Structural Systems for Tall Buildings

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Structural systems for tall buildings have gone through an evolutionary process. The rigid frame became popular in the first half of the 20th century but proved to be structurally inefficient beyond a certain height of tall buildings. The invention of the tubular structure in the 1960s allowed buildings to be built taller with low material consumption. Due to the obstructive nature of the closely spaced exterior columns of framed tubes and bracings of braced tubes, the core-outrigger system gained acceptance by the architects as it allowed them to freely articulate the façade design. However, the conventional tubular structures continued to retain their use for tall buildings to a lesser degree and later underwent a resurgence in modified forms. These and other advanced tubular forms in cutting-edge structural systems developed later continue to find application in modern times. This study presents a detailed narrative of different structural systems for tall buildings that is expected to assist structural engineers and architects to collaboratively select appropriate structural systems for tall buildings.

Keywords: tall buildings ; gravity-load systems ; lateral-load systems ; shear walls ; bracings ; rigid frames ; structural systems charts ; tube structures ; core-outrigger systems ; interior and exterior systems

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A principal characteristic of all tall buildings is their verticality or quality of tallness. As buildings become taller, both the gravity loads and lateral loads on them increase. One of the most fundamental attributes, which makes tall buildings of ever-growing heights physically possible, is to provide structural efficiency, i.e., using skeletal frames. Early multistory buildings were built using mainly masonry with low compressive strength. Thus, the walls carrying the weight from the upper floors needed to be very thick and heavy, so the buildings did not collapse under their own weight and thus became inefficient beyond a certain height.

The invention and application of the skeletal metal frame system, albeit in a rudimentary form, by William LeBaron Jenney for the Home Insurance Building of 1885 in Chicago, generally recognized as the first skyscraper of the world, marked the beginning of a new era for tall buildings. Although the Council on Tall Buildings and Urban Habitat (CTBUH) has defined "tall," "supertall," and "megatall" buildings, it has not formally defined a "skyscraper" [1]. Architectural historians have diverse opinions about what is the first skyscraper [2]. Ali and Moon offered some essential criteria for characterizing a tall building as a skyscraper and reconfirmed the Home Insurance Building as the world's first skyscraper to satisfy these criteria [3]. The skeletal system reduced the need for a large masonry mass to support the tall buildings. It also allowed for a rudimentary curtain wall system and interior daylighting. Later, a rigid moment-resisting frame (MRF) in which the beam-to-column joints are rigidly connected was developed, making taller and lighter buildings possible. However, the taller and lighter framed buildings faced a new problem of requiring plentiful structural material to resist lateral wind forces and reduce the building's sway. For tall buildings above 10 to 15 stories, the lateral sway due to wind forces becomes the dominant design criterion and central concern of structural performance. In the absence of a better structural system, all latter-day tall buildings, including New York's Woolworth Building of 1913, Chrysler Building of 1930, and the Empire State Building of 1931, employed MRF and wind bracing for lateral stability as needed.

Before 1965, the design of structural systems for tall buildings was conducted utilizing the planar rigid frame by fastening together beams and columns to create a stiff structural grid to resist wind loads. Fazlur R. Khan questioned this in 1961 and tackled the entire issue of structural systems for tall buildings [4]. He realized that as buildings become taller, there is a "premium for height" to be paid due to lateral loads. The demand for the structural system increases dramatically, resulting in an exponential increase in structural material consumption [5], pp. 40–41. Khan developed his revolutionary height-based chart for structural systems in a hierarchical order for tall steel and concrete buildings [6]. This paved the way for generating a plurality of structural systems and made it possible to design and build taller and more economical buildings. Many structural and modified systems appeared on the scene to conquer the sky, defining higher skylines of cities. In addition to the tubular structure and its various modified forms that Khan developed, he also described the "ultimate structure" in which he demonstrated that maximum efficiency could be achieved by progressively relocating the exterior columns to the corners of a rectangular braced tube [7].

Beginning in the 1980s, the open-exterior tall buildings became well-liked by architects instead of the externally obstructive framed and braced tubes. During the late 1980s and 1990s, and onward, the outriggers coupling the core and widely spaced perimeter columns, creating the core-outrigger system, gained more acceptance amongst architects. Meanwhile, structural systems such as composite structures, diagrids, and variations of tube systems, also appeared or began to appear on the scene. Starting from about 2000, many other structural innovations emerged to meet the challenge of increasing the heights of supertall and megatall buildings.

Details of Evolution of Structural Systems

The logic behind the development of structural systems rests on rational pragmatism, economy of material consumption, simplicity and elegance, and concern for constructability. In discussing the progression of structural systems for tall buildings, metamorphosis can be observed among them at different times. In the beginning, a tall building was of masonry construction occasionally supplemented with metal elements. This was followed by skeletal construction with the 10-story Home Insurance Building of 1885, marking the commencement of the metal frame skyscraper structure. In 1903, the 15-story Ingalls Building in Cincinnati, Ohio, designed and built by A.O. Elzner, was the first reinforced concrete high-rise building. The first detailed study of the “Effects of Scale” was carried out by Myron Goldsmith in a master’s thesis at the Illinois Institute of Technology (IIT), Chicago, in 1953, under the supervision of Mies van der Rohe [8]. A new era set in for taller and cost-effective buildings when during 1961–1969, the frame-shear interaction and, more remarkably, the tube systems were developed by Fazlur R. Khan. During 1966–1969, the groundbreaking height-based structural systems charts for tall steel and concrete buildings were developed by Khan. The 38-story reinforced concrete Brunswick Building using the shear wall-frame interaction principle and the 42-story reinforced concrete Dewitt-Chestnut Apartment Building using the framed tube concept, both located in Chicago and built in 1965, were engineered by Khan. Although the Brunswick Building resembles a tube-in-tube structure, it was designed, without regard for any tubular action, as a shear wall-frame interaction system, where the exterior frames parallel to wind direction were designed for shear wracking, and the three-dimensional behavior of the exterior frames was also captured by cantilever analysis [5], pp. 86–87. Meanwhile, in 1964, the 47-story reinforced concrete Place Victoria building in Montreal by Pier L. Nervi was built as the first application of the core-outrigger concept.

Completed in 1970, the 100-story John Hancock Center in Chicago was designed by Fazlur R. Khan as the first steel braced tube structure. The 20-story Control Data Center in Houston, TX, designed by Khan was the first modern steel-concrete composite building built in 1971. In 1973, the World Trade Center in New York City (destroyed in 2001) was the first steel-framed tube structure designed by Leslie Robertson. Shortly after, the 109-story Sears Tower in Chicago was built in 1974 and engineered by Khan as the first steel bundled tube structure. Khan’s 57-story One Magnificent Center of 1983 in Chicago was the first concrete bundled tube structure. In 1985, the 58-story Onterie Center in Chicago, also designed by Khan, was the first concrete braced tube building. Since circa 1985, and especially 1990 and onward, various structural systems have been used for tall buildings to cater to the demands of Postmodernism and later Pluralistic architectural styles.

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