Free spatial forms in architecture of selected tall buildings in 21st century

Abstract

High-rise buildings, i.e. with a height of more than 55 m above ground level, are characteristic landmarks that dominate large urban agglomerations, and the development of high-rise construction is characterized not only by the search for new, original forms, but also by rapid technical progress. Buildings over 400 m tall build in the Middle East and China stand out particularly. The evolving architecture of high-rise buildings results from trends and styles, and the use of developing digital methods enables the creation of technically complex spatial solutions. Two features are visible in the architecture of the presented objects: a streamlined, free shape, and a consequently increasing slenderness. It is also important to be pro-ecological, e.g. reducing energy consumption, which often affects the form of the object. The article reviews selected spatial forms of high-rise buildings designed and built in the 21st century.

Keywords high-rise building | skyscraper | form | design | architecture

Introduction

The development of high-rise construction, i.e. rising more than 55 m above ground level[1], initially in North America and then across other continents, has significantly contributed to the progress that has been made in construction technology. At the exhibition 'Early Modern Architecture, Chicago, 1870-1910' held at the Museum of Modern Art in New York in 1933, the skyscraper was presented as the greatest achievement of American architecture in the second half of the 19th century[2]. The characteristic high-rise building, distinct in the city landscape, is not only a symbol of the possibilities of modern building art, but also an important object of publicity and economy, strongly influencing urban planning; high-rise buildings are characteristic dominants in large agglomerations. Their forms vary, being influenced by the prevailing aesthetic preferences and style trends[3]. The construction of the World Trade Center towers in New York, designed by Minoru Yamasaki and engineers John Skilling and Leslie Robertson, was the pinnacle of evolution of high-rise buildings after World War II. The towers, completed in 1973, were an expression of decades of progress in implementing new technologies in the design and construction of high-rise buildings. The destruction of the WTC on September 11, 2001, triggered a deep reflection on the design assumptions and safety systems[4].

Technology remains one of the main drivers of innovation in skyscraper design. Some of the most remarkable design solutions in recent years have been realized through the use

[1] Regulation of the Minister of Infrastructure of 12 April 2002 on technical conditions to be met by buildings and their location, Journal of Laws 2002, No. of April 8, 2019, item 1065.

[2] *Exhibition of Early Modern Architecture: Chicago, 1870–1910*, New York 1933, p. 7.

[3] J. Pietrzak, *Koherencja struktury nośnej i formy przestrzennej w biurowych i wielofunkcyjnych europejskich budynkach wysokościowych*, doctoral dissertation written under the supervision of Prof. Wiesław Rokicki, Warsaw University of Technology, Faculty of Architecture, Warsaw 2018 (typescript in the WAPW library), p. 10.

[4] G. Nordenson, *Tall Buildings*, New York 2003, p. 8.

of advanced computer modeling. The expansion of digital analytical capabilities in the design of high-rise buildings has resulted in a significant strengthening of the role of the engineer. The most notable innovation in this regard is the introduction of diagonally stiffened steel plate shear walls. The first high-rise buildings were conceived as cuboidal matrices of vertical columns and horizontal plates, contemporary structures approach freely composed rigid external shells or three-dimensional spatial frames, creating new forms and relations of inside vs. outside. Another manifestation of innovation is the design of energy-efficient and environmentally sustainable structures, which also often affects the shape and architectural expression of a building. The progress made in the numerous new design aids created a strong impulse towards erecting buildings with streamlined, free architectural forms shaped independently of the structural system. Curvilinear, twisted forms are becoming more and more visible in contemporary design pragmatics.

The search for the spatial form of skyscrapers can yield many unique proposals. Some projects amaze with the courage of ideas and the complexity of implementation that is difficult to predict. Such concepts include the *La Tour Sans Fins* skyscraper (the endless tower) located in the prestigious *La Defense* district in Paris (Fig. 1), or the *Green Bird* building in the center of London. The authors of the *La Tour Sans Fins* building were the architects Jan Nouvel and Emanuel Cattani, and the design idea is the form of a straight pipe 460 m high, which dominantly "emerges" and "disappears" across the urban space. An unconventional and original idea is also the concept of the *Green Bird* building with a height of 442 m (100 storeys), proposed by architects from the Future System studio. The multifunctional facility is intended for offices, a hotel and apartments. The architects, creating such an unusual form of the building, claimed that its essence was to reduce the impact of winds. The *Green Bird* building was to be the tallest building in London (dominating the riverside skyline), with a distinctive feature of steel diagrid reinforcements in the façade.

Selected implementations of high-rise buildings

The analysis covered nine objects ranging in height from 144 to 414 m, built in 2004-2018 in Europe, North America and Asia. The selection criteria were the characteristic free form and the use of modern design methods.

The list of analyzed objects includes (name / location – city, designer, year of construction, height in meters and above-ground + underground storeys):

1. *Torre Agbar (Glories)*, Barcelona, Jean Nouvel, 2004, height 144 m, 35+4 storeys;
2. *Absolute World Building D*, Toronto, MAD Architects, 2012, height 175,6 m, 56+6 storeys;
3. *Pearl River Tower,* Guangzhou, Gordon Hill / Skidmore, Owings & Merrill, 2011, height 309,6 m, 71+5 storeys;
4. *Al Hamra Tower,* Kuwait, Skidmore, Owings & Merrill, 2011, height 414 m, 80+3 storeys;
5. *Cayan Tower*, Dubai, Skidmore, Owings and Merrill, 2013, height 306 m, 73+5 storeys;
6. *China Zun,* Beijing, TFP Farrells, KPF, BIAD, 2018, height 527,7 m, 109+8 storeys;
7. *Lotte World Tower*, Seoul, KPF, 2016, height 555,7 m, 123+6 storeys;
8. *Capital Gate*, Abu Dhabi, RMJM, 2011, height 160 m, 35 storeys;
9. *Evolution Tower*, Moscow, RMJM, Filip Nikandrov, 2014, height 255 m, 53 storeys.

These outstanding implementation projects were created in global design studios such as Foster Norman and Partners, or MAD Architects, Skidmore, Owings & Merill, Kohn Pedersen Fox Associates and RMJM.

The oval, symmetrical shape of the skyscraper body is a harbinger of changes in the way of thinking about a modern tall building.

Among the projects created by the Foster Norman and Partners studio, the building of the Swiss Re Group in London (Fig. 2a) attracts particular attention. A characteristic feature here is that the form of the building does not correspond to the surrounding buildings, which is already a controversial assumption. A similar object is the 144 m tall *Torre Agbar (Glories)* building (Fig. 2b), built in Barcelona, characterized by improved aerodynamics, and designed by Jean Nouvel and BAC Engineering Consultancy Group (structure). The building has 35 overground and 4 underground storeys, the structure is made of a shell-like outer frame and an asymmetrical inner core[5]. An interesting, one may even say ground-breaking, episode in city urban planning was the construction of six residential buildings in the *Absolute World Building D* complex (Fig. 2c) in the Mississauga suburb of Toronto, Canada. Particular attention is drawn to the construction of two high-rise buildings, completed in 2012, that have a curvilinear form which is the antithesis of the standard box-shaped designs by MAD Architects.

The conceptual design of the *Absolute World Towers*, also known as the *Marilyn Monroe Tower 56*, was created as a result of an international competition organized by a private development company. The competition aroused great interest in the architectural community with over 90 competition entries. The commercial success and spatial significance of the completed building resulted in an increased interest in the concept and the need to make another similar investment in the vicinity. In terms of shape, the design differed significantly from the typical, rectilinear shape. The organic, smoothly-flowing form of the building illustrated a more relaxed approach to design. The buildings are characterized by angular differentiation in their projections. In the higher one, 175.6 m tall (56 above-ground and 6 underground storeys), which houses 427 apartments, the "torsion" of the top floor plan against the base is 209°, in the second one, 158 m tall, it is 200°. The search for appropriate structural solutions led to the use of a steel plate shear wall (SPSW) structure of the building, which turned out to be sufficiently rigid in transferring loads, therefore no more complicated solutions in the form of curvilinear spatial structures were needed[6].

China and a few oil-rich Arab countries are currently the largest architectural testing grounds. The contemporary achievements of Skidmore, Owings & Merill, famous for designing high-rise buildings, are fascinating. Slender skyscrapers of unconventional form include the completed *Pearl River Tower* in Guangzhou, *Al Hamra Tower* in Kuwait and the *Cayan Tower* in Dubai, United Arab Emirates. Rising 309.6 meters high (71 storeys), the *Pearl River Tower* is located in the business district of Guangzhou. The author of the project was architect Gordon Hill (the project received a number of awards, including the Golden Award in the category of Ecology, Reduction of Coal Use and Environmental Protection). The construction of a multifunctional building with an area of 214,100 m^2 (71 storeys) took almost 5 years and was completed in 2011. It was supposed to be 58% more energy-efficient than conventional skyscrapers. When designing, special attention was paid to the most energy-consuming elements, such as ventilation and air conditioning. To achieve savings, technical solutions were used to reduce, recover, absorb and generate energy. This is another self-sustainable building (the assumption was to produce more energy than it would consume). The aerodynamic shape allows the air to move naturally along the façade of the building (the openings suck in the wind). The shapes of the openings create a suction (increasing air flow velocity almost 2.5 times) and powering the built-in wind turbines. An innovative solution

5 *Torre Abgar*, http://architectuul.com/architecture/torre-agbar (access 10.08.2020).

6 A. Frearson, *Absolute Towers by MAD*, https://www.dezeen.com/2012/12/12/absolute-towers-by-mad/ (access 16.08.2020).

is also the recovery of heat by accumulating it on the south side and transferring it to the north side. Mechanically controlled shutters are installed on the façade, which allow the building's interior to be kept at a constant temperature, which significantly improves ventilation and influences the architectural appearance[7].

Located in the city center, the *Al Hamra Tower* rises 414 m high (80 storeys overground, 3 underground), being the tallest building in Kuwait. The building featuring an 11-storey car park is a multifunctional complex with variety of purposes. In addition to the office part, the building has a shopping center, theater, cinemas and numerous restaurants and cafes. The construction of the skyscraper began in 2005, and completed in 2011. The unconventional form of the building, with the southern facade made of almost solid stone cladding largely resulting from the need to minimize the impact of the hot desert sun. The structure of the building features a complex geometry of torqued glass walls twisting around a solid spine[8].

The 306 m (73 storeys) *Cayan Tower* was built in Abu Dhabi, United Arab Emirates, in 2013. Construction began in 2006, and was completed in 2013. The building was supposed to "rotate" 90° like the Turning Torso in Malmö, but the idea was ultimately abandoned. In the end, a double-skin frame structure was created (the floor rotation in relation to the axis is 1.2°). The central shaft in the projection is a circle, the outermost columns have been tilted, and the remaining ones have been moved out eccentrically[9].

The modern high-rise *China Zun* building in Beijing, China (Fig. 3a) and the *Lotte World Tower* in Seoul, South Korea (Fig. 3b) are some of the latest skyscrapers designed by Kohn Pedersen Fox Associates. Beijing plans to build more than 20 skyscrapers ranging from 150 to 368 meters in the prestigious Central Business District. The 108-storey CITIC Tower, 528 m high, known as the *China Zun Tower*, is one of the tallest buildings ever constructed in China able to withstand earthquakes up to 8 magnitude on the Richter scale. It is the third tallest building in North China, after the *Goldin Finance 117* tower, and the *Tianjin CTF Finance Center* in Tianjin. The concept of the building was developed by the TFP Farrells architectural studio, and the design documentation was done by Kohn Pedersen Fox Associates (the design of the structure was created in the Arupa studio). The curved shape of the building resembles an ancient Chinese ceremonial vessel called zun, which was made of bronze and intended for ritual ceremonies. The adopted form makes it one of the most original skyscrapers that have been built in recent years in the world. The China Zun Tower building is a 60-storey multifunctional facility intended for offices, luxury apartments, and a hotel, also featuring 8 underground storeys. A garden is located on the roof of the skyscraper at 524 m above ground. The structure of the building consists of the inner core and cross-barred mega-columns running up the entire height. The core walls, 120 to 40 cm thick, are made of concrete, while the ceilings are made of steel beams[10].

The inspiration for the shape of the *Lotte World Tower*, built in Seoul in 2017, was the reference to calligraphy and traditional Korean ceramic art. The building, reaching 556 m high, has 123 overground and 6 underground storeys. The characteristic conical shape makes for a multipurpose building with the most attractive storeys dedicated to public use (entertainment

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7 R. Tomlinson II et al., *Pearl River Tower. Guangzhou*, "CTBUH Journal", 2014, Issue II, p. 12-17.

8 K. Rosenfield, *Al Hamra Firdous Tower / SOM*, https://www.archdaily.com/196714/al-hamra-firdous-tower-som?ad_medium=gallery (access 10.08.2020).

9 G.F. Shapiro, *Cayan Tower, Designed by Skidmore, Owings & Merrill*, https://www.architectmagazine.com/design/buildings/cayan-tower-designed-by-skidmore-owings-merrill_o (access 12.08.2020).

10 P. Liu, Y. Cheng, Y.-S. Zhu, *The Structural Design of "China Zun" Tower, Beijing*, https://www.researchgate.net/publication/308665927_The_Structural_Design_of_China_Zun_Tower_Beijing (access 30.08.2020).

venues with an observation deck and a rooftop cafe). The structure of the building consists of a system of megacolumns with a central shaft. The façade is made of silver glass panes embedded in white metal profiles. The skyscraper was built on a foundation slab with piles and should withstand an earthquake with a magnitude of 9° on the Richter scale[11].

Unusual designs of high-rise buildings were created in the Moscow office of GORPROJECT (in cooperation with the RMJM studio, the structure was developed by the GK-Techstroy engineering office). The *Capital Gate*, also known as the Leaning Tower, is located at the heart of the Capital Center in Abu Dhabi, United Arab Emirates. Built in 2011, elegant and sleek skyscraper is proof of modern possibilities of implementing spectacular projects, the essence of which is also to distinguish and emphasize the prestige of its investors. The 165-meter-high building consists of 36 overground and 1 underground storeys. It is characterized as the most leaning building constructed in the world (inclined 18° towards the west). The building houses offices, the Hyatt hotel, two restaurants and a leisure center. The characteristic core is made of a cable-concrete structure and surrounded by a system of steel trusses. The building was founded indirectly on 490 piles cooperating with the foundation slab. The modern Cardinal facade used is 51% more heat resistant than a standard facade, which reduces total energy consumption by about 15%[12].

Furthermore, the *Evolution Tower* skyscraper (Fig. 3c) was built in Moscow on the lot of the 3rd Moscow International Business Center. The goal of developers and architects was to create a recognizable, distinctive building that would become a new iconic landmark of contemporary Moscow. Construction began in 2007. The facility was commissioned in 2015. The 246-meter tower with 55 storeys was designed by architect Philip Nikandrov from the GORPROJECT office. The inspiration for the twisted form of the building was the sculpture "The Kiss" by Auguste Rodin. The skyscraper was intended by the author to symbolize technical progress expressed by spectacular achievements in construction. Each floor is rotated 3 ° relative to the previous one, and the total rotation of the last story relative to the first is 135°. The building was planned to provide about 65,000 m^2 of office space. The building also houses the Museum of the Moscow International Business Center, the Registry Office and a 2000 m^2 ballroom on the top floor. A number of changes had to be introduced in the design process of the structure. Ultimately, it consists of megacolumns with a diameter from 2.1 m at the bottom to 1.2 m at the top (spaced every 15 m) and the inner core. The curtain wall is made of composite, cold-bent glass panes set in aluminum frames[13].

Summary

High-rise buildings are important dominants in urban agglomerations, hence their shape is an important element in determining the landscape. The continuous development of high-rise construction manifests itself not only in the search for new original forms, but also in rapid technical and technological progress. With time, iconic buildings become more and more commonplace, although they always create a lasting image of the era and the place in which they are created. The use of cutting-edge digital modeling methods enables the creation of increasingly complex technical design solutions. In the architecture of the presented objects, two features are clearly visible: a streamlined, free-form shape and, consequently, an increasing slenderness, limited, however, by the maximum deflection of the top, usually taken as f = *H* / 750–1200, which results from the need to ensure adequate comfort of

[11] *Lotte World Tower*, https://www.arch2o.com/lotte-world-tower-kpf (access 02.08.2020).

[12] A. Devdas et al., *Capital Gate. Abu Dhabi*, http://faculty.arch.tamu.edu/anichols/courses/applied-architectural-structures/projects-631/Files/CapitalGate.pdf (access 02.08.2020).

[13] A. Watts, *Modern Construction Case Studies: Emerging Innovation in Building Techniques*, Birkhäuser 2016, p. 34.

use[14]. Buildings exceeding 400 m in height appear more and more often, mainly being built in China, Kingdom of Saudi Arabia and the United Arab Emirates. Thus, the question arises about the limits of human possibilities in pushing the height of buildings. Based on the conducted analyses, we can assume that the consequence and effect of further development will be new, even more unconventional spatial forms. Pro-ecological solutions, including energy-efficient, "self-sufficient", multifunctional facilities are becoming the basic, essential canons in design. Striving for the maximum use of solar and wind energy as well as the introduction of passive techniques affects the shape of high-rise buildings and their detailed solutions.

[14] R. Paruch, *Strukturalne determinanty form architektonicznych współczesnych budynków wysokich*, doctoral dissertation written under the supervision of prof. dr. hab. Eng. arch. Janusz Rębielak, Cracow University of Technology, Faculty of Architecture, Kraków 2019, https://repozytorium.biblos.pk.edu.pl/redo/resources/42033/file/resourceFiles/ParuchR_StrukturalneDeterminanty.pdf (access 20.08.2020), p. 87.

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