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DESIGN OF HIGH-RISE BUILDINGS: PAST, PRESENT AND FUTURE

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ABSTRACT

An overview of development of high-rise buildings is presented. Key advancements leading to high-rise buildings of today are discussed. Structural analysis and design considerations for modern high-rise buildings are presented and trends in design of tall buildings of the future are discussed.

KEYWORDS

High-rise building, tall building, wind engineering, seismic design, lateral analysis.

HISTORICAL DEVELOPMENT OF HIGH-RISE BUILDINGS

While cities like New York and Chicago can be considered as the birthplace of modern high-rise buildings, the history of multi-storey construction is much older. The tower houses of Shibam in Yemen (Figure 1) date back to 1600 AD representing one of the earliest examples of human habitation in multi-storey construction. These sun-dried mud-brick tower houses have been constructed up to 7 stories tall providing security as well as prestige for their inhabitants. In a dense cluster of 500 or so, these tower houses have earned a world heritage listing (UNESCO 1982) and the nickname of “Chicago/Manhattan of the desert” for the old city of Shibam.

Social, economic and technological developments in the latter parts of the 19th century created the environment for modern high-rise buildings to emerge in North American cities of New York and Chicago. Perhaps the two most important technological factors contributing to emergence of modern tall buildings were advancements in steel structures and vertical transportation (ie, lifts). Gustav Eiffel used pre-assembled iron components to design and construct his 300m+ tall tower in Paris in 1889 thereby doubling the height of the previously tallest man-made structure in the world (ie, Washington Monument, USA) and showcasing the viability of tall metal structures. In 1852, Elisha Graves Otis built the first fall-safe hoisting system, the “elevator”, which made the case for tall buildings much more feasible.



Figure 1. Tower houses of Shibam, Yemen (1600AD)



The Home Insurance Building in Chicago is considered as the first steel framed gravity system used in high-rise construction (Figure 2). The replacement of thick masonry bearing walls -the common gravity resisting system up to that time- with steel columns allowed large windows and entries to be introduced on the perimeter of the building transforming the architecture and functional flexibility of common high-rise buildings.



Figure 2. Home Insurance Building, Chicago (1885)

The Ingal Building (now called the Transit Building) built in 1903 in Cincinnati, USA, is considered as the first “reinforced concrete skyscraper” (Condit 1968). This 16-storey building was built by monolithically casting the columns, floors and walls in concrete of relatively low strength by modern standards ($f_c < 20\text{MPa}$).

The chronology of other key technological advancement leading to tall buildings of today includes:

- 1950’s: High-strength bolts replaced hot-driven rivets
- 1950’s: Emergence of glass-metal curtain wall facade - United Nations Secretariat Building, NY (1952)
- 1960’s: Electric arc welding dominated shop fabrication
- 1960’s: $f_c = 40\text{MPa}$ achieved for concrete strength
- 1970’s: $f_c = 65\text{MPa}$ achieved for concrete strength
- 1990’s: $f_c > 100\text{MPa}$ achieved for concrete strength

HIGHRISE BUILDINGS OF TODAY

The increasing rate of urbanization in recent decades has seen an accelerated trend in construction of high-rise and tall buildings worldwide, particularly in the emerging economies of the world. A fundamental economic driver for the growth of tall (particularly residential) buildings is the scarcity of land in the densely urbanised parts of the world. The competition for constructing the tallest building in a city, country, region or the world has acted as another driver for the growth of tall buildings worldwide. In the past decade or so, the race for constructing the tallest (Figure 3) has been extended to include the contest for constructing the most iconic and spectacular high-rise building often characterized by complex geometries and leaning/twisting forms (Figure 4).

These trends have put the structural engineers at the core of the design process for tall building projects. Whether it is in the choice of the lateral load-resisting structure (LLRS) and/or floor systems, or in the approach for integrating the structure in the overall geometry and architecture of the building, the decisions made by the structural engineer have a profound impact on the cost, amenity, constructability, and sustainability of tall buildings.

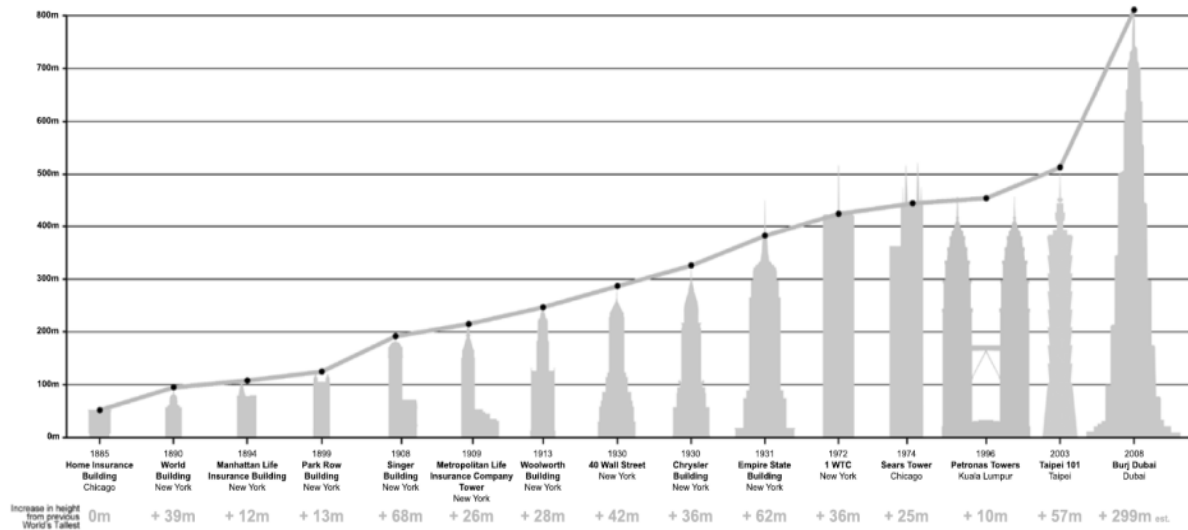


Figure 3. Progression of world tallest buildings (CTBUH 2010)



Figure 4. (a) Hearst Tower, New York; (b) Doha Tower, Qatar; (c) Capital Gate, UAE; (d) Shanghai Centre, China

Tall Behaviour

A building can be characterized as “tall” based on its absolute height, its relative height to the surrounding, or its slenderness. The Council on Tall Buildings and Urban Habitats designates heights of 200m, 300m and 600m as the thresholds for “tall”, “super tall” and “mega tall” status (CTBUH 2010). From a structural engineering point of view, as high-rise buildings get taller and more slender, their design becomes increasingly (and fundamentally) influenced by specific behavioural factors that are much less significant for shorter buildings. These factors include the dynamic response of tall buildings to wind loads both in the ultimate and serviceability limit states (ULS and SLS), and the differential axial shortenings of the vertical elements of tall buildings under gravity load effects. As far as these factors are concerned the absolute height of the building is not necessarily the best measure for “tall behaviour.” In particular, the magnitude of the dynamic wind response is more significantly influenced by the overall slenderness of the building and the natural frequencies of its fundamental modes (i.e., the first two sway modes about the principal axes of the building and its first torsional mode) than its absolute height.

The overall slenderness of a tall building is usually defined by its “height-to-base ratio”, being the height of the building divided by its narrowest plan dimension. Essentially, higher height-to-base ratios and lower natural frequencies increase the dynamic component of the response to wind. A building with a height-to-base ratio of more than around 5 and/or a fundamental natural frequency of less than approximately 0.2Hz is expected to respond to wind loads in a significantly dynamic way

(where building inertial effects are significant) or even in a potentially aero-elastic fashion (where building motion interacts with and influences the wind flow).

Structural Material

The structural materials used in high-rise buildings are typically one or a combination of (reinforced or pre-stressed) concrete, structural steel and composite systems. Structural material systems for high-rise buildings should be chosen by carefully considering architectural, economical and site factors. The economic drivers vary by geography as the relative costs of material, labour, time and space vary from one location to another. Other factors to consider in choosing the structural material include: local market preference/availability; project size/height; building form (regular vs complex); design considerations (fire performance, dynamic performance, adaptability, and the like); site location/access; and speed of construction.

Lateral Load Resisting Structure

The lateral load resisting structure (LLRS) -also referred to as lateral stability system or wind frame-consists of all structural elements which form part of the load path(s) for transmitting the lateral effects of all loads (wind, earthquake, eccentric gravity effects, unbalanced lateral earth pressures loads) from their sources to the foundation in any direction. These elements typically include walls, beams, columns, floor diaphragms, and footings.

Typical forms of LLRS for tall buildings include:

- Core and Frame (common for office buildings)
- Core and Shear Walls (common for residential buildings)
- Core and Outriggers: (used in office/residential buildings)
- Core and Belt Truss Frame (used in office/residential buildings)
- Trussed Tubes (used in tall to super-tall buildings)
- Bundled Tubes (common solution for super-tall building)

The effects of wind on LLRS can be considered in two parts, namely: (a) ULS load effects affecting the strength design of LLRS; and (b) wind motions due to dynamic response to SLS wind loads affecting the serviceability of the structure in terms of human perception (peak accelerations and velocities). Appropriate mitigation of the risk of perceptible wind motions in taller buildings would sometimes require provision of supplementary damping, often in the form of Tuned Mass Dampers (Kayvani 2008 and 2011)

The general principle behind efficient design of LLRS of tall buildings is to engage the perimeter structure (ie, columns) with the core(s) within the constraints of planning and architecture. By effectively engaging the perimeter columns the structural width of the LLRS (and hence its efficiency) is increased dramatically. Also as the perimeter columns are preloaded in compression due to gravity loads, they can resist wind-induced tensions (or, more accurately, decompression) very economically (with minimum need for tensile reinforcements). Adjacent cores are often engaged together with “header beams” (typically running across the lobbies) allowing the core boxes to act in a compound manner in resisting the lateral loads, ie, to develop “push-pull” couple over their cross-sections rather than simply bending independently. The perimeter columns can be engaged with the core(s) by either direct or indirect “shear linkage” elements. The direct shear links can be provided by outrigger walls connecting the core(s) and the columns. The indirect shear links can be provided by offset outriggers, belt walls, and the like.

Gravity Structure

The gravity structure of a high-rise building comprises of all structural elements which form part of the load path(s) for transmitting the vertical effects of gravity loads (ie, dead and live loads) from their sources to the foundation. Elements of the gravity structure typically include floor slabs, beams, columns, (bearing and transfer) walls, and footings.

Optimum design of typical floors is often a critical aspect of the high-rise building design owing to the cumulative benefits that can be realised by reduced self-weight and structural depth (in terms of floor-to-floor height). However, as the design of the typical floors get optimized for their strength (ULS) performance, their SLS performance in terms of deflections and vibrations becomes more dominant. This requires the floor vibration adequacy to be verified by resorting to computational mechanics where peak (acceleration) response factors are obtained and compared with tolerable limits in terms of human perception.

Differential Shortening Effects

Design of taller building can be affected by the differential shortening of its vertical structural elements under gravity loads. This is particularly critical when vertical elements are of reinforced concrete construction. Vertical concrete elements shorten differentially over time due to differences in elastic strains, shrinkage and creep effects. In particular, the core walls tend to shorten less than the tower columns. This is due to the fact that the permanent gravity stresses and strains in a core wall group (which form part of the LLRS) are often significantly lower than those of the columns which have a primary gravity load resisting function. Lower axial stresses will also lead to lower creep deformations. Furthermore, the core walls are typically constructed ahead of the columns. Hence, they are subjected to earlier shrinkage and creep effects. The net result could be a significant long term differential shortening between these elements.

The analysis of differential shortening is significant in terms of assessing both the geometric effects and the load effect implications. While the geometric effects of differential shortening are primarily about floor flatness, the load effect implications can be much more complex when the LLRS is statically indeterminate under gravity loads. The vertical indeterminacy occurs when “direct shear linkages” (as defined earlier) are present in the LLRS and would lead to redistribution of gravity stresses in the LLRS. The stress redistribution would change over time due to creep relaxation effects in the linkage elements further complicating the design of the elements of the LLRS, namely, the columns, walls, footings and shear linkage elements themselves (ie, header beams, outrigger walls, etc). In order to avoid an overly conservative (and hence costly) design approach (using envelopes of the upper and lower bounds of the indeterminate response), one can employ nonlinear FEA modeling concrete cracking and creep as well as the expected construction sequence (Kayvani 2010).

HIGH-RISE BUILDINGS OF TOMORROW

Although the drive to deliver good functional and economical design for high-rise buildings is unlikely to change fundamentally, the focus on producing energy efficient and sustainable design is expected to increase at an accelerating pace. This is a response to the fact that buildings consume 40% of energy use, 40% of material use, 30% of waste generation and 15% of water use globally, and that tall buildings are proportionally more material- and energy- hungry than lower rise buildings. In high-rise buildings the structure is a large portion of the overall cost and embodied energy, and hence, the structural engineer can significantly influence the overall sustainable design outcome.

Sustainable structural design goal can be achieved by addressing the three objectives: Reduce, Reuse and Recycle. Advanced analysis and design methodologies are allowing us to design increasingly more efficient structures (with just the required amount of material and no more). Also, new material technology is opening the way for reduction of embodied energy per unit of material (in terms of transport energy, sustainable supplies, and the like). The use of industrial by-products such as fly-ash, slag and silica fume as cement substitution can drastically reduce the embodied energy of concrete.

“Reuse” is about adapting the use of a high-rise building while keeping the original structure. There are growing examples of reusing of high rise buildings both in Australia (Figure 5) and internationally. To achieve future reusability of high-rise buildings, an important design consideration is provision of “planning flexibility.” This can be achieved in the design phase by generous choice of structural grid, live load allowances and the like (ie, use longer spans and larger live load that are more adaptable to

future reuse). The emergence of BIM as a repository of information for asset management (as-built drawings, mill certificates and the like) is also expected to facilitate future reuse opportunities. Future high-rise buildings are likely to be designed with more consideration for recyclability of structural components (beams, columns, etc).

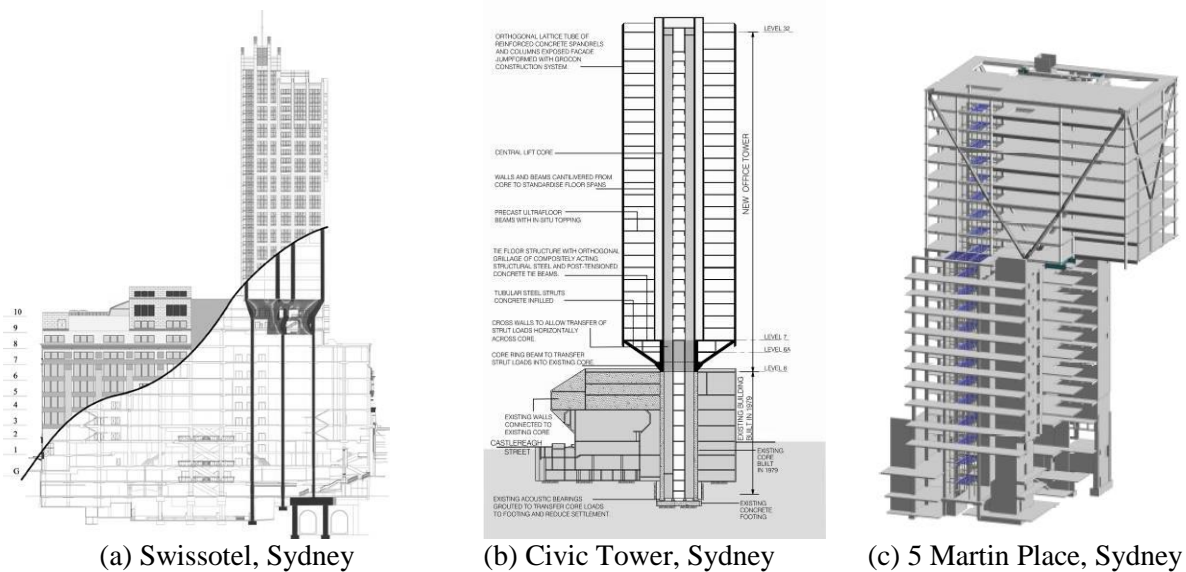


Figure 5. Building redevelopment and reuse

The other growing trend is in offsite fabrication of high-rise buildings. As labour costs escalate relative to material costs and as the construction safety and quality gain increasing attention, solutions involving prefabricated or manufactured structural components and building modules are gaining increasing popularity. There is a growing trend in construction of high-rise building from fully modular systems.

CONCLUSION

In this paper an overview of development of high-rise buildings was presented. Key advancements leading to high-rise buildings of today were discussed. Structural analysis and design considerations for modern high-rise buildings were presented and the trends in the design of tall buildings of the future were discussed.

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