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Structural Concepts for Ultra-Tall Concrete Buildings

Concepts de structure pour de très hauts gratte-ciel en béton

Strukturelle Konzepte für extrem hohe Betonbauten

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Joseph Colaco, born in 1940, received his Ph.D in structural engineering from the University of Illinois, Urbana, IL, USA, in 1965. For four years, he worked on tall buildings with the late Dr. Fazlur Khan. Joseph Colaco is now president of a consulting firm and continues in the design of tall buildings.

SUMMARY

In the last twenty-five years, there has been dramatic improvement in concrete technology namely high-strength concrete, pumping of concrete and advances in formwork. Concrete has structural design advantages for tall buildings due to higher mass and higher damping. This article describes concepts for ultra-tall concrete buildings up to one mile (1 600 m) high.

RÉSUMÉ

Pendant les derniers vingt cinq ans, il y a eu un progrès énorme dans la technologie du béton, à savoir : le béton a haute résistance, le béton pompé, et le progrès dans les coffrages. L'avantage du béton armé dans les gratte-ciel est dû premièrement à sa masse, secondement à l'effet d'amortissement. Cet article décrit des idées pour l'étude de très hauts gratte-ciel, jusqu'à mille six cents mètres de hauteur.

ZUSAMMENFASSUNG

In der letzten fünfundzwanzig Jahren sind in der Betontechnologie grosse Fortschritte erzielt worden, insbesondere bei den hochfesten Betonen, beim Pumpbeton und in der Schalungstechnik. Infolge grösserer Masse und grösserer Dämpfung weist die Betonbauweise für grosse Bauhöhen Vorteile auf. Der Beitrag beschreibt Konzepte für extrem hohe Betonbauten mit einer Höhe bis 1600 Metern.

1. INTRODUCTION

In the last twenty-five years, there have been dramatic advancements in the technology of construction of tall concrete buildings with the advent of new forming systems such as slip-forming, flying forms, gang-forms, etc. Also, the development of ultimate strength design, the development of structural light-weight concrete, the development of high strength concrete, the use of admixtures (such as superplasticizers), and concrete pumping techniques have given concrete a great boost for tall structures. The evolution of structural systems particular to concrete construction, notably by the late Dr. Fazlur Khan, gave rise to the potential for taller concrete structures. In 1968, One Shell Plaza in Houston, a 50-story all light-weight concrete building was designed and constructed and became the tallest concrete building in the world. In the 1970's, Water Tower Place in Chicago was built and to this day, holds the record as the world's tallest concrete building at 864 feet (263m) in height. The tallest concrete structure, however, is the CN Tower in Toronto which is 1,500 feet (457m) tall. In 1977, the 75-story, 1,000 foot (304m) tall Texas Commerce Plaza was constructed in Houston. This building is the tallest exterior composite building in the world and has two unique features: First, all the concrete in the project was pumped and second, self-jacking exterior gang-forms were used for the construction of the exterior composite frame. The pumping of the concrete to 1,000 feet (304m) stands today as a record for the tallest height of pumping of concrete with a single-stage pump. The self-jacking exterior forms enabled the construction to proceed at a very rapid pace, and 72 floors of the building were constructed in eleven months due to this combination of techniques.

2. DESIGN CONSIDERATIONS

Tall buildings in non-seismic areas are governed not so much by strength considerations but by performance characteristics under wind loads. The most important considerations here are the sway of the building under wind loads and the motion perception that affects occupant comfort. Due to the inherently higher moments of inertia in concrete members and the higher modulus of elasticity for higher concrete strengths, concrete building design is generally not governed by the sway limits under wind loads. It is known that in tall structures, the two most effective methods of obtaining better motion perception performance under wind loads is to increase the mass and to increase the damping. Both of these factors favor concrete buildings. A concrete building will have a mass in the range of 10 to 25 pounds per cubic foot (160 to 400 Kg/m3) and a damping value ranging from one to two percent of critical damping. Both these values are higher than those for other materials and hence, concrete buildings perform better from motion perception considerations.

The evolution of economical structural systems for tall buildings in general has given rise to two guiding principles:

- Utilize as much of the gravity load as possible to resist the resultant axial forces due to wind load.
- Concentrate the gravity loads on the periphery of the building and preferably, at the exterior corners.

In structures made of very light-weight materials, it is essential that the two principles be followed to get economical design. The transfer of the gravity load to the exterior of the building results in the need for horizontal transfer elements (beams or trusses) at discrete levels in the building. These levels are the so-called "interstitial floors" and their costs offset some of the savings. In conventional building design (less than 100-stories tall), the gravity load transfer elements have to span in the range of 200 feet (60m). The spans will increase for taller structures.

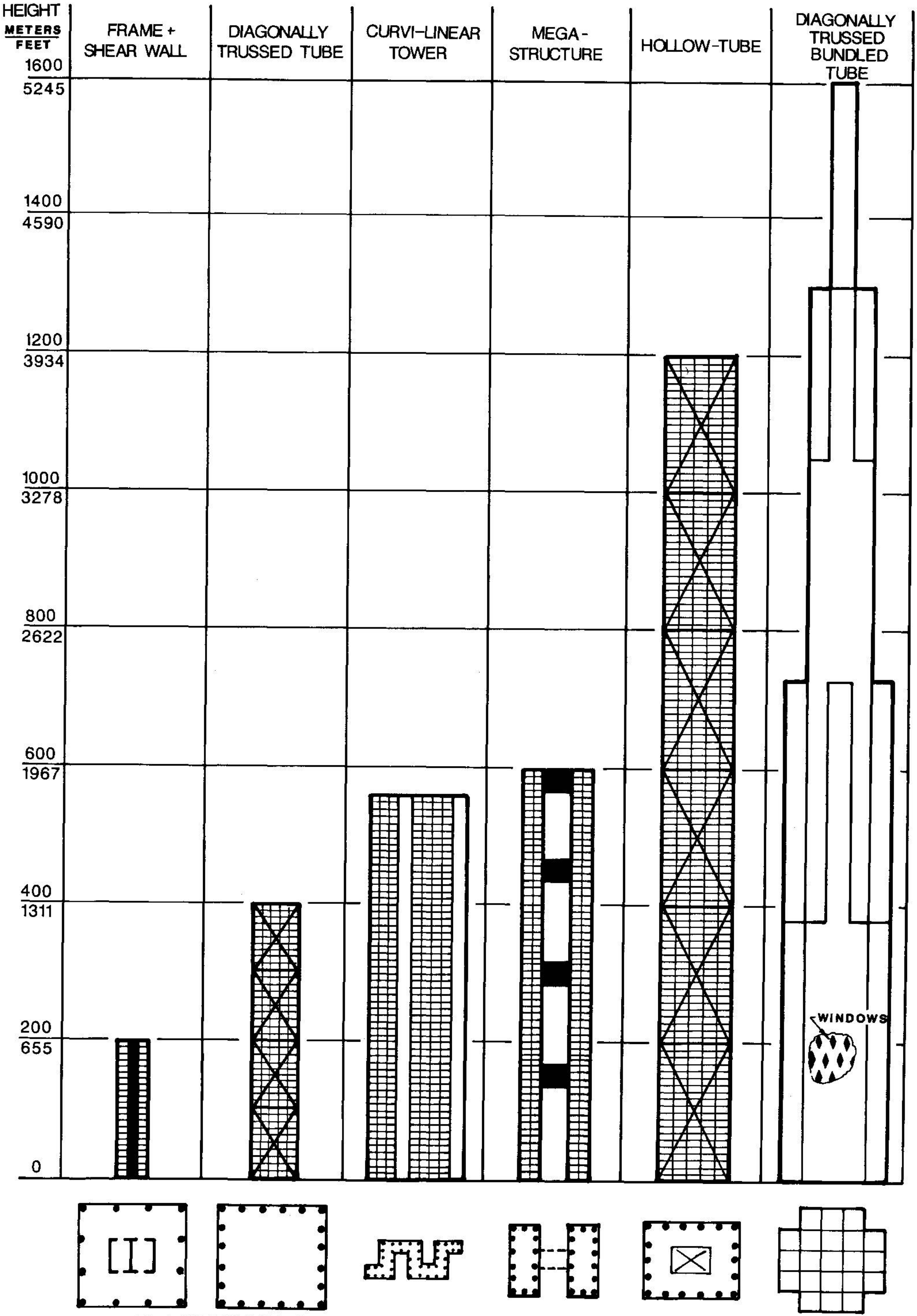

Fig.1 OPTIMUM STRUCTURAL SYSTEMS IN CONCRETE

In concrete structures, because of the high gravity load, it is seldom necessary to have these gravity load transfer elements. For ultra-tall structures (greater than 100-stories tall), the principles enunciated earlier can be achieved by several techniques. Fig. 1 shows a range of structural systems:

(a) Shape of the building in plan: Utilizing curvi-linear shapes or bent "hat" shapes to achieve maximum "depth" with a relatively narrow floor plan, large resistances can be built-up. This is analogous to the development of corrugated decking used for floors and roofs.

(b) "Megastructures": These consist of individual rigid building blocks that are linked together at discrete levels.

(c) "Hollow-Tubes": These are buildings where the inside of the floor plan is hollowed-out into an atrium (or a series of atria). The shape naturally tends to satisfy the two principles of design. If the building loads are further concentrated in the corners, additional advantages are gained.

(d) "Bundled-Tubes": In this concept, load bearing walls or columns are placed to subdivide a floor plan into cells. The columns will be "diagonally" braced. In the case of walls, the openings needed for architectural function are so arranged as to preserve the integrity of the wall.

3. DESIGN EXAMPLE

It was decided to investigate the feasibility of constructing a mile-high (1,600m) building in concrete as shown in Fig. 2. The selected building is 500 feet (150m) square at the base in order to obtain a good aspect (height/width) ratio, arranged in modules 100 feet (30m) square. Diamond shaped windows are the result of designing a "trussed bundled tube." This results in an extremely rigid exterior that resists a major portion of the wind loads and other forces.

Interior columns are spaced 20 feet (6m) on centers along the modular lines and are run continuously from top to bottom without any transfers. This forms 100 ft. (30m) square, column-free open spaces that meet most occupancy needs. As the elevators drop off, the structural modules are dropped off as shown in Fig. 2. The modules top out at 1,250 feet (381m), 2,400 feet (732m), 3,450 feet (1,051m) 4,250 feet (1,296m) and then on to the top of the building at 5,280 feet (1,600m). This gives the building a tapered appearance on the skyline.

A precast floor slab system was considered for the floor framing but a "super-waffle" with ribs at 20 feet (6m) on centers in each direction was finally selected. The waffle ribs are 2 ft. 3 in. (68cm) deep at the midspan and 3 ft. 6 in. (1.06m) deep at the columns. The 5-1/2 in. (14cm) floor slabs are light-weight concrete to minimize some of the dead load coming down the structure. An advantage of the waffle floor slab is that it distributes gravity loads very well. A drawback is the large amount of formwork required.

Wind pressures increase gradually from the bottom to the top. Using the Canadian Building Code, the gust response factor G is 1.02. Wind shear at the base is about 95,000 kips (43,100T) and the base overturning movement is 230 million kip-feet (32 x 106T-m). The sway is approximately 8 ft. 6 in. (2.6m) which is height divided by 621. The maximum wind stress in the exterior wall at the base is approximately 825 psi (58 kg/sq. cm), whereas the gravity stress under working loads is 6,100 psi (430 kg/sq. cm).

The fundamental period is 25 seconds and the building weighs 25 lbs./cu. ft. (400 Kg/m3) which is substantially higher than any other type of construction. For a damping value equal to 2% of critical, the Canadian Code analysis indicates acceleration at the top of the building to be higher than desirable. Experience has shown that compared to wind tunnel results, this analysis

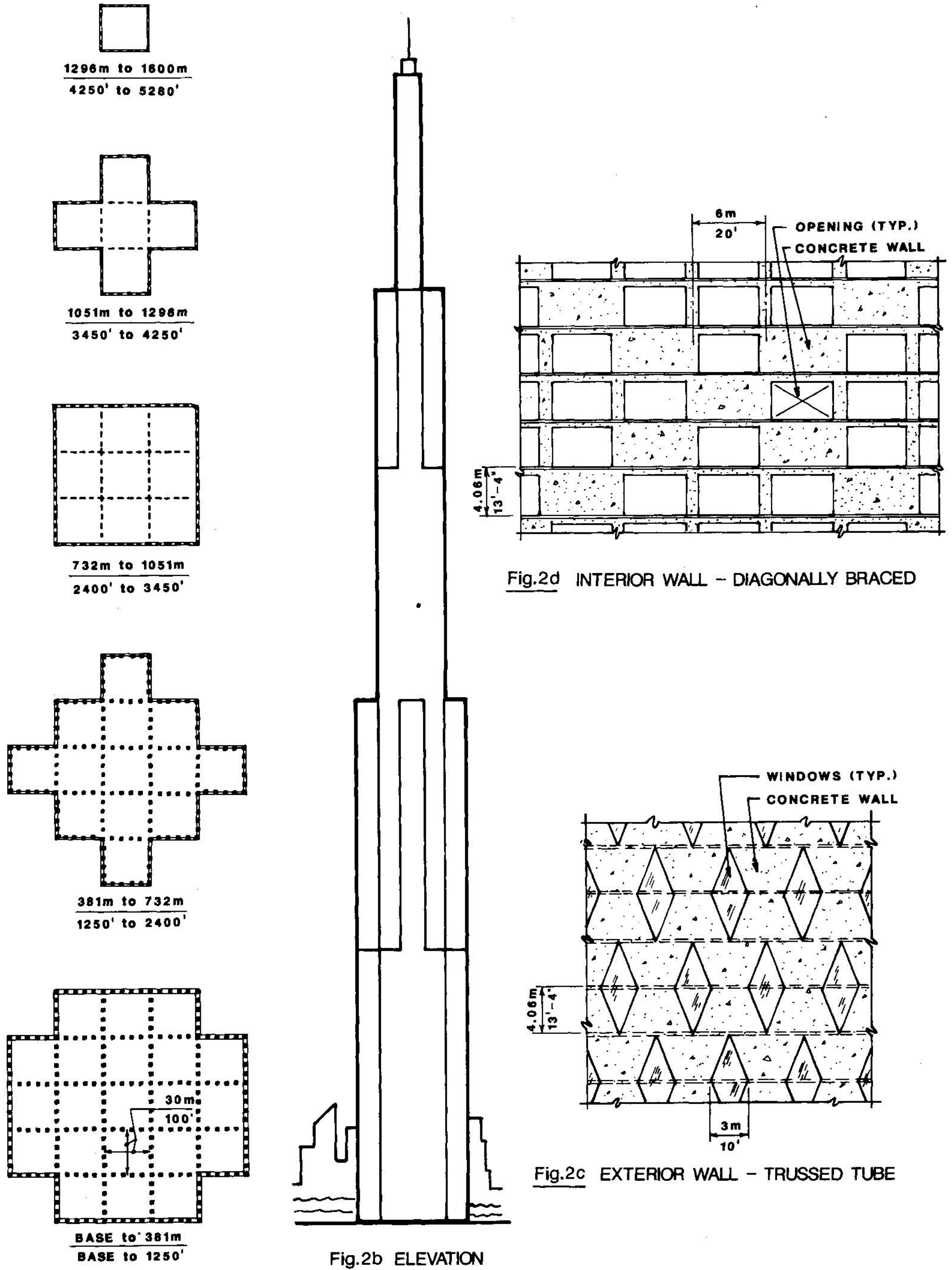

Fig.2a PLANS

Fig.2b ELEVATION

Fig.2d INTERIOR WALL - DIAGONALLY BRACED

Fig.2c EXTERIOR WALL - TRUSSED TUBE

Fig.2 MILE-HIGH BUILDING

overestimates acceleration by 25% - 30%. Since the building is so massive, it is unlikely that tuned mass dampers or an active damping system will be viable. Hence, other means, such as openings through the building, will be needed to minimize the accelerations.

Because of the dia-grid arrangement of the main building structure, the foundation is a mat 550 feet x 550 feet x 18 feet thick (168m x 168m x 5.5m thick). It could be thinned out at the center of each module, however, to reduce the concrete volume. The foundation loads are about 46 kips/sq. ft. (224T/sq. m.) so a minimum allowable soil bearing of 50 kips/sq. ft. (243T/sq. m.) is necessary - a bearing capacity available in several major metropolitan areas.

One of the main problems with using architectural exposed concrete, as we propose for this skyscraper, is that the exterior structure is subject to temperature variations. In the southern part of the United States, with mean low winter temperatures of 20°F (17°C), the average temperature of the exterior columns at the lower levels would be 49°F(9°C). Since the temperature on the inside is 70°F (21°C), there is a 21°F(12°C) differential between the exterior and the interior. In northern climates, this differential jumps to 35°F(21°C). The interior arrangement of the concrete columns with diagonals has the ability to resist these thermal movements although more detailed analyses are needed for the forces in the cross walls and resulting exterior wall movements.

There are several reasons that concrete was chosen for this "mile-high" structure. Combining architecture and structure saves a great deal of cost in the building skin. Concrete is a naturally fireproof material that does not, in general, require additional fireproofing. Monolithic concrete is able to absorb thermal movements, shrinkage and creep, and foundation movements.

Because of the continuity of concrete members, the structure has a great deal of redundancy. Deflections are low and the structure is inherently stiffer than any other kind of construction.

4. CONSTRUCTION TECHNIQUES

Recent analysis has shown that a cost effective way to design concrete columns is with 1% to 2% reinforcing and as high a concrete strength as possible. This is the philosophy that was used for column and wall design throughout the building. The maximum concrete strength at the base is a readily available 14,000 psi (1,000 kg/sq. cm.). Reinforcing is kept to a minimum for simplified detailing, especially at the splices.

A job-site batch plant, located in one of the basement levels, is essential. Since concrete can now be pumped to 1,000 feet (300m), hoists will lift the concrete to a height where the pumps will take over for the last 1,000 feet (300m).

Insulated, self-jacking forms will be used for the columns and walls. All materials and personnel hoists will be on the inside of the building to provide protection against the weather. Since the walls are very thick, insulation and other techniques will have to be devised to gradually dispose of the heat of hydration.

5. CONCLUSION

The conclusion is that concrete buildings even a mile-high are technically feasible. Concrete offers many advantages for tall buildings and, with careful planning, most of the disadvantages associated with height can be overcome.