High-Rise System Developments in Concrete

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1. Introduction

Developments in concrete high-rise buildings have undergone a dramatic evolutionary change in the last twenty-five years. Simple systems, such as shear wall buildings that were exclusively used prior to the 1960's, have been transformed to a considerable number of systems suitable for commercial, residential and mixed uses up to 80 stories or more. In many cases, the reinforced concrete elements have been combined with structural steel to produce a more effective mixed system. The progressive development of higher-strength concrete together with advancement in mechanization of formwork and placement methods have fueled this systems development. The advantages offered by concrete, with respect to moldability for shaping as well as massivity and rigidity for structural purposes, have been exploited to the fullest. This paper is developed somewhat as a review of the systems developments that have occurred in the past twenty-five years together with discussion of some current applications.

2. Special Merits of Concrete

a. Lateral Load Resistance:

Concrete has been said to be the cheapest material that one could buy on a global basis which can readily be molded and so placed in the building to accept lateral forces. The properties of concrete that are most attractive are its rigidity and its ability to be cast into different types of structural elements. 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. It is well known that equivalent cantilever-type structures are most efficient at resisting wind forces and developing the needed lateral stiffness. Such cantilevers can be produced by placing walls around building cores so that the core wall system can be considered a cantilever tube. Similarly, if the punched wall is placed on the exterior, the entire exterior form can be utilized as a cantilever tube system. The proportionality of the members of the punched tube, the wall thickness and the shape of the wall can all be controlled readily to fit any particular structural requirements and this aspect of customizing to meet different requirements makes concrete particularly suitable for the lateral load resistive system. In mixed steel-concrete systems, concrete is used in vertical elements only while horizontal framing is

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obtained from structural steel. The mechanization of formwork for the construction of vertical elements has significantly contributed to economy and speed of these systems. Panelized shear wall formwork, slip forms, gang forms and automated form lifters all contribute to this construction efficiency.

The reliable production of higher-strength concrete has extended the application to taller structures in the range of 50 to 80 stories. Concrete strengths in the range of 6,000 to 8,000 PSI are commonly used, whereas in some cases, strengths up to 12,000 PSI have been utilized. The aspect of higher elastic modulus with higher strength again contributes to improved rigidity.

In tall structures beyond 50 stories, the aero-dynamic behavior and the resultant motion perception are important structural considerations. Pure steel buildings tend to become lighter which, for the same fundamental period, will cause higher motion perception levels. Significant perception improvements can be obtained with a larger mass in the system for the same fundamental period of vibration. In addition, the higher mechanical damping of concrete assists in the reduction of perception levels. Because of these properties, concrete is being more readily adopted in taller structures. However, massivity of members may cause space and planning inefficiency in structures beyond about 80 stories, unless even higher-strength concrete is available in the future.

b. Floor Framing

Earlier floor framings were beam and slab arrangements cast in place with board forms. These were labor intensive and slow to construct. These were soon replaced by pan joist and waffle joist systems which were standardized into certain sizes and depths. Spans up to about 30 ft. were possible, after which the framing was very massive. Initially, the pans were of metal and were either 20 or 30-inches wide which limited their range of applicability. The same type of system is now made more efficient and lighter by use of molded fiberglass form pans which can readily be adapted to spacings up to 7'-6". The pans can be fabricated into the entire spans and can either be lifted into place or mounted on table forms. This development alone has made high-rise floor systems more economical and adaptable. Post-tensioning of ribs in this system is being used more frequently which further reduces the depth and materials involved. With these developments, spans up to 40 ft. are possible with lighter floor framing.

Flat plates and flat slabs are obviously unique to concrete construction and they are advantageous where minimum floor-to-floor height is required. Flat plates are typically used for apartment buildings where the flat surface of the flat plate is merely painted to form the finished ceiling. Flat slabs with drop panels with or without capitals are used in garages, warehouses and various such applications.

c. Architectural Concrete

The integral fire protection capability and the ability to be finished into a tough weatherproof surface makes exposed concrete systems possible. The ability to be molded into different shapes offers concrete special advantages in various articulated architectural expressions. In high-rise buildings, a significant cost is that of cladding and the window wall. Architectural concrete offers a more economical alternative. In many instances, special exposed aggregates or color-controlled concrete has been utilized. The recent development of durable epoxy paint systems further enhances this type of application. Architectural concrete also truly integrates the structure with the enclosure as in the case of the punched wall tubular system or other similar systems. However, the effects of temperature foreshortening of exterior columns need to be considered when used in structures beyond 20-25 stories in extremely cold climates.

3. Types of Structural Systems

Several structural systems that have been utilized in the past twenty-five years are briefly outlined. Fig. 1 shows some of the system possibilities in a chart form with an indication of the range of applicability in height or number of stories.

Frame buildings, which rely on predominant Vierendeel frame action, are suitable only up to about 10-20 stories. This is the forerunner to many newer systems after the 1960's where frame beams were made part of the beam-slab floor framing. In some applications, standard pan joists or waffle slabs were used, with the pans at the frame lines filled in and reinforced for frame beam action. Currently, this frame system is generally used for low-rise buildings in the 4 to 6-story range.

Structural systems which derive all their lateral stiffness and strength from only shear walls are feasible up to about 30 to 40 stories. For higher structures, the wind stresses tend to control the design and, therefore, the increased thickness of the shear walls would reduce the core and structural efficiencies. A primary advantage of this system is the absence of any wind framing requirements outside the core area and the floor may be designed for gravity loads only. If span dimensions on the order of 25 ft. do not reduce the floor rentability, an ideal solution would be a flat plate. The result is a lower floor-framing labor cost and lower floor-to-floor height. The reduced height and cubage of the building also result in window wall and mechanical savings.

Initial versions of shear wall buildings were plane elements connecting columns in two directions. Later versions organized the walls around the central building core so that the core wall system can be considered as an internal cantilever tube.

Frame-shear wall interacting systems were a logical extension of the shear wall system which was generally created by the addition of shear frames on the fascia. The shear wall-frame interaction brought about substantial structural benefits in terms of lateral load resistance and strength.

In this system, the fascia plane frame parallel to the direction of the lateral load was considered in the interaction with the core walls. Many outstanding examples of this system up to 40 stories (Brunswick Building, Chicago) currently exist. A study of some recent efficient buildings indicates that the frame stiffness is large enough to reduce the free cantilever deflection of the wall to about one-third its value after interaction. Since the interaction involves two subsystems, studies for optimum combination should be performed. In general, shear walls should be positioned for large gravity load tributary areas which not only reduce the possibility of uplift, but also increase the capacity to resist wind overturning moments because of the increase permitted in the stresses when wind forces are considered.

Framed-tube structures when properly proportioned will develop high efficiencies. Wide columns and deep beams at spacings on the order of 6 ft. to 10 ft. will develop an effective cantilever mode of behavior. The absence of the core walls is an advantage in core planning and mechanical distributions. The development of the equivalent cantilever tubular system represented a significant milestone in the evolution of tall building systems. While all previous system 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 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. With this innovation, the structure had emerged from the interior to the exterior, thereby significantly impacting the architectural expression of the facade and the shaping of the overall form. The material most readily adaptable to create the wall-like structure was concrete where wide columns and deep beams were cast monolithically in a closely-spaced formation. The structural proposition was one of examining different spacings and member proportions, while that of architecture was one of articulation of the tube character. Many notable structures, such as the One Shell Plaza Building in Houston and others, were built with this principle.

The development of the interior core system as a wall tube and that of the exterior as a framed tube offered opportunities for larger stiffness and, therefore, higher heights when the two were combined to form a "tube-in-tube" system. In some mixed steel-concrete system forms, this system is used with the floor element replaced with steel framing.

While punched-tube systems offered considerable latitude for application into high-rise concrete buildings, it is well to remember that system developments in structural steel were also occurring. It was then possible to borrow from steel to concrete and vice versa and tailor them for the nature and technology of either concrete or steel. The bundled-tube system of the Sears Tower in Chicago was adaptable to bundling or clustering of concrete tube systems. Such modulations allowed not only clustering, but also vertical profile modulations. They were then suitable for multiple-use structures or structures demanding variable floor sizes. The integration of space and architecture with structure further promoted advances in systems technology.

The exterior-braced, trussed-tube system, which was a unique development in steel tubular buildings such as the John Hancock Center in Chicago, was also adaptable to concrete. The concrete tube character was that of a punched wall. Diagonalization was then achieved by filling in window fenestrations in the path of the diagonal. This diagonalized tube was more effective in stiffness development and when combined with ultra-high strength concrete, it can produce considerable economic benefits. Architecturally, a new vocabulary is created with a true structural expression.

Systems for apartment buildings use flat plates without drop panels almost exclusively. The advantages are lower floor-to-floor height, a flat surface which is merely painted to produce the finished ceiling, better sound isolation between floors, adequate fire resistance between floors and a more economical type of construction. Columns or walls can be introduced at closer intervals than in an office building. In most cases, shear walls are sufficient to carry all the lateral loads. Exterior framed tubes, with or without interior walls, are also possible in conjunction with flat plates. Bundled-tube systems with full cross walls, which are only penetrated by the corridors, may be more effectively used in apartment buildings.

4. Recent Concrete High-Rise Systems

a. Olympia Center, Chicago

A recent example of a multiple-use concrete 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 is 118 ft. x 172 ft. at the bottom which reduces to 60 ft. x 172 ft. at the apartment levels. The building is transitioned from the 5th to the 30th floors by a continuous curve, as shown in Fig. 2. This transition is consistent with the requirements for an exterior framed-tube system in concrete, in that 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 the 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's 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. All these grid modulations are within the vocabulary of a concrete framed tube which can readily be molded to different requirements as a bearing wall. The floor framing shows a wide pan joist type of framing for the longer-span office framing to flat plate framing for the apartments.

b. <u>One Magnificent Mile, Chicago</u>

The 57-story One Magnificent Mile project typifies another approach to achieving vertical modulation of spaces--that of bundling or clustering of different tubes. The system once used for the Sears Tower is now used for a multiple-use project in reinforced concrete. 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. 3). 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 have all three tubes, are occupied by commercial and office space with the rest devoted to apartments. It should be noted that the double 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. The wall character of the concrete framed tube again provides the context for a variable facade grid between office and apartment occupancies.

c. <u>Onterie Center, Chicago</u>

Onterie Center is a multi-use, high-rise complex located on the Lake Michigan shore line near Downtown Chicago. It is comprised of two towers, a 58-story main tower with a tapering auxiliary low-rise building (Fig. 4). The total building with an area of 92,000m^2 is divided into five distinct areas by function. On the ground floor of the main tower and the connecting low-rise building are the main public lobby and 1,860m^2 of commercial space. The parking area occupies the basement and four floors above the lobby. Floors 6 through 10 of the tapering base, as well as floors 2 through 11 of the auxiliary tower, provide office space and are organized around two interior atriums. The sky lobby at level one includes a health club, swimming pool, hospitality room and mechanical equipment space. Levels 12 through 58 consist of one, two and three-bedroom apartments, for a total of 593 units.

Mixed-use, high-rise structures demand flexibility in column spacing and core layout. Therefore, maximum structural efficiency and functional flexibility can be achieved by utilizing the exterior frame of the building only for the lateral force-resisting system. In the Onterie Center's main tower, the entire lateral force-resisting system is achieved by closely-spaced exterior columns and spandrels of reinforced concrete construction. Additional lateral stiffness and structural efficiency were achieved by in-filling the window space with concrete in a diagonal pattern. These reinforced concrete in-fill panels act not only as diagonal braces as in steel high-rise structures, but also act as shear panels as well (Fig. 5).

By going diagonally across the building, the in-fill panels tie columns and spandrels together and help to evenly distribute the gravity loads on adjacent columns. They also help to reduce the shear lag in the tube frame and thus contribute to the structural efficiency of the system. As a result, the entire lateral stability of the building is achieved by two exterior diagonalized tubular channels located at each end of the tower structure. Interior columns carry gravity loads only, thus allowing more flexibility in planning the interior space and eliminating the differential creep between the core walls and adjacent columns, had a core wall been utilized in resisting lateral loads.

5. Mixed Steel/Concrete Systems

Mixed steel/concrete systems have emerged into a well established new system that can be used as readily as either steel or concrete systems for high-rise buildings. Such mixed systems involve reinforced concrete and structural steel components which together resist all the forces of gravity and wind. A wide variety of mixed forms that is generally applicable, such as the composite tubular system and concrete core braced systems, have been widely used. 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 framings are used in mixed systems, which are advantageous because of their ability to span longer distances with lighter members and make possible larger column-free space. Steel is also more effective as gravity columns because of its slenderness and size.

a. First Canadian Centre, Calgary

The First Canadian Centre in 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 tall. A sculpted form and a form which provides diagonal vistas to mountains and the city was highly desirable for this prominent corner site. The result was a two-tower concept, each one facing a street. Each tower is similarly shaped, basically involving a parallelogram with truncated and re-entrant corners. Each tower also involves a variation in vertical profile, which can be observed from the model photograph. The structural concept 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. 6. The tube system on the exterior is a combination of framed tube with beams and columns and solid walls at the corners. The structural essence of the concrete framed tube wall is that of a bearing wall and as such, the punched wall and solid wall are both compatible parts of the system. The columns are provided at 9'-8" centers along the flat faces and along the diagonal lines.

b. Southeast Financial Center, Miami

The Southeast Financial Center is a high-rise office development in the downtown area. It consists of a 53-story office tower reaching 730 ft. above grade and is the tallest building in Miami. The site has views to the east over Bay Front Park and as such, the orientation of the office toward the east and a dramatic profile modification at the top floors to optimize vistas was a design requirement.

An extremely rigid and efficient wind-resistive structural system was required to resist high wind forces. In addition, a more massive structure would alleviate potential difficulties with foundation uplift. A composite bundled-tube system was selected over others as being the most appropriate to meet the criteria. The bundled tube is composed of an approximate rectangular tube and a stepped triangular tube (Fig. 7). The common wall between the two tubes is made up of solid walls and a beam-column arrangement. The provision of this interior frame line was essential to improve the tubular efficiency. The interior 40 ft. spans and core framing are framed with non-rigid, simple steel members. The use of the concrete composite tube had the following advantages: (1) development of extreme rigidity and strength for wind resistance; and (2) massiveness of concrete eliminated potential uplift difficulties and produced better dynamic behavior.

c. Tower 49, New York

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 as can be provided in structural steel. The attitude here is one of a real curtain wall which can be easily manipulated and geometrically applied to a light structure which can support the exterior bays of the floor. 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.

Initial systems were constructed utilizing step-form techniques, whereby the core would be advanced 3 or 4 floors ahead of the exterior steel by forming one floor at a time. Recent use of individually adjustable slip-form jacks makes slip-form techniques practical for building applications. In this process, the core would be slip-formed in its entirety in a short period of time prior to erection of steel. Floor beam connection details and attachments will have to be suitably planned to accommodate slip-forming.

Fig. 8 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.

Conclusions

Considerable advancements have been made in furthering the systems methodology for concrete high-rise buildings. Improvements in construction methods and the strength of concrete have freed the constraints on ultra-tall, concrete structures. Innovative systems combinations involving steel and concrete are being used to best utilize the merits of each.

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