High rise system concepts

Autor(en): **Iyengar, Hal**

Objekttyp: **Article**

Zeitschrift: **IABSE congress report = Rapport du congrès AIPC = IVBH Kongressbericht**

Band (Jahr): **14 (1992)**

PDF erstellt am: **22.07.2024**

Persistenter Link: https://doi.org/10.5169/seals-853167

High Rise System Concepts

Concepts pour les structures de maisons hautes

Konzepte für Hochhaus-Tragsysteme

Hal IYENGAR
Structural Engineer
Skidmore, Owings & Merrill
Chicago, IL, USA

Hal Iyengar is a Partner and Chief Structural Engineer of Skidmore, Owings & Merrill, Architects & Engineers, Chicago. He has received degrees from Universities in India and the University of Illinois, Urbana. Major projects include the Sears Tower and John Hancok Center, Chicago.

SUMMARY
This paper presents concepts for tall building structural systems developed since the introduction of the tubular system. The influence of changing aesthetic considerations and that of contextural relationships in the urban setting structural form and system is presented. Structural systems for multiple-use buildings and stacked atrium concepts are discussed together with newer structural systems including mixed steel-concrete and superframe structures. Some recent examples of exposed steel systems are also included.

RÉSUMÉ
L'étude présente divers concepts appliqués aux structures des maisons hautes depuis l'adoption des systèmes tubulaires. Elle rend compte de l'influence de l'évolution sur le plan esthétique et des relations contextuelles en milieu urbain entre forme et système de structure. Elle examine les systèmes de structure des bâtiments à usage polyvalent et les concepts d'atrium étagés ainsi que les systèmes de structure plus récents en construction mixte acier-béton et les concepts de super-cadres. sont également présentés. Des exemples récents de systèmes d'ossature apparente en acier sont également presentés..

ZUSAMMENFASSUNG
Das Referat befaßt sich mit Konzepten von Tragsystemen für Hochhäuser seit Einführung des Rohrsystems. Es bespricht den Einfluß sich ändernder ästhetischer Erwägungen und kontextueller Beziehungen bei der städtebaulichen Planung auf Bauform und Bausystem. Darüber hinaus werden Bausysteme für Mehrzweckgebäude und übereinander angeordnete Atriumkonzepte sowie neuere Baukonzepte wie Mischformen aus Stahl und Beton und der "Superrahmen" diskutiert. Das Referat führt ebenfalls einige neuere Beispiele von sichtbaren Stahltragwerken an.

1. INTRODUCTION

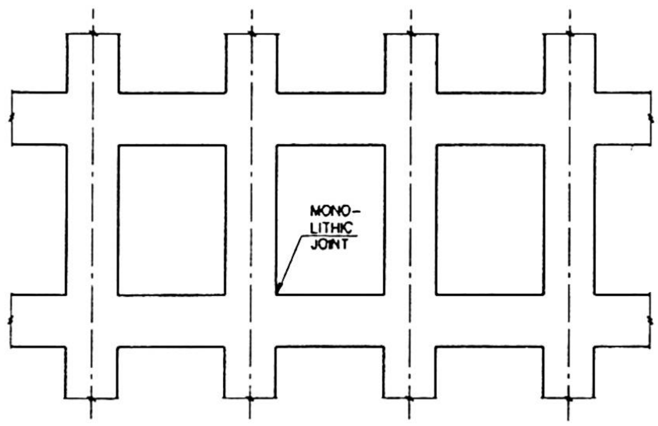
The structural systems for tall buildings have undergone a revolutionary process since the introduction of the tubular system. The rectilinear prismatic ideal of the 1950's and 1960's has been replaced by shaped, non-prismatic forms, mainly to respond to site geometry, urban planning issues and the visual impact of the varying vertical profile. The tubular system has been very adaptable to such changes and various refinements, such as the bundled tube and clustered tube, have responded well to such shape modulations. Mixed steel-concrete systems, particularly the composite tubular system, have further enhanced the application to such shaped forms. New architectural concepts are emerging, which incorporate internal and stacked atriums. New structural systems, such as the "superframe" are being developed to respond to the needed space flexibility. This paper will examine these developments on a conceptual basis.

2. TUBULAR SYSTEM

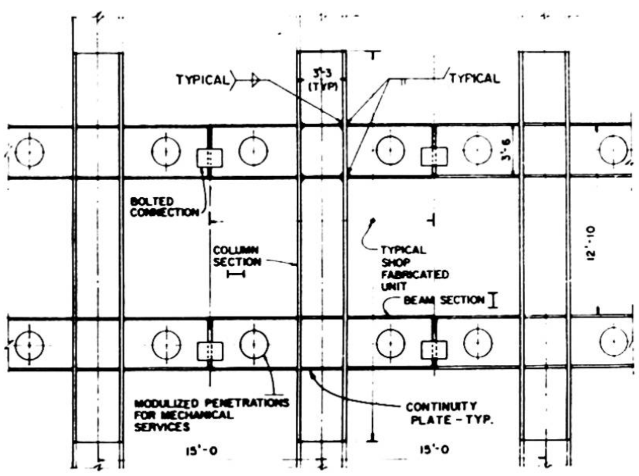
The development of the equivalent cantilever tubular system in the mid-1960's represented a significant milestone in the evolution of tall building systems. Earlier structural systems placed the lateral load resisting frame only in the interior in a plane frame arrangement in two directions. Some later versions introduced shear trusses or shear walls in the building core to provide some degree of stiffening by a vertical cantilever element. Partial tubular systems engaging the exterior frames with core trusses by means of belt and outrigger trusses also evolved. While all of these different improvements contributed to extend the range of application of frame type behavior, the radical departure occurred only when the structure was placed on the perimeter and was so interconnected as to act like a three-dimensional cantilever utilizing the entire exterior form. The characteristics of this exterior structure were that of a wall, giving rise to the terminology "tube structure" to designate the silo-like cantilever behavior of this structure. The material most readily adaptable to create the wall-like structure was concrete where wide columns and deep beams were cast monolithically (Fig. 1a) in a closely spaced formation. The adaptation of the exterior tube frame to structural steel required considerable welding, which in a closely spaced column format, was not cost effective. However, the development of a shop fabricated unit (Fig. 1b), where all joint welding can be done in the shop in a horizontal position; the unit then transported and field bolted, allowed this principle to be applied to the steel. The trussed tube involving exterior diagonalization also evolved as a unique solution utilizing structural steel. Fascia diagonals are interconnected between spandrels and columns to form a truss on each building facade. (Fig. 1c) This produced equivalent cantilever behavior similar to that of the framed tube and in fact, was more efficient because of reduced shear lag. The vocabulary of the exterior tube has been well established both in steel and concrete and a wide variety of buildings from 30 to 110 stories using this system have been constructed.

3. THE SHAPING OF EXTERIOR TUBES

The contextual relationship to the urban grid and massing with respect to neighboring buildings, as well as the aesthetics of a non-prismatic form, are all factors which impact the form and shape of buildings. The rigidly organized bay frame vocabulary allowed little freedom for such shaping without drastically reducing structural efficiency. The exterior tube by its very nature can allow considerable latitude in shaping. The basic requirements are that the tube structure be continuous and of a closed form on the exterior of the building. The overall depth and width of the shape, the degree of asymmetry and the height-width ratio all affect the efficiency of the form.



(a) Concrete Framed Tube Wall



(b) Steel Framed Tube

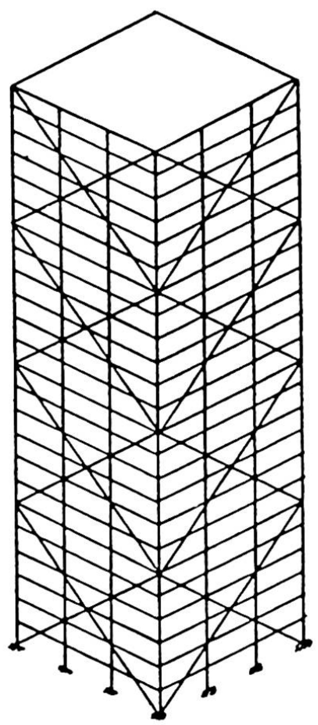


Fig. 1 Exterior Framed Tubes

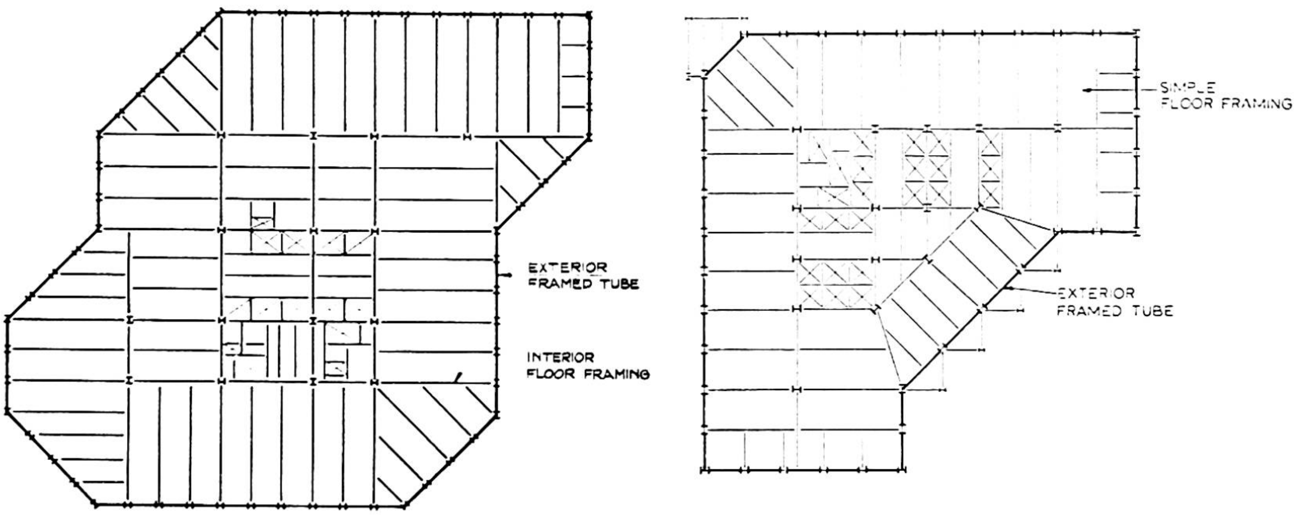
The Sixty State Street Project, Boston, Massachusetts (Fig. 2a) is a 45-story office tower which was configured as practically a free form to preserve sight lines from neighboring tall buildings. An exterior steel framed-tube was used with columns at 3m on center with a prefabricated "tree" type erection unit.

The 45-story Madison Plaza Tower, Chicago, Illinois (Fig. 2b) was conceived as a square shape with one corner truncated providing a series of steps along the diagonal face. This allows an open plaza at the corner in this tight urban site, as well as providing a crystalline, glazed, stepped facade for vistas to Lake Michigan and the City. The exterior line is taken along the linear diagonal rather than a stepped one to preserve the efficiency of the tube. 750mm and 900mm deep rolled beam sections were used as columns with the typical erection unit.

4. THE BUNDLED TUBE

The concept of bundled tubes was introduced with the Sears Tower, Chicago, Illinois. (Fig. 3a) The need for vertical massing variation in a modular fashion created the idea of bundling smaller size tubes which can rise to different heights. The structural efficiency of the overall form is greatly enhanced because of the presence of the interior frame lines which reduce the shear lag effect of a pure exterior tube.

The modularity and the conceptual basis of the bundled tube have a broad application. The cells or tubes can be arranged in a variety of ways to create different massing. It can be applied to 30 stories as well as ultra-tall structures. Further, the shape of each tube itself can be changed to any other closed clustering shape. The concept of bundling is equally applicable to both steel and concrete.



(a) Sixty State Street, Boston, Massachusetts

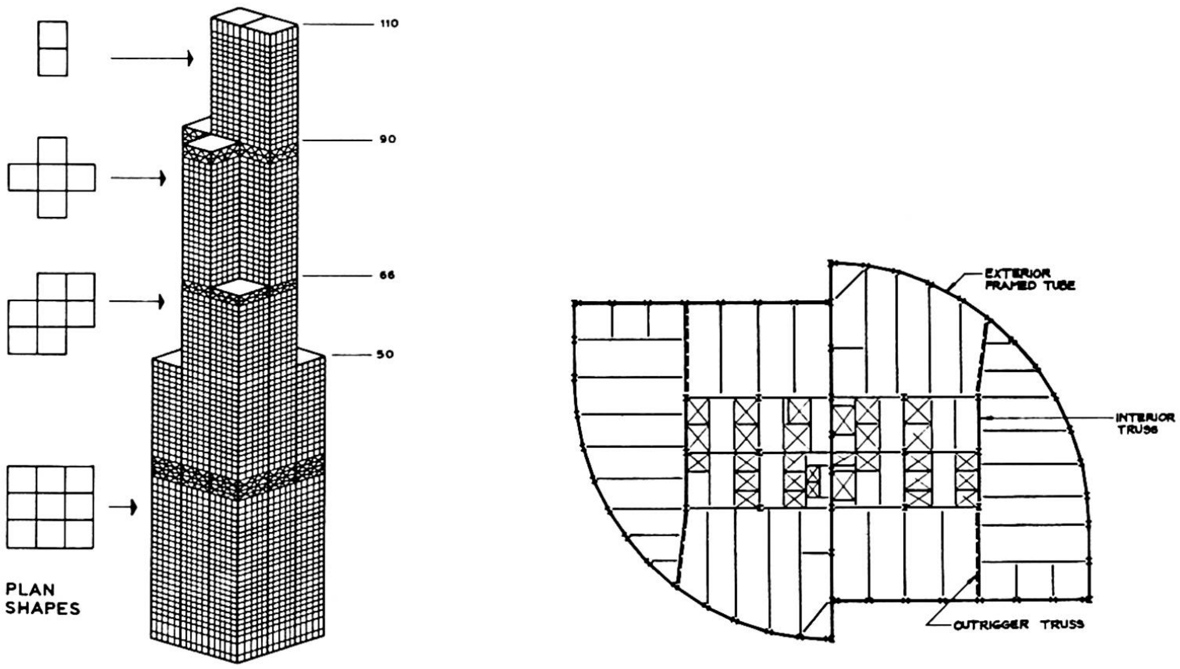
(b) Madison Plaza, Chicago, Illinois

Fig. 2 Shaped Tubular Buildings

A recent building derived from the Sears Tower system is the Allied Bank Building, Houston, Texas, which is another example of the bundled framed tube application. The shape is formed by two quarter circles placed anti-symmetrically about the middle tubular line. See Fig. 3b. The column spacings are 4.5m with the usual "tree" type construction. The system also uses two vertical trusses in the core which are connected to the exterior tube by outrigger and belt trusses. Significant improvement in tubular behavior is obtained because of the participation of the trusses in reducing shear lag.

5. MIXED STEEL-CONCRETE SYSTEMS

Mixed steel-concrete [1] systems have been established and are now used as readily as either all steel or all concrete systems for high-rise buildings. A wide variety of mixed forms are generally applicable, such as the composite tubular and the concrete core braced systems. The properties of concrete that are most attractive are its rigidity and its ability to be cast into different types of structural elements. Therefore, most mixed system compositions rely on concrete for lateral load resistance. Shear wall elements and/or punched wall or framed-tube elements with monolithically cast beam-column joints are primary elements used for lateral load resistance. Steel floor faming in mixed systems is advantageous because of the ability to span longer distances with lighter members and make possible larger column free space.



(a) Sears Tower, Chicago, Illinois   (b) Allied Bank, Houston, Texas

Fig. 3 Bundled Tubes

The First Canadian Centre, Calgary, Canada consists of two towers and a 10-story banking pavilion, located in an L-shaped site in downtown Calgary. The two towers are 64 and 43 stories. A sculpted form which provides diagonal vistas to the mountains and city was highly desirable for this prominent corner site. Each tower is similarly shaped, basically involving a parallelogram with truncated and re-entrant corners. The structure is based on a tube-in-tube concept involving an exterior reinforced concrete framed-tube and an interior shear wall core tube. Structural steel floor framing and other interior steel columns complete the system, as shown in Fig. 4.

A recent trend in exterior architecture has been to express facade steps, protruding triangular bays and other facade profile modulations. These demand a lighter structure on the exterior which can be provided in structural steel. In these instances, a structure that is concentrated in the core of a building for wind resistance will offer flexibility of framing on the exterior. A logical mixed combination here is a concrete shear wall core which resists all wind forces surrounded by simple steel framing for floors and exterior columns.

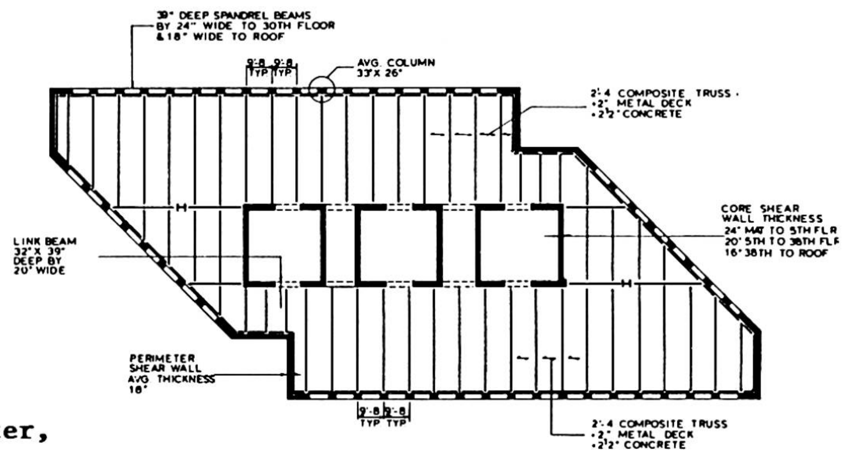


Fig. 4 First Canadian Center, Calgary, Canada

Fig. 5 shows an example of a 44-story core braced system which was configured to fit an unusual site. The core is augmented by fascia moment frames.

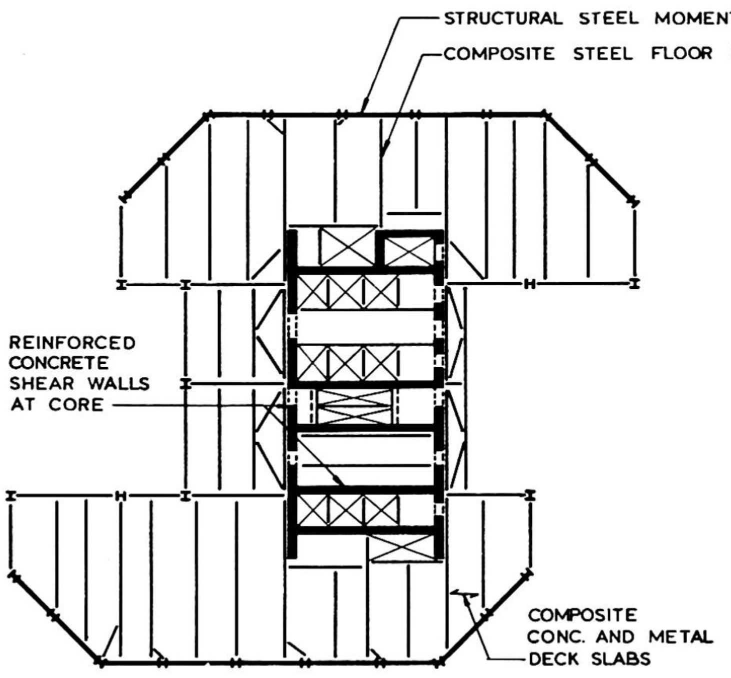


Fig. 5 Tower 49, New York, New York

6. MULTIPLE-USE TOWERS

Multiple use towers, which incorporate vertical stacking of different occupancies such as parking, commercial, office and residential, have become attractive to address concerns about the quality of inner-city life and better utilization of energy resources. The functional planning of spaces often influences the choice of a structural system. [2] In terms of floor spaces, office and commercial buildings use longer-span structural systems consistent with the space requirements, whereas housing and apartment buildings use relatively shorter span structural systems consistent with residential room sizes. Although both reinforced concrete and structural steel are used for office buildings as well as residential buildings, the structural systems are quire different. The office building requires longer spans as well as much more complicated mechanical and electrical systems, almost invariably using false ceilings, whereas residential buildings with less complicated mechanical and electrical systems, do not require the use of false ceilings except for special cases. Flat-plate, reinforced concrete slab construction has therefore become the most accepted floor system for residential buildings whereas beams, joists or grid beam (waffle) systems are used more frequently for office and commercial buildings. The generally desired stacking of residential over office, and office over commercial, and commercial over parking, brings about a form which needs to be wider at the lower floors and narrower at the top to create the effective lease spans for different occupancies. A gradual reduction of the span from the top to bottom makes the overall structural system continuous on the exterior, rather than a wedding cake type arrangement which results in discontinuous, incompatible structural pieces.

A recent example of a multiple-use tower in Chicago is that of the 64-story Olympia Center. The program involved 3 floors of below-grade parking, 6 floors of department store, 17 floors of office and 40 stories of apartments. The floor size of 36m x 52m at the bottom varies to 18m x 52m at the apartment levels. The building is transitioned from the 15th to the 30th floors by a continuous curve, as shown in Fig. 6. The moldability of the concrete makes such a curvature possible. Another aspect of a commercial-office-apartment combination is the integration of the facade fenestration requirements in the same system. Commercial space requires very little window fenestration, office space requires regular fenestrations reflecting the modular nature of the office space and apartments require combinations of opaque and window spaces reflecting requirements of different rooms. In addition, in the Olympia Center, two-story duplex apartments were desired which required removal of the spandrel beams over the living room width. The bearing wall nature of the framed tube permits different degrees of openness desired for different occupancies. A study of the building structural elevation reveals more solid portions in the commercial area, a consistent framed-tube grid in the office areas and a more flexible grid which begins to open up at the apartment levels with duplexes in the middle of the faces, eventually growing out to the corner areas and finally turning into a bay frame structure at the top few floors. The floor framing shows a wide pan joist type of framing for the longer span office framing and flat plate framing for the apartments.

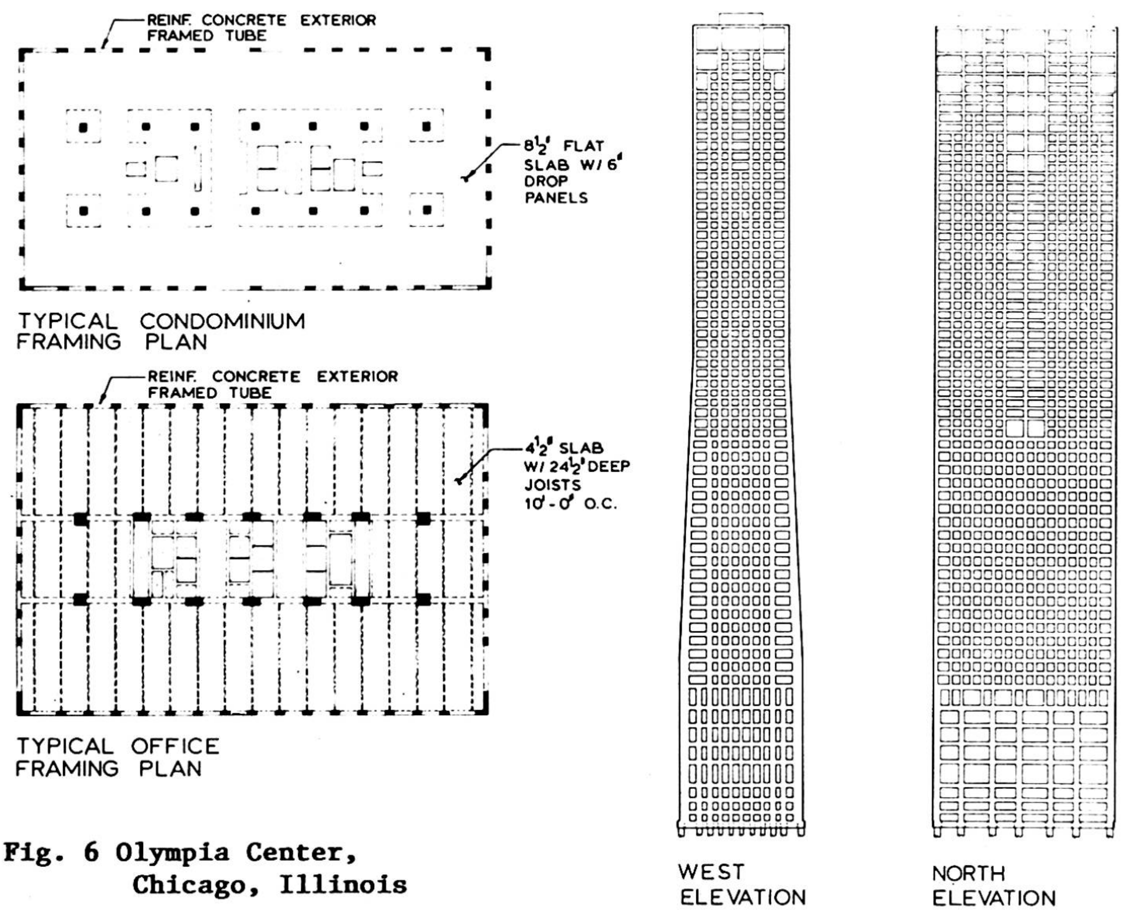


Fig. 6 Olympia Center, Chicago, Illinois

The 57-story One Magnificent Mile Building, Chicago, Illinois [2] typifies another approach to achieving vertical modulation of spaces, that of bundling or clustering of different tubes. The free-form structure is composed of three, near hexagonal, reinforced concrete framed tubes with the highest tube at 57 stories and the others at 49 and 22 stories each. (Fig. 7) The arrangement of tubes and their orientation was determined from the site configuration and optimization of vistas to Lake Michigan. The clustering principle was highly useful in molding the overall form around this L-shaped site with a diagonal frontage. The hexagonal shape for each tube created a highly faceted format for the overall architectural form. The lower 20 stories, which include all three tubes, are occupied by commercial and office space with the rest devoted to apartments. It should be noted that the two and single modules are especially suited for apartment layouts. The floor system is a reinforced concrete, flat slab system in both office and apartment floors. The structure for the tubular lines involves columns at close centers and deep spandrel beams.

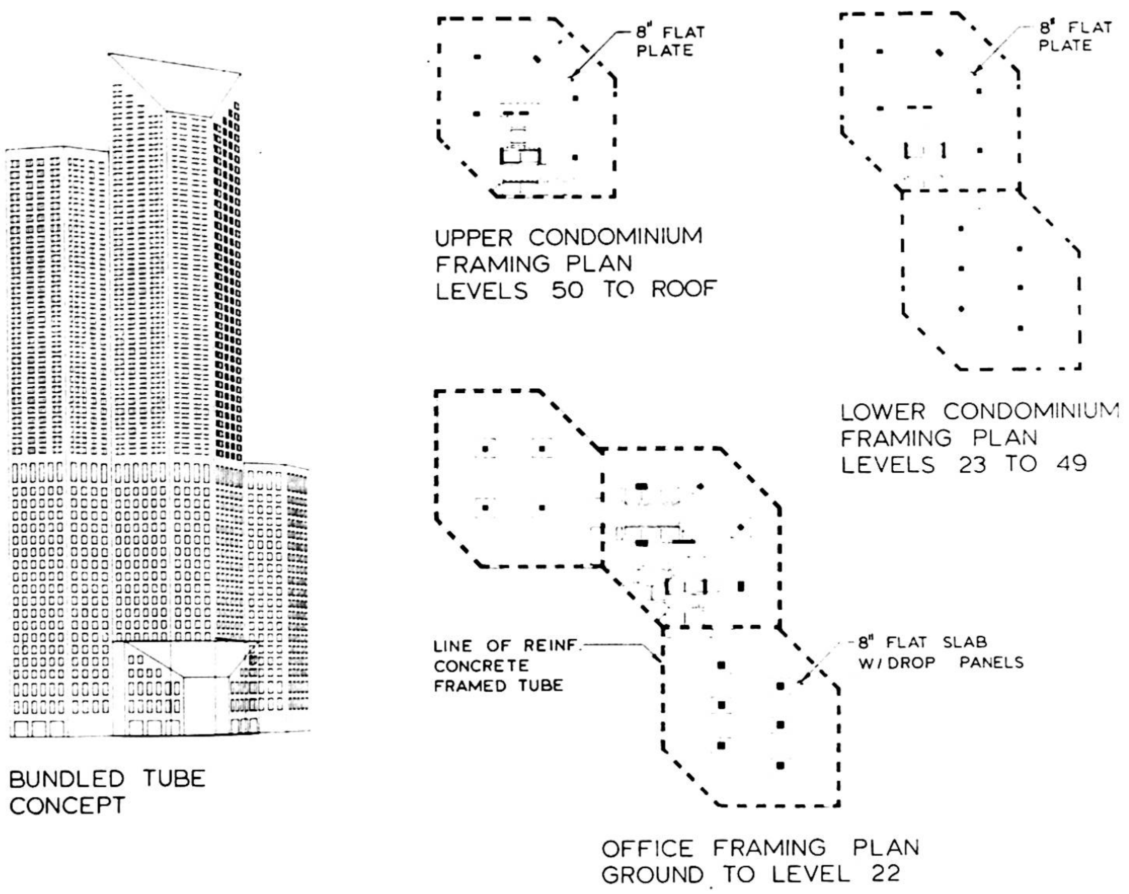


Fig. 7 One Magnificent Mile, Chicago, Illinois

7. SUPERFRAME SYSTEM

Superframes are megaframes in the form of a portal which are provided on the exterior of a building. The portal frame of the superframe is composed of vertical legs in each corner of a building which are linked by horizontal elements once in about 12 to 14 floors. Since the vertical elements are concentrated in the corner areas of a building, maximum efficiency is obtained for resisting wind forces. The vertical legs and the horizontal links are themselves frames with large dimensions in the plane of the frame.

The concept of the stacked interior atrium evolved from energy conservation ideas relating to the amount of the exterior facade exposed to the outside environment. A volume of squatter form with large floor plates will reduce the proportion of window area to the floor area. [3] However, large quantities of interior spaces are not optimum for prime office rental. The object of interior atriums is to remove interior volumes of spaces that are considered undesirable and provide for exciting three-dimensional sheltered spaces. The window wall at the atrium would then be considered equivalent to an exterior wall and thus, improves the quality of prime spaces. These atriums can be shaped in a way to provide a variety of floor configurations and sizes. The vocabulary of stacked atriums and the vertical organization is shown in Fig. 9. Full floors separate these atriums and the formations of portal openings on the facade express these atriums and also allow for access to exterior light without heavy structural encumbrance. Superframes are then equivalent cantilever forms which integrate this principle of stacked atriums. In order to maximize the cantilever efficiency, the members of the portal frame, namely, the verticals and horizontals, will have to be considerably stiff in their own plane. Fig. 8 shows two steel possibilities and a composite variety where the superframe elements are made of reinforced concrete. In Fig. 8a, a broad diagonalization like that of a trussed tube is used for the elements. In Fig. 8b, a more delicate diagrid bracing is provided to the elements. The difference is in the possibilities for architectural expression. Superframes can also be conceived in a composite form, where the vertical legs of the superframe are punched wall-like elements which are interlinked by steel trusses. The interior framing would then be in structural steel as in the composite tubular system. The rigidity and moldability of concrete makes possible these punched walls or framed tube elements to develop an overall equivalent cantilever when properly interlinked. See. Fig. 8c.

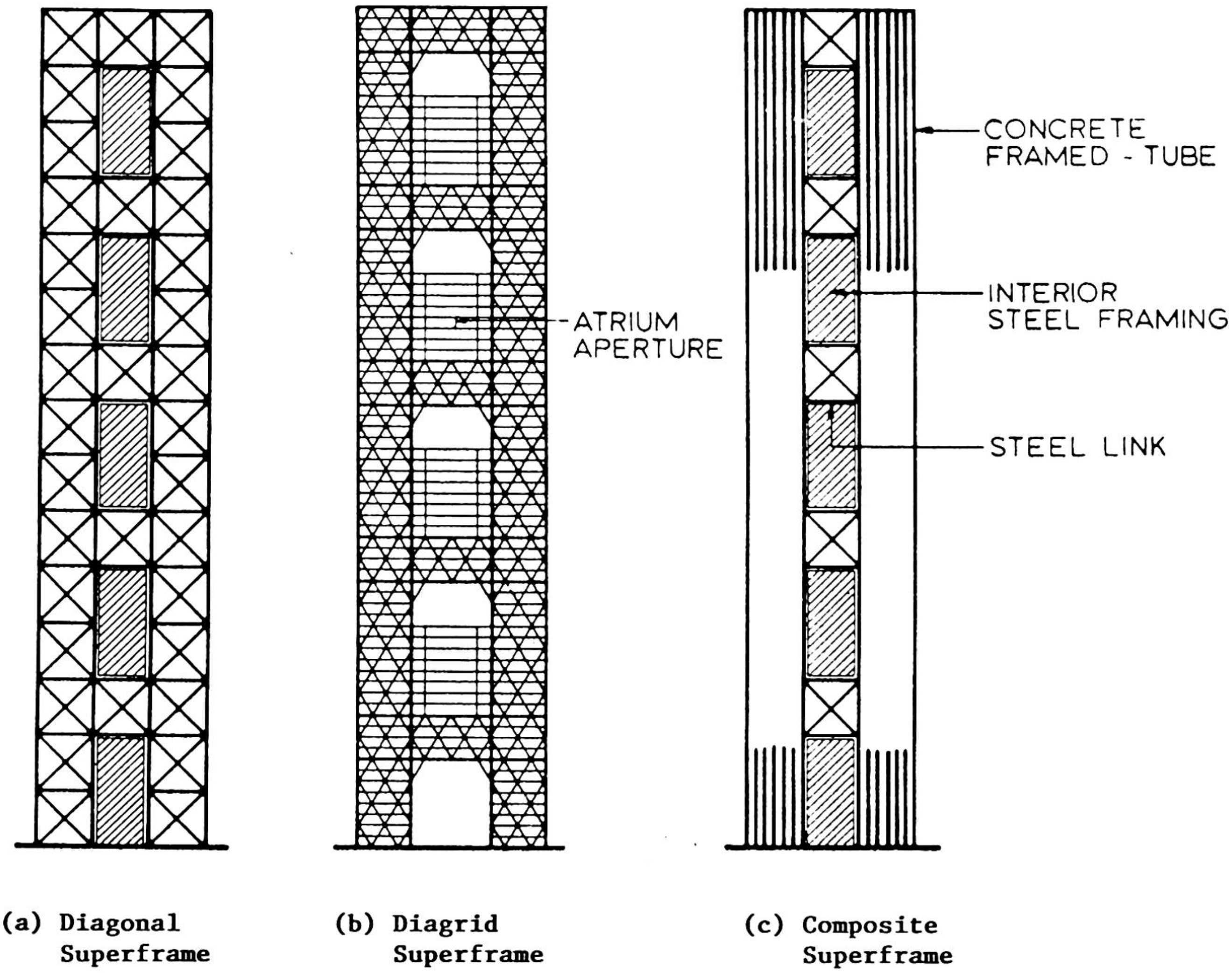


Fig. 8 Superframe Concepts

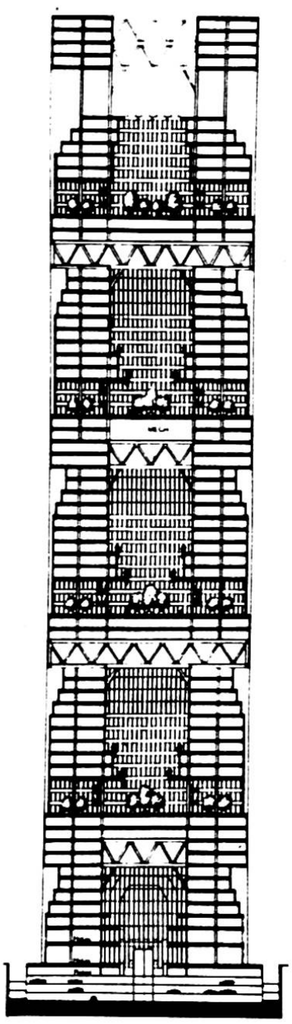


Fig. 9 Stacked Atria-Superframe Concept

8. EXPOSED STEEL SYSTEMS

The beauty and essence of exposed structural steel can form the basis for architecture in multi-story buildings. The exposed steel frame may range from simple beam-column expressions to more intricate arrangements of trusses, arches or other exotic forms. From an architectural point of view, a clearly articulated structure on the exterior is desired. This articulation is characterized by the crisp proportions of steel I-beams, columns, and built-up members, and the honest expression of the connecting joints both bolted and welded. Structural functionalities, such as primary compression or tension elements or joint load-carrying mechanisms can be appropriately expressed and proportioned. The architectural aesthetic is based on clearly defining open web-like forms to allow the play of daylight through the structure. This must be balanced by the need for robustness and structural integrity, particularly at the member joints.

The issues of corrosion and fire protection must be addressed in engineering exterior exposed steel buildings. Improvements in corrosion protection through the development of durable, long-life, fluorocarbon paint systems have enhanced exposed steel construction. The use of state-of-the-art fire engineering concepts in designing exposed steel frames has gained momentum. Analytical approaches to determine the steel temperatures when exposed to different fires, as well as the determination of the character and nature of the fires, are now well documented and accepted.

A recent example of an exposed steel system is shown in Fig. 10. [4] The Broadgate Project is a major office development on the northeast edge of the City of London, located adjacent to the Liverpool Street Train Station. The railroad tracks cover most of the site and must be left intact and usable, thus requiring that the project be built to span over a large portion of the tracks, supported on columns only where permitted by the track and platform layout. The main block of Exchange House is a 10-story office building, 78m x 54m in plan, supported on four (4) segmented, tied, parabolic arches that span the 78m over the railroad tracks below. The two exterior arches, their ties and the columns and beams that frame into them are located so as to create a 2m wide gallery at the perimeter creating a structural expression for the building.

The architectural form, expression and articulation are all based on the exposed, painted steel structure. The building enclosure forms a smooth metal and glass skin background to enhance the clarity of the structure. Member proportions and joint details follow strict structural logic to express directly the functions and workings of the structure. (Fig. 10)

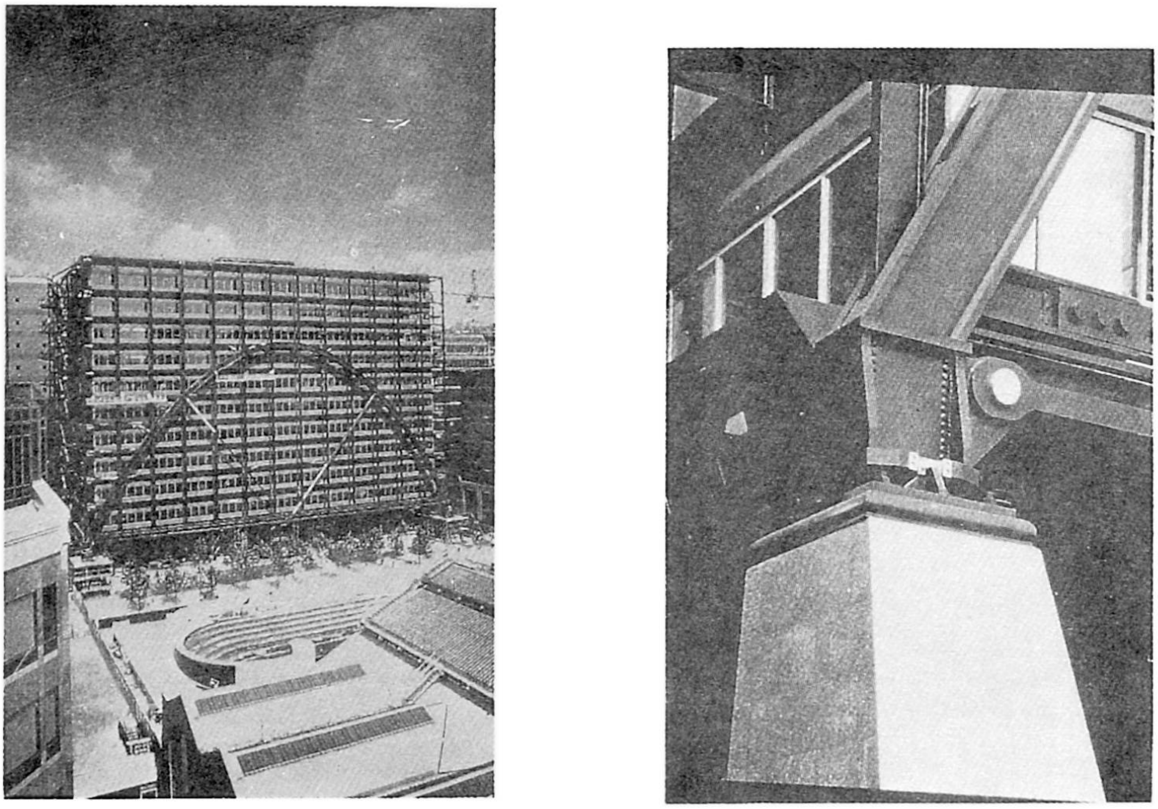


Fig. 10 Exchange House, Broadgate Project, London, England

Hotel Vila Olimpica is a hotel, residential, commercial and office development on the waterfront in Barcelona, Spain. [5] Under construction now in preparation for the 1992 Olympics, the complex consists of a 6-story office block, a low-rise retail and public space, and a 44-story hotel-apartment tower. The apartment tower, the most prominent element in the composition, has an X-braced steel frame pulled away from the exterior curtain wall. The form of the exterior structure and the articulation of its connections, together with the shadows it casts upon the metal-and-glass curtain wall, establish the primary architectural character of the tower. (Fig. 11)

The hotel tower is square in plan, roughly 33 meters on a side, with its steel framework placed away from the curtain wall an additional 1.5 meters. Each side of the steel frame has two X-braced bays flanking a center bay of moment-connected spandrel beams. Additional X-bracing at the bottom, middle and top of the center bay tie the two X-braced frames together so they act as a unit.

The tower's interior layout of individual, compartmentalized hotel rooms gave the structural designers an opportunity to create an external steel framework that is completely free of fireproofing. Fire engineering and high-temperature structural analysis showed that the steel structure will remain safe when exposed to the most severe fire that can be expected from such a compartmentalized floor plan.

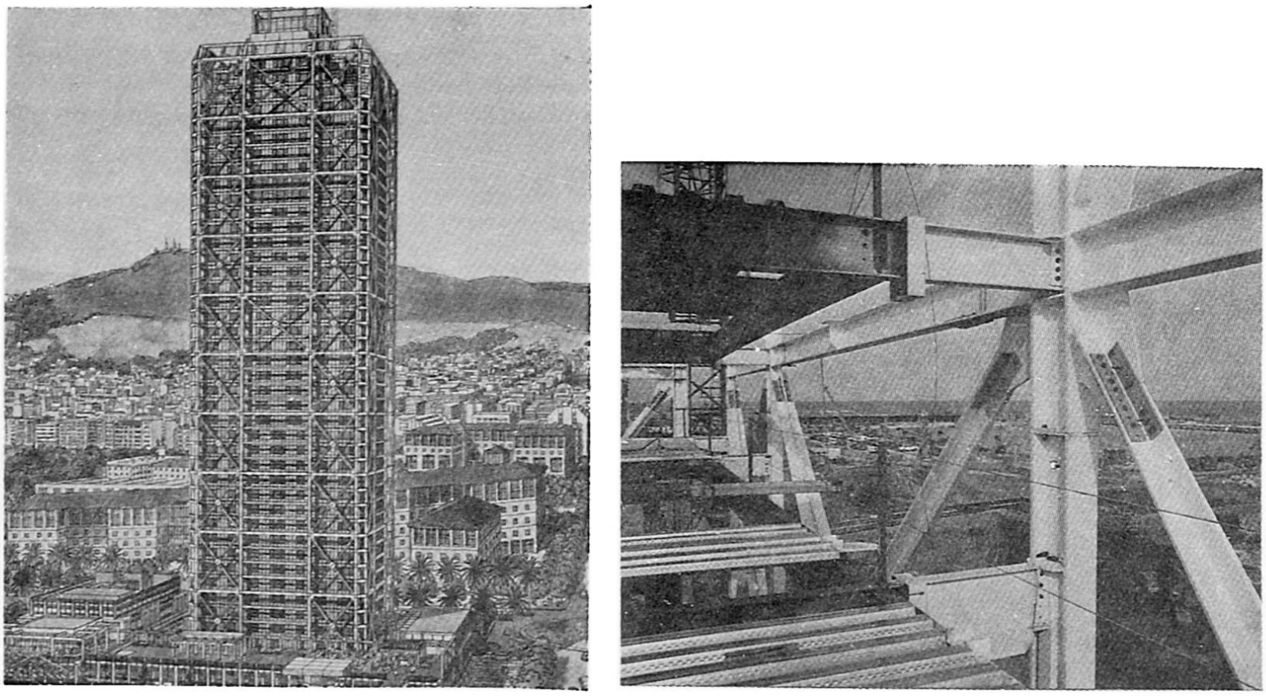


Fig. 11 Hotel Vila Olimpica, Barcelona, Spain

9. CONCLUSIONS

Structural systems for tall buildings will continue to be influenced by building form and urban massing considerations. The principle of an equivalent cantilever as demonstrated by the tubular system will continue to be dominant. The bundled tube and clustered tube system will provide some degree of needed flexibility regarding massing and functional integration. Newer structural forms which integrate with special concepts, such as the superframe, will further evolve. Future structural systems will often borrow elements from previous systems if they can be utilized efficiently and a combination is derived to suit the needs of a certain project. Combinations may involve framed tubes, bundled tubes, trussed tubes, mixed systems, superframes, etc. The ability to analyze any three-dimensional structure on the computer readily and economically and verify its behavior and efficiency will permit such systems methodology to flourish.

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