

Architectural and Structural Analysis of Selected Tall Buildings in Warsaw, Poland

J. Szolomicki, H. Golasz-Szolomicka

Abstract—This paper presents elements of architectural and structural analysis of selected high-rise buildings in the Polish capital city of Warsaw. When analyzing the architecture of Warsaw, it can be concluded that it is currently a rapidly growing city with technologically advanced skyscrapers that belong to the category of intelligent buildings. The constructional boom over the last dozen years has seen the erection of postmodern skyscrapers for office and residential use. This article focuses on how Warsaw has recently joined the most architecturally interesting cities in Europe. Warsaw is currently in fifth place in Europe in terms of the number of skyscrapers and is considered the second most preferred city in Europe (after London) for investment related to them. However, the architectural development of the city could not take place without the participation of eminent Polish and foreign architects such as Stefan Kuryłowicz, Lary Oltmans, Helmut Jahn or Daniel Libeskind.

Keywords—Core structure, raft foundation, tall buildings.

I. INTRODUCTION

WARSAW plays a part in the history of European high buildings. In addition to historic buildings, from 1907-1910, the first high-rise building (PAST building) was erected, with a height of 52.0 m [1]. In the years 1931-1933, the Prudential building was erected with a height of 66.0 m (currently Warsaw Hotel). At the time of its opening in 1934, it was the second tallest building in Europe. An important impulse in the development of high construction after World War II was the construction of the Palace of Culture and Science in 1955. This 230-meter symbol of Socio-Realist architecture permanently broke the pre-war scale of Warsaw's buildings. The next high-rise projects did not have to wait for long. In 1974, the Hotel Forum was built and was the second building exceeding 100 meters. After more than 20 years of domination of the Palace of Culture and Science in the landscape of Warsaw, other high buildings, such as the Marriott Hotel (150 m) and Intraco I and II (140 m) were built. The 1990s saw a big boom for high-rise buildings in Warsaw. It has continued uninterrupted until today. At the beginning of the 21st century, the trend to erect high-rise buildings was still continuing, which resulted in the construction of several of them. A tall building is nowadays a symbol of wealth and prestige, and often becomes a tourist attraction with a great vantage point. It is one of the sources of progress in the fields

of construction, material, and technology of erection, creating new landmark of a city. The contemporary skyline of Warsaw is composed of two independent landmarks. One in the form of historical buildings of Old Town and the other, located in the distant background of the New City with high-rise buildings [2].

The article presents six selected Warsaw skyscrapers, two of which serve as residential premises and the remaining ones as office premises. These skyscrapers are located in the Śródmieście district. The two residential skyscrapers were erected among dense residential buildings in important places and the office blocks were erected in the frontages of main streets.

II. CHARACTERISTICS OF TALL BUILDINGS IN POLAND

The development of high-rise buildings is closely linked to the search for efficient construction materials, enabling buildings to be constructed higher, faster and safer. Initially, steel was the leading material in the structure of high-rise buildings. This was because concrete technology was not sufficiently developed and the concrete that was produced had a much lower strength than steel. At present, there is a growing interest in concrete as the main structural material in these types of objects. Over the past years, there has also been significant progress in the field of modeling the physical and rheological properties of concrete. Added admixtures allow for a significant increase in strength, accelerate concrete curing and enable construction works to be carried out at both very low and very high temperatures. Contemporary ultra-high performance concretes (UHPC) have a strength of greater than 150 MPa.

Taking into account today's technology of erecting of reinforced concrete structures, the leading and inseparable element of the construction process are formworks that form all structural elements. In order to ensure the efficient erection of a structure, a self-climbing formwork system is required. It is a device that ensures full independence of the work of the formworks from the crane and minimizes sensitivity to the wind. Peri and ULMA systems are used to build platforms with formwork systems in Poland.

The development of concrete technology and methods of construction organization have not only allowed for the construction of increasingly higher skyscrapers, but also for the diversification of their forms and shapes. The design of tall buildings with complex forms has also facilitated the development of computer technology. The higher computing power of computers has allowed for the creation of more advanced engineering programs that allow models to be

J. Szolomicki is with the Wrocław University of Science and Technology, Faculty of Civil Engineering, Division of Building Physics and Computer Aided Design, Wrocław, 50-370 Poland (corresponding author, phone: 48 505995008; fax: 48 71 3221465; e-mail: Jerzy.Szolomicki@pwr.edu.pl).

H. Golasz-Szolomicka is with the Wrocław University of Science and Technology, Faculty of Architecture Wrocław, 50-370 Poland (e-mail: Hanna.Golasz-Szolomicka@pwr.edu.pl).

created that better represent the real behavior of a structure. It is especially visible in high-rise buildings that have been built in the last twenty years. Contemporary projects destroy the stereotypes of high-rise buildings and surprise us with their original forms.

Skyscrapers are conducive to the development of innovative solutions not only in the field of construction, but also for vertical communication, the reduction of energy consumption,

improving the comfort of staying in their interiors and also safety of people. The organization of activities and the modern equipment of high-rise buildings mean that they can be classified as "smart buildings". Excellent examples of such buildings are Warsaw Trade Tower, Rondo 1, Cosmopolitan Twarda, Złota 44, Warsaw Spire, and Q22, which are analyzed in the further part of this paper (Figs. 1 and 2).

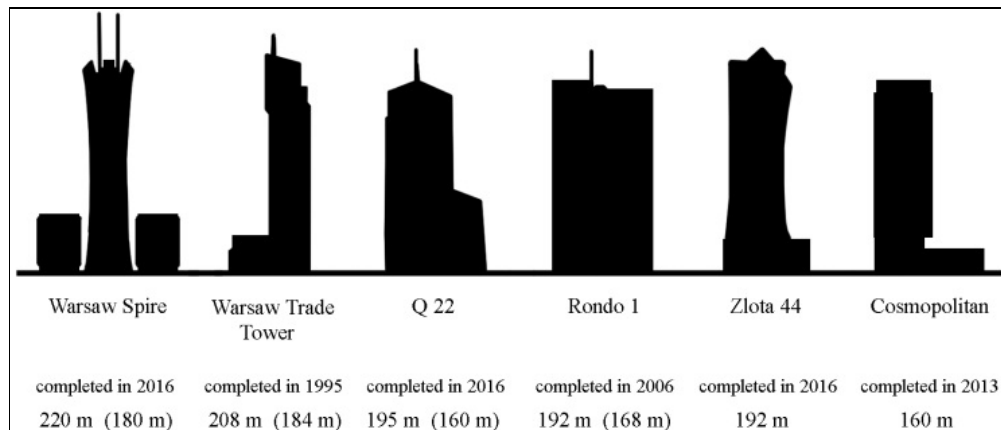


Fig. 1 List of the height of selected skyscrapers in Warsaw

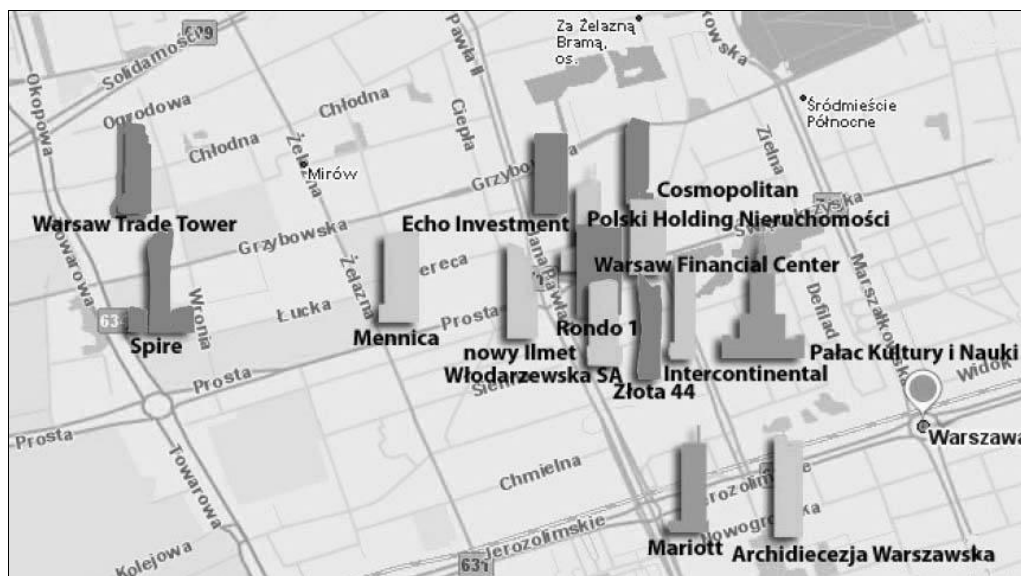


Fig. 2 Arrangement of tall buildings in Warsaw downtown

III. STUDIES OF TALL BUILDINGS IN WARSAW

A. Warsaw Trade Tower

Warsaw Trade Tower is an office skyscraper with a reinforced concrete and steel structure. The building is 184 m high (208 m with spire) and contains 43 floors above-ground level and 3 below, Fig. 3. The skyscraper was designed by the architects Hermanowicz, Majewski, Wszyński, Divanna and Epeloguuru [3]. In addition to offices, the first two floors above-ground level perform commercial functions and the

three underground floors as a car park.

The basement of WTT is designed on a circular plan inscribed in 2 incomplete intersecting squares and on the plan of a semicircle connected to a rectangle on the upper floors. The body of the main building is a half-cylinder surrounded on three sides by cuboidal risalits of various heights and widths, Fig. 4. From the north-west side, a quarter-cylinder was added to the basement. The building was designed with entrances from the north and east, which lead to the lobby with a reception area of six floors, surrounded by a 3-floor

glass mezzanine supported on rectangular columns. The lobby was roofed with a steel glazed structure. The highest risalit adjoins the building the south. A slightly lower risalit is in the western part and the lowest one, associated with the lobby, is in the eastern part. The elevation of the building, in the shape of a half-cylinder, has high rectangular windows separated by horizontal strips of frames that are filled with aluminum sheet and non-transparent glass. The façade has both vertical and horizontal divisions, however, it is the vertical divisions that dominate. In addition, the horizontal stripes of the shutters divide the façade into four floors. The skyscraper in the basement has a pedestal made of gray granite, while the elevations of the risalits are covered with red granite slabs. Stone pilasters were distinguished in the façade of the risalits, between which were installed windows that correspond to the divisions of the main part. In this arrangement, every two floors of windows are separated by a cornice. The north-western façade is accentuated in the basement with two-floor columns and two black granite columns. The massive stone block is covered with a light glass roof. Above it rises a glass façade which is partly connected to a stone façade with pilasters. The upper part of the façade is emphasized by a vertical mast fixed in horizontal brackets and a narrow vertical break. The eastern entrance façade is distinguished by red granite pilasters, steel vertical beams with a convex triangle cross section and horizontal aluminum frames.

The foundation of the building is located in an excavation protected by a diaphragm wall, which has a thickness of 80 cm and reaches to a depth of 11 m. The Warsaw Trade Tower has a raft foundation that cooperates with 156 piles and barrettes.

The skyscraper's load-bearing system was designed as a core-and-column system. The dimensions of the reinforced concrete core change with the height in the range from 29 m to 21 m in width. The steel columns on the lower floors are rectangular and adjacent to the building's façade with their longer side. With this solution, they are not in the interior of the building and allow the free formation of office space on each floor. The rounding of the top parts of the building significantly reduces the impact of forces caused by wind pressure. Due to the applied architectural form, this is only from the eastern directions. The WTT spire is a metal mast crowned with a transmitter antenna attached to the building on steel rings. The spire starts at the height of the 32nd floor and has a total length of 85 meters.

From 2015-2016, the skyscraper was thoroughly modernized. As a result of the implemented changes, the building gained a number of facilities that set the standards for modern office buildings. The most important changes include the modernization and reconstruction of a lobby set on a few floors and the creation of a special conference and event space on the 35th floor. At the same time, the building successfully passed the environmental certification process by the BREEAM In-Use method and obtained a very good rating in the Asset Performance category.

B. Rondo 1 Tower

Rondo 1 Tower is a complex created by two buildings with

a reinforced concrete structure: an office skyscraper with a height of 164 m (194 m with spire), which contains 40 floors above-ground level and two underground floors and a 10-story commercial-service building [3], Fig. 5. Both buildings are integrated with a glazed connector, which constitutes as a winter garden. The buildings were designed by Larry Oltmans from the architectural studio Skidmore an also Owings & Merrill in cooperation with the Polish studio AZO. In June 2006, the building was awarded the main prize at the 2006 CEPIF in the category of the best office building in the CEE region.



Fig. 3 Warsaw Trade Tower

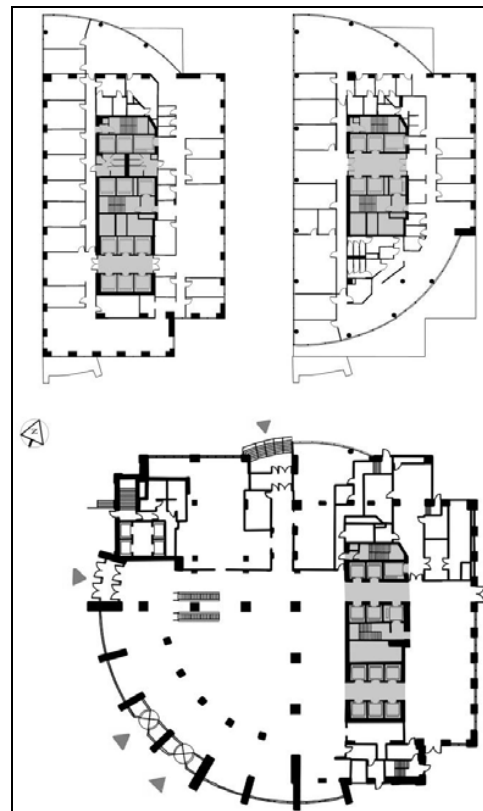


Fig. 4 Warsaw Trade Tower: floor plans

The Rondo Tower building is built on a rectangular plan ending with half an ellipse on the north side as shown in Fig. 6. The main tower is a rectangular block completed semi-circularly, which was enlarged with a rectangular solid from the eastern side and two rectangular solids of different height and width from the western side. On the western side, three risalits were added to the main block with an increasing height, fulfilling the functions of vertical communication. The building has three towers with six lifts leading to different levels. In addition, there are two sets of elevators and staircases in the main body. There are three entrances to the building, from the north-west (from the roundabout), west and east. The main entrance from the north-west side was emphasized in the elevation with four massive cornices. The façade of the building is distinguished by a rounded part (with a shallow blend) on the axis, an aluminum pilaster with variable texture at the end of a semicircular façade and an extended block with elevators underlined with an aluminum curtain wall with horizontal divisions. In the elevation, we can distinguish vertical windows with a separated narrow strip above them, which corresponds to the floor height. The windows of individual floors are finished with a flat horizontal cornice. The individual glass modules are a frame structure of individually designed, extruded aluminum profiles that are screwed in the corners of the frame and with a peripheral drainage system.

The foundation of the building is located in an excavation protected by a diaphragm wall with a thickness of 80 cm reaching up to a depth of 15 m. The building has a raft foundation with variable thickness that is deepened under the core and also has 62 barrettes [4]. The construction of the building is made in the core-and-column system. Due to the relatively small area of individual stories, the size of the core was significantly reduced. This was compensated by the introduction of a dense grid of columns. The construction of the communication part of the building consists of reinforced concrete transverse walls connected to each other by a skeleton of steel beams. Both blocks are connected to each other by steel crossbars (mega bracing) and girder beams on which trapezoidal sheets are laid. These sheets form the permanent formwork for the cast-in-place reinforced concrete slabs.

The building uses a DALI system, which individually controls the lighting and blinds. This is to adjust the light intensity to the outside lighting conditions. 100% of the electricity used in the building comes from wind energy. Rondo 1 Tower is the first office building in Central and Eastern Europe was awarded the LEED GOLD certificate by the American organization U.S. GREEN BUILDING COUNCIL.

C. Cosmopolitan Tower

Cosmopolitan Tower is a reinforced concrete residential building, which consists of two parts. The lower part has a service and recreation function, while the upper part has a residential function. The skyscraper is 160 m high and contains 45 floors above-ground level and five floors

underground as shown in Fig. 7. Its designer is Helmut Jahn from the American architectural studio Murphy-Jahn.



Fig. 5 Rondo 1 Tower

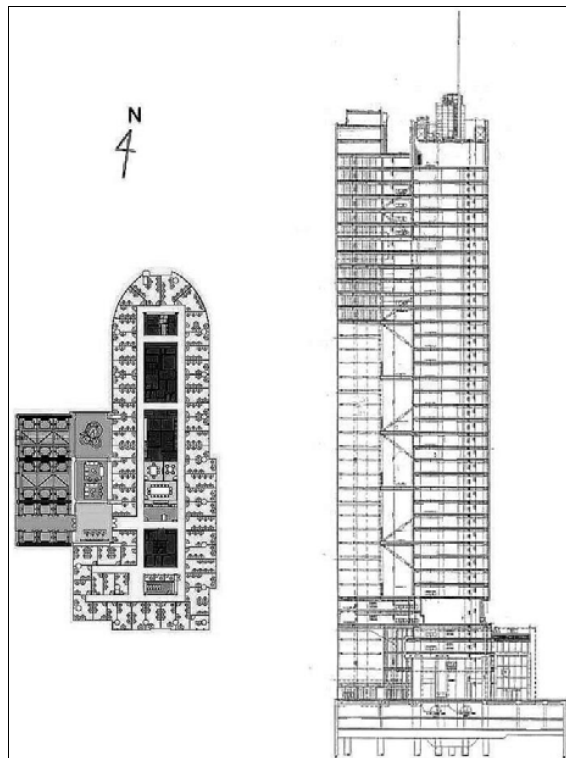


Fig. 6 Rondo 1 Tower: floor plan and section

The main residential block of Cosmopolitan Tower is designed on a rectangular plan with a centrally formed shaft in which there are two staircases and a set of five elevators. The tower rises on a four-floor podium crowned with a terrace on the plan of an elongated pentagon, in which there are shops, a restaurant and office space. From the eastern side, the podium is extended by an additional wing intended for cafes, galleries, and offices. A four-floor shaft emerges from the podium, on which the cuboid block is based with an overhanging rectangular plan located perpendicular to the base. Luxury

apartments are located in the higher part, which has 36 floors, Fig. 8. There is an observation terrace on the 42nd floor. The building is accessed from the south side, which is accented with a long glass roof suspended on steel cantilevers. The northern and southern elevations have a symmetrical layout, while the side elevations (eastern and western) are split with four risalits on each side. The façade of the skyscraper is made of high rectangular windows with horizontal, non-transparent panels in the upper part extending from floor to floor.



Fig. 7 Cosmopolitan Tower

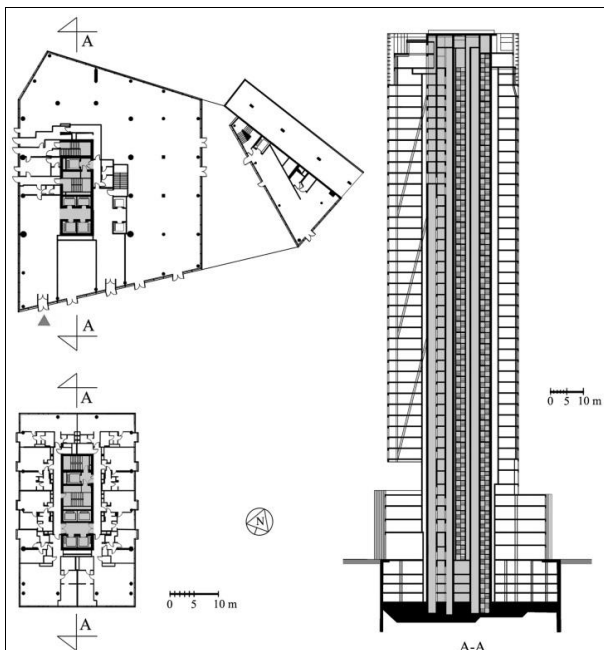


Fig. 8 Cosmopolitan Tower: floor plans and section

The external wall is based on a steel structure bracket-mounted to the edge of the floor slab. To cover the façade of the building, glass of different textures and appearance is used smooth or fritted, which creates a façade with a variable degree of transparency. In addition, the façade is

complemented by bands of shutters that emphasize the vertical divisions in the northern, eastern and western façades.

The foundation of the building is located in an excavation protected by a diaphragm wall with a thickness of 80 cm that reaches up to a depth of 27 m. The skyscraper has a raft foundation with variable thickness that cooperates with piles and barrettes. The structural system of the building is a skeletal, column-and-slab floor structure with a central, monolithic core. The floor slabs were designed as a reinforced concrete, monolithic, bi-axially reinforced structure. The slab floors are based on the central core and column grid around the core, but there are also zones where the slab floors are supported on girders. Starting from level 6 of the southern side, the floors are extended in relation to the lower floors by 9.40 m. It is a significant cantilever overhang, causing a large overload of the entire structure. The edges of the floor slabs in the suspension zone are based on a system of steel diagonal bars acting on the principle of cable hangers connecting the wall of the core with the external column. Each cable hanger covers ten floors of the overhang zone and is about 35 m long. It is made of 75 or 109 ropes made of high-strength steel. The ropes are placed in casing pipes, which are exposed to cement grout ensuring adequate thermal insulation. All the columns of the high-rise building were designed as a composite, i.e. reinforced concrete with a steel core and circular cross-section.

D. Zlota 44 Tower

Zlota 44 is a residential tower with a height of 192 m with 54 floors above-ground level and 2 underground floors, Fig. 9. The above-ground part of the building consists of a low section with 6 parking levels, a technical level and a level designated for leisure and recreation functions. There is also a high section with 45 residential floors. The building was designed by American architect Daniel Libeskind and was erected in the place where the City Center building used to be located. Zlota 44 tower won four prizes in the 2015-2016 International Property Awards in the following categories: the best residential building in Poland, the best apartment in Poland, the best residential tower and the most exclusive interior design.

Zlota 44 tower is designed on a rectangular plan in the basement, with the residential part being on a quadrilateral plan with a central shaft in which six lifts and two stairwells are located. The basement of the building is made up of an 8-story cuboidal podium, in which there is a restaurant, fitness club, conference center, cinema, steam room and swimming pool [5]. A high cuboidal block emerges from this podium, onto which a concave-convex spherical form is embedded as shown in Fig. 10. From the west side, the rectangular cuboid block was hung over the podium. In the south-western part, the entrance zone is accentuated by an arcade supported on rectangular columns. The floors of the podium have vertical windows filled with glass or aluminum sheet divided by diagonal concave or convex aluminum strips. The ground floor is separated from the upper floors by a profiled cornice led on a diagonal line. Aluminum and glass panels create

bright and dark stripes in the façade. The cuboidal shaft has an elevation with vertical divisions created by rectangular panels filled with windows or aluminum sheets. Above the windows is a strip corresponding to the height of the floor. In the façade with vertical and horizontal divisions, vertical divisions dominate, which are accentuated by strips of aluminum panels distributed irregularly and at different heights. The concave-convex part has horizontal divisions filled with glass panels or aluminum sheet that form strips with an irregular height. The building has a three-glass modular façade fixed to the slab floor. The façade of the skyscraper uses two shades of a blue laminate of glass and aluminum, which create a dynamic pattern.



Fig. 9 Złota 44 Tower

In the foundation of the skyscraper the foundations of the previous building were partially used. The raft foundation was made on a milled slab and is pin-connected to an existing diaphragm wall [4]. The applied foundation system can be described as piled-rafts cooperating with barrettes. The previous construction system was used as an expansion element and a waterproof membrane. The reinforced concrete structure of the building is made of the core-and-column system [6]. The crowning of the skyscraper is a steel structure and serves as a two-level penthouse. Due to the asymmetrical shape of the building and the different shape of the individual floor plane, the core of the building is not located in the center. For this reason, the wall bands were additionally introduced to cooperate with the core. The stability of the building is provided by the core that contains staircases, a lift and installation shafts as well as external stiffening walls that are perpendicular to the core and joined to it by three rows of connecting beams. The floor slabs in the high residential part are designed as multi-polygonal cross-reinforced slabs with stiffening of their edge in the form of an edge beam. Some floor concrete slabs, due to heavy loads, were pre-stressed in

several stages. The entire building, due to its form, has many inclined columns, which are often in two planes.

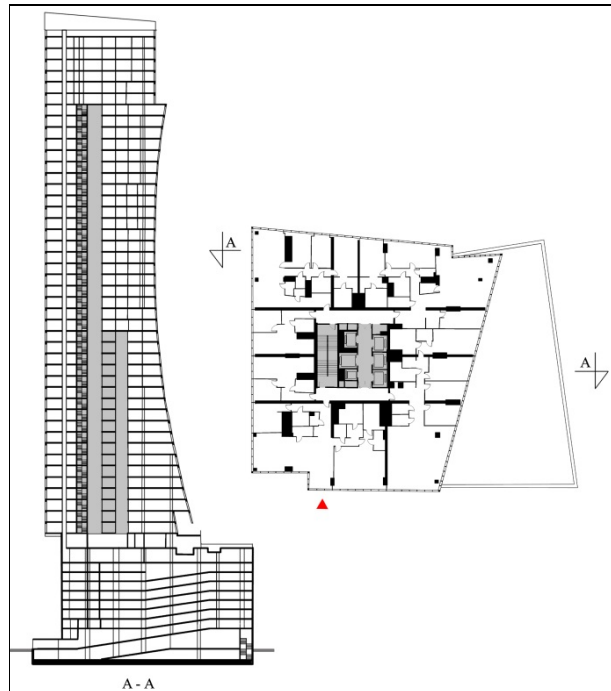


Fig. 10 Złota 44 Tower: floor plan and section

E. Warsaw Spire

Warsaw Spire is an office complex with a reinforced concrete structure, which consists of three buildings: a 180-meter high skyscraper (220 m with spire), which contains 49 above-ground level floors and five underground floors, and also two side buildings with heights of 55 m as shown in Fig. 11. It also has five underground floors connecting the complex into a uniform structure. The design of the skyscraper and adjacent buildings was developed by the Belgian architectural studio M. & J-M. Jaspers-J. Eyers & Partners, in cooperation with the Polish-Belgian Architecture Design Studio. The Warsaw Spire skyscraper received the main 2017 MIPI Awards in the category of the best office investment in the world.

The main building is designed on an ellipse plan with cut corners with a hyperboloid section as shown in Fig. 12. The entrances are located on two axes of symmetry, with the main western entrance from the street being underlined with a concave-convex steel roof supported by large cylindrical columns. The western and eastern entrances are underlined with a vestibule on a half-circle plan. The remaining entrances are arranged symmetrically around the elliptical lobby with a mezzanine connected to the central communication shaft. In the façade, the ground floor is surrounded by long sides of the ellipse with columns converging in a V-shape. The basement façade is made up of high and wide rectangular windows. Vertical windows are separated by horizontal window stripes over the entrances on the east-west axis. The main elevation is made of a glass curtain wall based on triangular steel supports

and with horizontal and vertical divisions, in which three floors of windows are separated by a cornice with a semicircular cross-section. In the façade of the building with vertical divisions, convex cornices create distinct horizontal divisions.



Fig. 11 Warsaw Spire

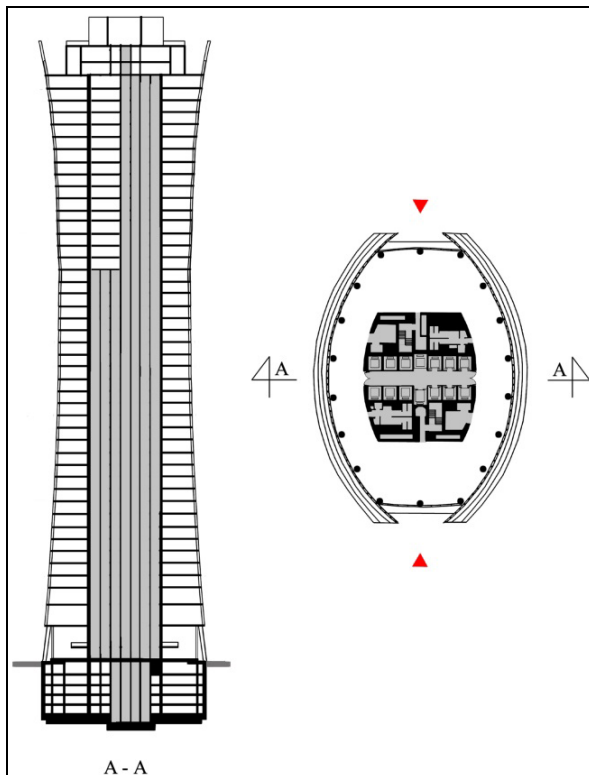


Fig. 12 Warsaw Spire Tower: floor plan and section

At the top of tower building, the façade has the form of two

asymmetrical flanges, and exceeds the floor of the last office storey about 20 m.

The foundation of the building is located in excavation protected by a circumferential diaphragm wall with a thickness of 80 cm, a length of over 500 m and a depth of 55 m [4]. Due to the great depth of the excavation, the diaphragm walls were anchored in three rows. The skyscraper has a raft foundation with variable thickness, is deepened under the core and cooperates with piles and barrettes. The skeleton of the entire complex is made of pre-stressed concrete slabs [7]. The main load-bearing structure of the building is a slab-and-column system with a central core [5]. There are 18 reinforced concrete columns on the edge of the slab floors.

Warsaw Spire enlivens the space with light and color, not only through light surfaces. The dynamic illumination of the façade has a total of 88,000 individually programmable elements. Some of them illuminate the vertical and horizontal edges of the building, which has a total length is one kilometer. Philips engineers designed a special profile to assemble contour fittings that are equipped with a diffuser in order to scatter light.

F. Q22 Tower

The Q22 Skyscraper is a reinforced concrete office building with a height of 155 m (194 m with spire). The building contains 42 floors above-ground level and five underground floors as shown in Fig. 13. The design of the Q22 office building was made by the Kuryłowicz & Associates studio in cooperation with the Polish branch of BuroHappold. The name of the Q22 building derives from crystal, which symbolizes technology and timelessness.

The Q22 skyscraper is designed on a rectangular plan in the basement and a pentagonal plan on the upper floors. The building's body, which resembles a quartz crystal Fig. 14, consists of a high part with 42 floors above-ground level and a low part with 17 floors [8]. The lower block is characterized by a sloped roof to the south. Both parts are connected to a triangular niche. A deep and high niche was made in the southern wall of the lower block. The building has two entrances: the north side and main entrance in the west leading to the lobby with 30-meter high reception. On the elevation, the ground floor with the height of two floors is separated from the upper floors by a horizontal plane over a hanged cornice. This cornice emphasizes the corners of the building from the façade's main side. The entrance zone is distinguished by an overhanging roof made of aluminum plates. The façade of the building is made of a segmented aluminum curtain wall system. The elevation consists of high rectangular windows with a height of one floor. Only the ground floor has windows that are twice wide. The north façade of the high tower (has a blend) in the upper corner accentuated by wider windows and a cornice. The entire height of the floor has transparent glazing without divisions and profiles visible from the outside, characterized by high transparency, sun protection, and thermal protection. In accordance with the BIPV system, photovoltaic modules based on mono-crystalline cells were installed in the structure

of the glass wall. The skyscraper is equipped with a DALI digital lighting control interface.

The foundation of the building is located in an excavation protected by a diaphragm wall with a thickness of 80 cm that reaches up to a depth of 32 m [4]. The skyscraper has a raft foundation with variable thickness that cooperates with piles and barrettes. The structural system of the building is a column-and-core structure. Due to the atypical shape of the body, the core of the building is not located centrally and slender columns change shape in the underground part. In order to achieve similar spans of the floor slabs, an additional row of columns was used on both sides of the core. The columns were made as a composite and reinforced by rods in the SAS system. Five underground floors were constructed in a casing made of diaphragm walls.



Fig. 13 The Q22 Tower (Echo Investment)

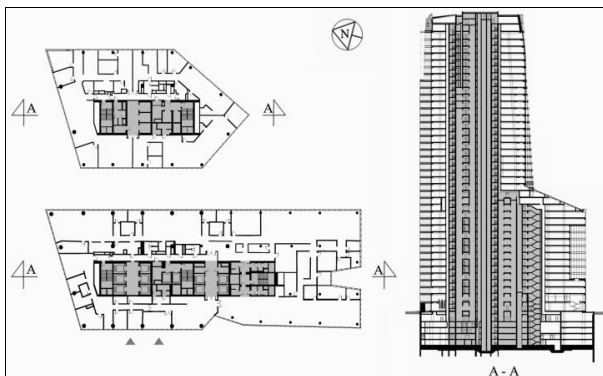


Fig. 14 The Q22 Tower: floor plans and section

IV. CONCLUSION

High-rise buildings, just like all building systems for which system of forces act, must fulfill four basic criteria: stiffness, stability, strength, and durability. The design of a high-rise building starts with the formation of its spatial stiffness against vertical and horizontal forces. As the height of the building

increases, the importance of horizontal forces is greater in the process of selecting its load-bearing structure. The main problem is the choice of an appropriate structural solution that would fulfill the requirements for ultimate limit states (strength criterion) and serviceability limit states (stiffness criterion). The selected type of load-bearing structure of a high-rise building must be characterized by an adequate strength to transfer all loads and impacts and appropriate stiffness determined by the permissible amount of swing of the apex of the high building subjected to a given horizontal load.

High-rise buildings with a reinforced concrete structure in Poland and in the world have gained much popularity over the last several years, mainly due to their utility advantages and greater fire safety in comparison to steel structures. All the skyscrapers presented in this paper have a reinforced concrete structure with the exception of the steel structure of the Warsaw Trade Tower.

Reinforced concrete high-rise buildings in Warsaw most often use the core-skeleton structural system. In each case there is a stiffer core and a combination of columns and walls with slab floors, and possibly beams or walls. In the presented skyscrapers, original structural solutions were used, an example of which can be the Cosmopolitan Twarda Tower with a structure of pre-stressed concrete slab floors suspended on ropes. Geometric form is also a very important element, and reduces the streamlined impact of wind to an acceptable level (Złota 44 Tower).

In high-rise buildings that are currently being erected, BIM software is used to create a three-dimensional model for defining the details of materials and technologies. Application of this technology allows significant savings to be achieved during the implementation of the investment and its subsequent operation.

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