every fourth floor (the next support point of the beam), the small-scale triangulations "see" the core load first and then translate the force back to the major triangulations through truss action."/7/.

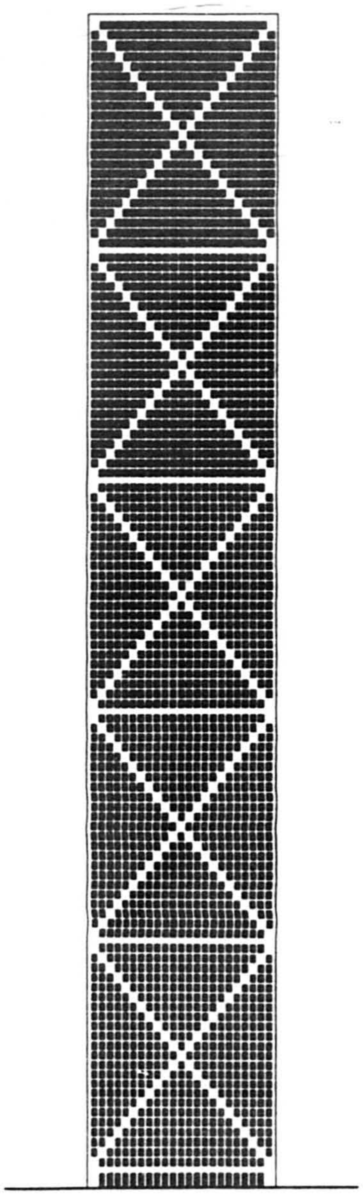
To increase stiffness against lateral loading as well as structural efficiency it is necessary to omit all the interior (only gravity-loaded) columns as well as the exterior columns between the corner columns of the building. The resulting structure is a "four-corner-column, diagonalized tube". This is the ultimate possible improvement of structural efficiency for tall buildings. The gravity loads of all floors hereby are transferred to the four corner columns by secondary systems. By spatial transfer trusses at every 20 floor,for example. At the four-corner-column type truss tube the corner columns are heavily loaded and therefore they have to be sized in a remarkable dimension: The corner columns should be designed as the service cores of the building. Because of their immense gravity loading and because of fire safety requirements the four corner columns should be designed as concrete tubes. The diagonals of the truss usually are tension and compression loaded, depending on wind directions. Therefore they can be designed very effectively as steel



members. The resulting structure is a mixed system: Corner columns made out of concrete, the diagonals as well as the secondary systems made out of steel.
For a width to height ratio not to exceed 1:7 and for usual plan dimensions the four corner column type truss tube seems to be economic up to the range of 150 stories.

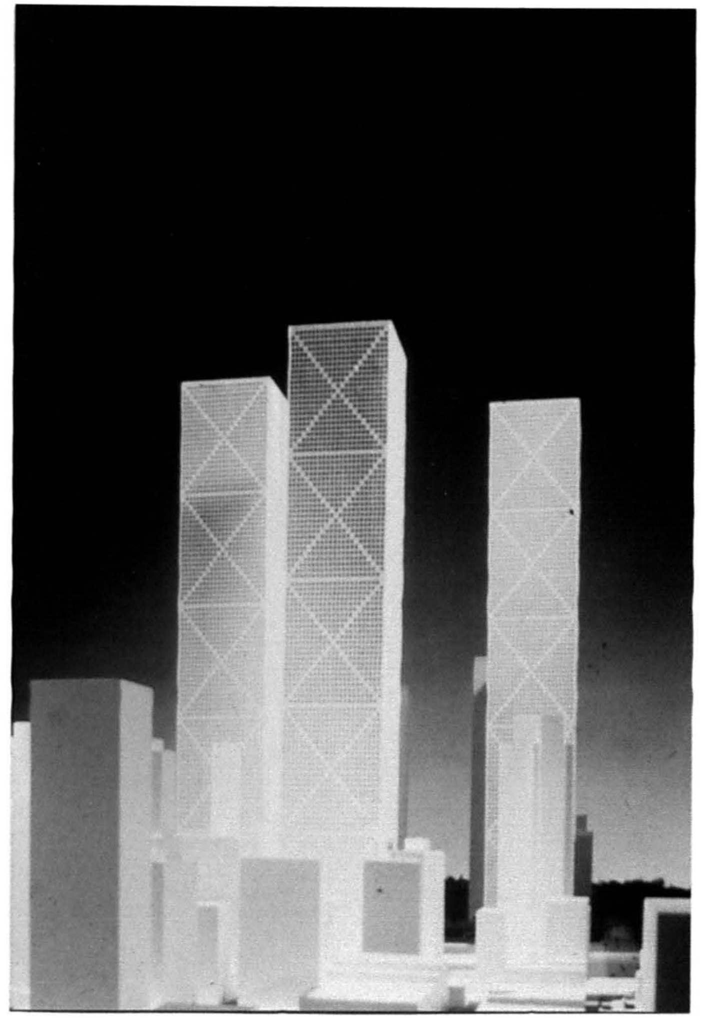
For the Bank of the Southwest Building (a: H.Jahn,e: Le Messurier, under construction, Houston) a similar type of structure has been proposed: Here the truss as well as the four corner columns are within the interior of the entire building. Eight concrete columns of remarkable size are connected by four vertical steel trusses. The concrete columns do not work as service cores. The structural system has a width-to-height ratio of 1:7.5.



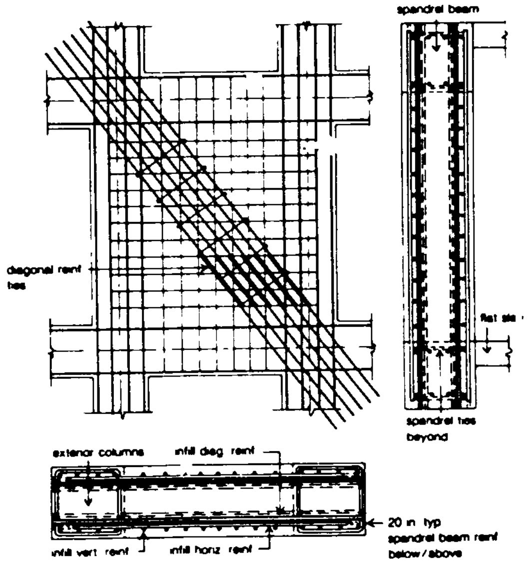


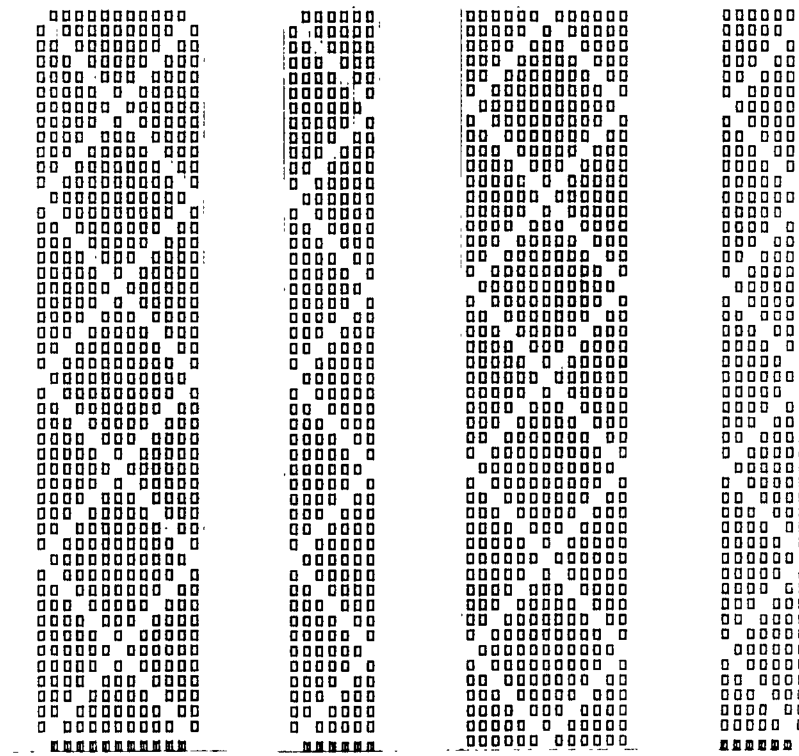
Concrete versions of the Column-Diagonal-Truss-Tube principle have been investigated first by Goldsmith, Khan and Hodgkison at the IIT in Chicago.

In his graduate-thesis Hodgkison tested this solution and he designed some 110-story 1450ft high buildings for a redevelopment area in Chicago: Columns spaced at about 10ft centers, spandrel beams and blocked out windows at each floor in a diagonal pattern create the tubular behavior of the building's structures. Structural efficiency hereby indicates practically no premium for height./31/.



The 50-story 780 Third Avenue Building (a/e: SOM, compl.1983, New York City) is the first realized concrete version of the Column-Diagonal-Truss-Tube type structure. Building's height is 167m. The width-to-height ratio of the 470,000 sqft tower is about 1:8.





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