

Innovative Technologies and Future Trends in Tall Building Design and Construction

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Abstract:

Tall buildings have always relied on technological innovations in engineering and scientific advancements. Technological breakthroughs in areas such as structural systems, design and construction methods, elevator systems, natural lighting and ventilation systems, as well as new materials, coupled with the latest digital revolution, have incrementally changed the overall architectural design of tall buildings throughout the world. Today the focus continues to be on new technologies and materials that exhibit enhanced properties.

This paper focuses on the technological and engineering developments, and their impact on the design and construction of tall buildings by presenting a number of case studies, which have been constructed, being constructed and being proposed as well. It first provides an historical background on the early development of tall buildings, then it presents the innovative technologies applied in tall buildings, by means of architectural design, innovative structural systems, new and smart materials, improvements in elevator systems and façade technologies, via the help of latest applications. Next, it examines the future trends in tall buildings and finally it engages the reader in a discussion on the issue of height limit from economic, technological, and ego perspectives.

Keywords: Tall buildings, Structure, Form, Nanotechnology, Smart materials, Façade, Natural ventilation, High-strength concrete, Self consolidating concrete.

1. Introduction

Increasing density in urban areas is now widely accepted as necessary for achieving more sustainable cities to reduce environmental impacts on green areas and energy consumption, thus struggling with climate change. The concentration of people in denser cities offers much greater efficiency in energy and resources than the expanded expenditure in infrastructure and mobility. According to the UN's forecasts, 70% of the world's projected nine billion population will be living in urban areas by the year 2050 [1]. This means that 2.8 billion people will move into cities over the forthcoming 40 years; with the annual rate of 70 million people per year. In this context, it seems that tall buildings are the only solutions for urban agglomerations and living dense.

Given the recent scale of the major population shifts, the vertical city decorated by tall buildings is increasingly being seen as the most viable solution for many urban centers. According to the Council on Tall Buildings and Urban Habitat (CTBUH) [2], there have been 320 proposed buildings 500 meters or taller; with 97 buildings taller than 300 meters already under construction around the world in 2012. The vast majority of these buildings are designed to be constructed, or

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readily being constructed with the advent of state-of-the-art technologies, such as lateral load bearing systems, vertical transportation, energy damping systems, and etc. These buildings also utilize innovative approaches for sustainability, such as renewable energy systems, latest façade technologies and smart materials produced by nanotechnology. These innovative technologies are employed not only for structurally and architecturally efficient tall buildings, but also to offer the best solutions for occupant health, as well as for more sustainable built environments.

This paper primarily examines the latest and innovative technologies applied for the sustainable tall buildings of the future. After providing a historical background of technological development of tall buildings, the innovations and technological developments will be revealed. Finally the height limits for tall buildings is discussed.

2. Historical and Technological Development of Tall Buildings

Throughout the history, tall buildings are the result of the complex interaction of many events and innovations in structural and mechanical systems, as well as artificial lighting, curtain wall systems, and etc. The tall building typology has emerged with the office function in 19th century in New York and Chicago. The prosperity of these cities were greatly attractive for people, who leaved in rural areas and then moved into these cities for their wealth. As the population grew rapidly in urban areas, demand appeared towards more and more floor area for living and working, also driving the land prices high. Consequently, the land areas in city centers became more valuable, introducing the tall building type, which paid money from the land to its owner.

The birth of the tall buildings can be directly associated with the development of structural systems. The first examples were constructed by load-bearing masonry walls, thus making them very heavy, so they necessiated stronger foundations piled into the stiff bedrock, which would have been impossible without the invention of steam powered drilling and digging machines in the 1830s[3] [*]. Also the early tall building developments were based on economics; increasing rentable area by stacking office spaces vertically, and introducing as much natural light as possible was the prior task. In order to achieve this task, new technologies were developed upon the conventional load-bearing masonry walls that had relatively small openings. The result was the iron/steel frame structure, which minimized the depth and width of the structural members at building perimeters. Economically favorable, mass-produced rolled steel became available after 1856 through Henry Bessemer's invention. This "Bessemer process" enabled the emergence of steel skeleton-frame structures [4]. This development in structural technology was supplemented by the "curtain wall," which was hung from the exterior frame at each floor. Since it was not structural, it could be made of thinly cut stone, glass, metal, or any other material that could be mass-produced. 10-story Home Insurance Building (1885) is generally recognized as the first tall building for being supported with a steel-framed structure, instead of load-bearing masonry walls. However, top floor offices were not attracting tenants until buildings were equipped with safe elevators until the invention of the safety elevator by Elisha Otis Graves in 1854 [5]. The Equitable Life Insurance Building (1870) in New York was the first office building to use passenger elevators. Fireproofing became a big issue in the 1870s, after Chicago and Boston experiencing serious fires in 1871 and '72. As Chicago's city center was destroyed by the fire, wooden structures had to be replaced mostly by fireproofed steel. Peter Bonnett Wight was one of the researchers of new approaches in fire safety. The 70s were fertile years as electric lighting and steam-driven, forced draft ventilation systems became available in buildings,

breaking down the least barriers to safe and comfortable tall buildings [6].

The late 19th century and the early 20th were many inventive years, and the structural engineers developed new types of foundations, fire resistant structures, wind bracing, emergence of cast iron and steel, curtain walls and many others. Masonry construction was on its peak by the construction of Monadnock Building (Chicago, 1891) with 15% of the ground floor area occupied by masonry walls [7]. By the turn of the century, the technical limitations slowly disappeared. Before the mid of the 20th century the height limit passed over 300 meters with the Chrysler Building of 1930 and Empire State Building of 1931, in New York. Even though the heights were significantly increased during this period, there had not been much conspicuous technological evolution. In terms of structural systems, most tall buildings in the early 20th century employed steel rigid frames with wind bracing. Due to the absence of advanced structural analysis techniques, they were over-designed, and very heavy with enormous amounts of structural steel.

After the World War II, the era of mass production came and the International Style emerged by the architects educated in Europe and influenced by Bauhaus. The major driving force of tall building developments was economy in this era. Mies van der Rohe's contribution to tall buildings' evolution was great. 860-880 Lake Shore Drive apartments (Chicago, 1951) and Seagram Building (New York, 1958) were the remarkable examples of this new approach. The International style continued until the late 1960s, the time of the construction of Minoru Yamasaki's collapsed World Trade Center twin towers (New York, 1969).

Technological innovations for tall buildings have undergone dramatic changes since the demise of the conventional rigid frames in the 1960s. Changes in the structural form and organization of tall buildings were imperative because of the emerging architectural trends in conjunction with the economic demands and technological developments in the realms of rational structural analysis and high-speed digital computers. Beginning in the 1980s, the previous design approaches in tall buildings were replaced by innovative technologies in structural systems, such as diagrids, mega frames with core and outriggers, involving tubes, artificially damped structures, and etc. Not only the structural systems, but also the architectural design trends also changed dramatically. Non-orthogonal, out-of-box forms, such as twisting, tilted and leaned forms emerged with the advent of new structural innovations and digital design/analysis methods. Now the demand for high-quality and sustainable tall buildings, equipped with advances in environmental technologies is increasing. Proliferation of information technology has facilitated the design and construction of tall buildings with limitless possibilities. The prevalent green movement has propelled the design of today's tall buildings employing intelligent technologies and smart materials. In the following section these technologies are presented.

3. Innovative Technologies in Tall Buildings

3.1. New Architectural Forms and Design Trends

Tall buildings of the past were mostly designed in box-forms dictated by the repeating floor organizations, and strict rules of structural systems, such as rigid frame and core interacting systems. The contemporary tall building designs are no longer monolithic vertical extrusions of

an efficient floor plan, and do not have box forms dictated by the structural scheme. In the light of structural developments and digital revolution, complex forms, such as twisting, tilted, leaned, bundled, free and regional forms inspired by cultural motifs, can be designed and constructed by creative architects. Petronas Twin Towers, Jin Mao Tower, Taipei 101, Bahrain World Trade Center and Shanghai WFC are the initial and remarkable examples of this new trend.

One common approach in the design of these various and out-of-box forms is to eliminate the strong wind loads on the high altitudes for the task of achieving efficient structures, which are also comfortable for the occupants for that of decreased motions caused by the wind [8]. Integration of these aerodynamic design principles, which will be handled again in the following sub-section, as in the case of Swiss Re Tower in London, Shanghai Tower in Shanghai, Burj Khalifa in Dubai, and many other tall buildings constructed, also decreases the amount of structural material, thus contributing to the sustainability of this building type. Aerodynamic forms of contemporary tall buildings have chamfered or rounded corners, streamlined forms, tapered forms, openings and notches. For instance, Pearl River Tower's (Guangzhou) funnel form façade is designed to catch wind not only to reduce the building's motion but also to generate energy via the wind turbines. Due to the nature of the strategy, which manipulates building masses and forms, this approach blends fittingly with architectural aesthetics. Another approach is to incorporate porosity into the fabric of the building. This can be observed in the Aspire Tower in Doha (Qatar) and the O-14 Building in Dubai, UAE.

3.2. Innovations in Structural Systems

Structural system plays a significant role in determining the overall form and efficiency of a tall building. As mentioned before, the tall building typology shifted from North America to Asia during the last two decades, and the most significant trend related with tall building construction in Asian countries is designing iconic and out-of-box forms. Behind these new forms are the products of the contemporary technology and innovative structural systems, such as mega frames, diagrid systems, core and outrigger structures, buttressed core, and etc.

As tall buildings become increasingly taller, the danger of collapse due to wind, earthquake and gravity loads also grows up. A tall building's slenderness ratio has a major influence on its structural efficiency. Although for wind loads dynamic influence becomes important at a slenderness ratio of about 4 and above, it starts being highly critical at higher values [9]. Aerodynamic modifications in conjunction with structural optimization are effective design approaches for reducing wind-induced vibrations in tall slender buildings, as mentioned in the previous subsection. The principal approach is to "confuse" the wind by disrupting its flow as a boundary layer and not allowing it to re-organize by creating mild turbulence around the building. Such modifications are implemented by providing a building's cross-sectional shape, varying the cross-section along the height, slotted or chamfered building corners, fins, setbacks, openings, sculptured tops, and etc. Different types of damping systems in such buildings can also significantly improve structural efficiency [10].

As the latest innovation in the structural systems of ultra tall buildings, "buttressed core system" is employed by Bill Baker in the tallest building of the world, Burj Khalifa. As a residential tower, the building required floor plates with shallow lease spans, maximizing the

amount of exterior window area. As a very tall tower, it also required a wide footprint to provide sufficient stability to resist high wind loads. The Y-shaped arrangement of the plan with reinforced concrete shear walls around a central hexagonal reinforced concrete core satisfies both of these requirements. The resulting buttressed core is an extremely efficient solution for a super tall residential tower [11].

The large concrete structural core acting as a solid tube is now gaining more significance in super tall buildings to resisting lateral loads. This was also employed in the unbuilt, 610 meters tall Chicago Spire Tower project, designed by Santiago Calatrava and engineered by SOM. The concrete core is also a reliable part of the structure to evacuate during emergency, such as fire or terrorist attacks.

A wide variety of systems to resist lateral loads are being employed today since excessive lateral displacement caused by an earthquake or wind load is important in the design of a skyscraper. Outriggers, connecting the core and the mega frame are widely used to single structures of less than 100 stories for controlling lateral displacement. However outriggers are not enough to control this displacement for ultra heights. In this context, another recent approach in increasing the efficiency of ultra tall buildings is to design twin-tower-type or bundled-type structures and connect them with skybridges, which enable to control the displacement of each single unit. The Petronas Twin Towers in Kuala Lumpur (88 story, 452 m), the proposed Incheon Tower in S. Korea (102 story, 487 m) and East Pasific Center in Shenzhen (70 story, 300 m) are the remarkable examples of this approach. In this approach the outrigger system is effective in controlling lateral displacement on central floors, whereas the skybridge is effective on upper floors. According to Chae and et al., the skybridges, especially placed on top floors, can be used for moving and evacuation in emergency, however they are not proved to be efficient [12]. Consequently placing skybridged on top floors must be taken into careful consideration when designed for evacuation.

Another new system invented by Nejad and Kim [13] is the Beehive or Hexagrid system for tall buildings. This system, very similar with diagrids, is configured by locating hexagonal and diamonds along the exterior perimeter surface of the building in order to maximize their structural effectiveness, as well as the aesthetic appearance as well. This strategy is experienced by Nejad and Kim on a 80 story building with the optimized angle and hexagon members; as a result, it is found that hexagrid structures are much more effective in minimizing shear deformation, since they carry shear by axial action of the diagonal members, while other structures carry shear by bending of the vertical columns and horizontal spandrels. Being a self-reliant structure, the use of this system is not wide yet. Very few examples, such as the SinoSteel Plaza in Tianjin, utilize this system. Providing mostly column free exterior and generous amounts of daylight, this system offers roughly 10 to 15 % structural material reduction, necessitating less foundation materials, as well.

3.3. Smart Materials and Nanotechnology

Tall buildings have always relied on technological innovations in materials and scientific advancements. Technological breakthroughs in materials science have incrementally molded the form, height, and design of the buildings, as well as their sustainability performance.

A major transformation is likely to occur for tall buildings in the realm of smart and nanomaterials. Smart materials are characterized by improved and enhanced physical properties, which can be modified to have better performance than ordinary materials. Advances in physical sciences have led to a new generation of smart materials, particularly those comprising acoustical, luminous, electrical and thermal environments of buildings. Ritter [14] divides these materials into six categories; piezoelectric, electroactive, photostrictive, thermostrictive, magnetostrictive, chemostrictive materials, shape memory alloys and fiber optic sensors. These smart materials can constitute the components of a smart structure, which is an electronically enhanced, non-biological, physical framework that has a definite purpose. The structure functions to resemble a biological organism and adapts to changing conditions in the environment. For example; piezoelectric materials convert mechanical energy into electrical energy when strained. Piezoelectric dampers have been developed as an example of controllable materials, which can be incorporated into tall buildings. Effectively the dampers incorporating these smart materials (i.e. piezoelectric) are used as a part of a smart structure in order to respond to the motions without sensors and actuators. This form of damping has been tested in Japan on a 30-storey building, and it was found to be effective in reducing the accelerations experienced under particular levels of wind loading by up to 50%, compared to an undamped case [15]. These materials can also be integrated with a tall building's structural members to generate electrical power under the effect of wind loads.

There are other forms of smart and controllable materials, such as Shape Memory Alloys (SMAs), which have been discovered to use in aeronautical industry. SMAs can be used as temperature sensors for automated ventilation systems or as actuators for sensing and monitoring devices in tall buildings.

NanoTechnology (NT) has also wide applications in the construction industry, and is a very attractive area of study for innovative tall buildings for a number of design objectives [16]. With nanotechnology the primary properties of traditional construction materials, such as concrete, can be improved and the functionalities can be enhanced, i.e. paintings/coatings, or glass may gain self-cleaning, antimicrobial and pollution reducing properties. For example, when exposed to ultraviolet light, TiO_2 nanoparticles in paint breakdown the organic and inorganic pollutants that wash off in the rain. The nanoparticles also decompose air pollution particles, such as formaldehyde. Another application is the solar nanotechnology, where ultra-thin, amorphous silicon, organic and inorganic solar cells derived from nanocrystals can convert sunlight into electricity. With nanotechnology, tiny solar cells can be printed onto flexible, very thin light retaining materials, which has a great potential of use in tall buildings of the future. Nanomanipulated exterior coatings or nanoencapsulated corrosion inhibitors, such as Nanotec can be applied to concrete structural members as weatherproof coating in order to prevent corrosion of steel members [17]. NT can introduce new materials to fill existing gaps, such as silica aerogels for thin and effective or transparent insulation.

Concrete is the cornerstone of the construction industry, and for tall buildings as well. Concrete construction has always had an inherent advantage for tall building design, since it provides a significant amount of stiffness and damping for the structure. However, it was not until more recent advancements in material technology that concrete systems took the lead in high-rise construction. The proportion of all-steel tall structures in the 100 tallest list was 90% in 1970,

however with the shift in favor of concrete or composite materials, the proportion of steel structures decreased and concrete and composite structures climbed up rapidly [18]. The advances in concrete construction technology, such as self-climbing robotic formworks, reusable forms, prefabricated reinforcement cages, and state-of-the-art concrete pumping systems for ultra heights, allowed the speed of concrete construction to compete with steel [19]. Also Very High Strength Concrete (VHSC), Self-Consolidating or Self-Compacting Concrete (SCC), Lightweight concrete, and other concrete mixtures led the concrete to be the only alternative structural material for ultra tall buildings, such as the 828-m, 160-storey high Burj Khalifa in Dubai and 1000-m, 167-storey Kingdom Tower in Jeddah. VHSC defined as having compressive strength of 240 Mpa, has steel fiber reinforcement incorporated in the mixture and achieves a flexural tensile strength of 40 MPa [15]. Typical high-strength concrete mixes have been noted as having ductile tensile and capacities, which are not enhanced as much as compressive strengths, however VHSC is an attempt to overcome this issue. This innovative structural material will provide a potential route to smaller cores and columns in taller buildings of the future.

SCC has been widely used in large area mass concrete pours, such as foundation rafts of tall buildings. Typical examples are the Al Faisallah tower in Riyadh (6000 m^3 at $375 \text{ m}^3/\text{hr}$) and the Landmark Tower in Abu Dhabi ($16\,000 \text{ m}^3$ at $400 \text{ m}^3/\text{hr}$), where the use of SCC enabled the full pours to be carried out without construction joints. Equally important, SCC reduces the risk of problems with concrete placement and compaction where multiple layers of large diameter bars are used.

Burj Khalifa, completed in 2010, utilizes very strong, high density concrete composed of Portland cement in combination with silica fume, fly ash, and ground granulated slag, resulting in a structure which is stiff, strong and highly constructible. The superstructure of the Burj Khalifa is supported by a large 3.7 meter thick reinforced concrete mat, which is in turn supported by 1.5 meter diameter bored reinforced concrete piles. The mat utilizes C60 self-compacting SCC. Advantages of this type of concrete include the high uniformity of placed concrete, ease of placement, elimination of vibration, reduced bleed water and reduced labor. The mat was placed in four sections in order to minimize thermal effects. The superstructure uses concrete strengths that vary between C80 to C60 for the lateral system. Lower concrete strengths are specified for the horizontal framing. Higher strength concretes were considered but since the structural system distributes the loads so effectively, higher strength concrete was not required.

Lightweight concrete has also many benefits for tall buildings. The typical lightweight concretes have a density of around 14 to 19 kN/m^3 and have been used beneficially, for example the 52-storey One Shell Plaza in Houston (1971), is the tallest lightweight concrete in the world. Another form of lightweight concrete is the Fiber-reinforced Aerated Lightweight Concrete (FALC), which is produced to combine the advantages of fiber-reinforced concrete with increased flexural and tensile strength, and lightweight concrete.

With the advent of nanotechnology, nanocarbons, particularly carbon nanotubes and carbon nanofibers have also attracted significant attention for the improvement of cement-based composites. Carbon nanofibers are highly customized in their production specifications, and play a key role in specialized industries, such as Formula 1 cars and large blades for wind turbines. Tall buildings subjected to dynamic wind loads can employ these composites in a similar way to

reduce the weight of the structure and increase the strength of columns, girders, trusses, and beams of super tall buildings in the future. A 40-story multi-use Carbon Tower, designed by architect Peter Testa, has been proposed this nanomaterial for the primary structural systems, as a visionary project [17].

In the past decade the industrial waste product-based additions, such as fly ash and sewage sludge, have gained attention to their potential to reduce the cost and environmental impact of cement material. The addition of fly ash can improve the durability of concrete, reduce water requirements, improve finishability characteristics, however the early strength of fly ash is low because of the slow pozzolanic reaction in the mortar [16]. In contrast, adding SiO₂ nanoparticles can activate fly ash increasing this speed of reaction.

3.4. Innovations in Vertical Transportation

Vertical Transportation (VT) system of a tall building, consisting of elevators and escalators, impacts the efficiency of floor area and energy efficiency of the building as well. It is economically very important, since it determines the area needed for the core, and also the vertical travelling time for the occupants. VT generally accounts for about 5 to 10 % of the building's energy consumption. Contemporary and efficient tall buildings must take the advantage of latest technological innovations and recent solutions in order to maximize the VT efficiency by providing realistic transportation and distribution times, while minimizing the energy consumption of the elevators. For example a regenerative elevator driver motor is recently developed and being experienced in Pearl River Tower in Guangzhou to generate electric power by the movement of the lifts.

Elevator manufacturers are now producing elevators for mid- and high-rise buildings that are extremely energy efficient. These traction elevators have improved controls, hardware, and other systems that not only use less energy, but are much more compact, efficient, and even generate electricity that a facility can use. The most energy efficient elevators now have software- and microprocessor-based controls instead of electromechanical relays; in-cab sensors and software that automatically enter an idle or sleep mode, turning off lights, ventilation, music, and video screens when unoccupied; destination dispatch control software that batches elevator stop requests, making fewer stops and minimizing wait time, reducing the number of elevators required; personalized elevator calls used with destination dispatch controls that eliminate the need for in-cab controls [20].

The latest innovation in elevator technology is the UltraRope developed by Kone, one of the leader companies in the industry. Comprised of a carbon fiber core and a unique high-friction coating, KONE UltraRope eliminates the disadvantages of a conventional steel rope. Instead of interwound steel hawsers, Kone's hoisting line comprises four carbon-fiber tapes sealed in transparent plastic. With this carbon-fiber tape the cabin can rise up at once to the heights above 500 meters. It is extremely light meaning that the elevator energy consumption in tall buildings can be reduced significantly. It is also extremely strong, highly resistant to wear and abrasion, and has an exceptionally long lifetime - at least twice that of conventional steel rope. After testing in for several years in Finland, it is first used in Marina Bay Sands in Dubai [21].

3.5. Façade Technologies

Building façade is a major passive design component, which governs the heating and cooling loads in tall buildings. Designers should be very careful in façade design, providing solutions that meet the architectural requirements without compromising the energy targets and occupant comfort. Tall buildings with traditional glazed curtain walls allowing sunlight to penetrate indoors cause unwanted heat gain and loss, thereby increasing cooling/heating. To manage sunlight appropriately and provide occupant comfort, innovative curtain wall and window systems and glazings are developed to regulate the sunlight. Different types of glass and film coatings, such as low-E, are also available on the market to enhance the performance of façade.

Among the tall building façade solutions are the use of double skins, occasionally triple skins, adaptable or responsive facades, but most remarkable are the facades with operable windows or openings, which enable Natural Ventilation (NV). The naturally ventilated buildings utilize wind to provide natural free ventilation when the weather conditions outside are available, and cooling as well, rather than using only mechanical air-conditioning, which is energy intensive and may cause uncomfortable indoor environments for the occupants. These facades can provide continuous or controlled ventilation according to the outside weather conditions. Besides improving the energy performance of a tall building, NV plays a key role in providing both good indoor air quality and acceptable thermal comfort for occupant, if integrated correctly [22]. In addition, the employment of NV in an office environment can help to mitigate noise and health problems, such as sick building syndrome caused by mechanical HVAC systems. The RWE HQ Tower in Essen (1996), Commerzbank in Frankfurt (1997), GSW HQ in Berlin (2002) are the initial and remarkable examples, which take the benefits of natural ventilation in tall buildings. Among the recent examples are the Swiss Re Building in London (2004), 1 Blich Street in Sydney (2011) and KfW Westarkade in Frankfurt (2010).

Another recent approach in façade technologies is the responsive skins. This new generation of high-performance envelopes have contributed to the emergence of sophisticated assemblies combining real-time environmental response, advanced materials, dynamic automation with embedded microprocessors, wireless sensors and actuators, and design-for-manufacture techniques. In the realm of high-performance tall buildings, the envelope has become the primary site of innovative research and development. Borrowing a set of terms from the discipline of biology and applying some principles already in natural processes, is now commonplace in architectural design of innovative tall buildings with skins that are smart, intelligent, interactive and responsive, such as the Al Bahar Towers in Abu Dhabi.

4. Visions for the Future of Tall Buildings

Cities of the world are fastly growing because of the increase in their urban population. In these circumstances, they will have to grow vertically, since the horizontal expansion will be very dangerous and unsustainable for green lands. Also horizontal expansion must be constrained by limitations of the horizontal scale of infrastructure and services of a city. In addition, green lands, farming and other agricultural activities will probably grow vertically. Future cities no longer will be flat, but rather be a three-dimensional manifestation of horizontal and vertical architecture, thus necessitating enormous tall buildings, or in other words, vertical cities, which were previously visionary skyscraper projects.

Many of the visionary tall building projects were in fact proposed in the late twentieth century, for East Asian cities, like Tokyo, Shanghai and Hong Kong, due to the limited lands for settlements and high population density. For example, the population of Tokyo is about 35 million, and the city is starving for land. In this circumstances, vertical cities are becoming the only solutions for drastic population growth and urbanization problems. During these peak problems, Japanese architects reached at the highest point of creativity, and produced many visionary projects for the city. Also there are many other visionary tall building project for East Asian and North American cities, as well. The examples of these visionary projects can be stated as the Holonic Tower, Sky City 1000, Bionic Tower, Millenium Tower, Shimizu TRY 2004, Ultima Tower, X-Seed 4000, all envisioned for Tokyo, and NOAH for New Orleans, BoA for Boston. The common features of these visionary projects are that, they are all vertical cities in the form of a tall building, accomodating thousands of people and providing and urban life within a single structure. The realization of these projects heavily depends on the future innovations of structural systems, materials, construction methods, and provision of sustainable systems, including renewable energy systems.

5. Discussion and Conclusions

There have been remarkable innovations related with tall buildings, enabling the realization of ultra heights in an efficient manner. Structural system improvements and technological innovations, including new and smart materials, damping systems, elevators, responsive facades, energy efficiency are named to be a few. It is clear that the structural system to support supertall buildings of enormous scale is no longer a major impediment in buildings to great heights. The range of heights of recently proposed megatowers change between 600 meters (Holonic Tower, Tokyo) and 4 000 meters (X-Seed 4000, Tokyo). A building height of 509 meters by Taipei 101 in Taipei, Taiwan and 828 meters by Burj Khalifa in Dubai, UAE have already been reached, and the 1000 meters high Kingdom Tower in Jeddah, Saudi Arabia is on the process of construction. There are some other projects of greater height, which are also being considered for construction, such as the Nakheel Tower (1000 m) in Dubai, Sky City (838 m) in Changsha and Signature Tower (638 m) in Jakarta.

The tall buildings of the future will probably have an unprecedented height with an innovative structural system and material, yet not developed, or possibly a new version of the existing systems, or the combination of two or more systems and materials. The important question is that to which limit will the height of the tall buildings rise up? There are three answers for this question, the first is the nature of the human who will be imposed to live in these vertical prisons, apart from the natural environment; the second is the economic power of the communities; and the last answer is the ambition of the people who are willing the own the tallest building of the world. The height of a tall building is mainly dictated by market-driven real estate considerations, environmental and aviation factors, ego-driven prestige and a sense of competition; as well as practical considerations, such as the structural system and material availability, fire safety, energy demand, and etc. Today technology 1000 m or taller buildings is possible. However, designers must not forget that these ultra tall buildings will accommodate people, who will to live close to the nature. So the only limit is the nature of the human.

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