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# Tokyo Skyscrapers: Technologically Advanced Structures in Seismic Areas

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***Abstract*****—**The architectural and structural analysis of selected high-rise buildings in Tokyo is presented in this paper. The capital of Japan is the most densely populated city in the world and moreover is located in one of the most active seismic zones. The combination of these factors has resulted in the creation of sophisticated designs and innovative engineering solutions, especially in the field of design and construction of high-rise buildings. The foreign architectural studios (as, for Jean Nouvel, Kohn Pedesen Associates, Skidmore, Owings & Merill) which specialize in the designing of skyscrapers, played a major role in the development of technological ideas and architectural forms for such extraordinary engineering structures. Among the projects completed by them, there are examples of high-rise buildings that set precedents for future development. An essential aspect which influences the design of high-rise buildings is the necessity to take into consideration their dynamic reaction to earthquakes and counteracting wind vortices. The need to control motions of these buildings, induced by the force coming from earthquakes and wind, led to the development of various methods and devices for dissipating energy which occur during such phenomena. Currently, Japan is a global leader in seismic technologies which safeguard seismic influence on high-rise structures. Due to these achievements the most modern skyscrapers in Tokyo are able to withstand earthquakes with a magnitude of over seven degrees at the Richter scale. Damping devices applied are of a passive, which do not require additional power supply or active one which suppresses the reaction with the input of extra energy. In recent years also hybrid dampers were used, with an additional active element to improve the efficiency of passive damping.

***Keywords*****—**Core structure, damping systems, high-rise buildings.

## I. INTRODUCTION

JAPAN is one of the most densely populated countries in the world, with its capital Tokyo, one of the 47 prefectures, being its largest metropolis. Japan also has one of the most active seismic zones in the world. Geological instability triggers about a thousand earthquakes each year. The combination of these factors has resulted in the creation of sophisticated designs and innovative engineering solutions, especially in the field of the design and construction of tall buildings. Over the past several decades, the Japanese have learned to construct buildings to minimize the damage caused by earthquakes. Over 140,000 people died during the Great Kanto earthquake in 1923, which almost completely destroyed Tokyo. The Tohoku earthquake and tsunami of 2011 was the most expensive catastrophe in the world with estimated damage of $ 235 billion.

Until the early 1960s Japan's law on construction standards limited the maximum height of buildings. Frequent earthquakes in Japan mean that strictly defined construction standards are needed that require skyscrapers to implement security infrastructure, such as quake dampers and special deep foundations. The highest skyscrapers in Tokyo are mostly office buildings of diverse use, with the exception being the Tokyo Metropolitan Government Building designed by Kenzō Tange, which was the highest in the city when it was built in 1991.

The urban form of Tokyo is largely a consequence of the reconstruction that occurred after the Second World War. In comparison to Europe, where historic brick and stone buildings were built, old buildings in Japan were mostly wooden, and very few of them were reconstructed. Urban development was regulated by successive laws: the Kihon Hojan building law was introduced in 1950, the planning a new city law (Shin Toshi Keikaku) was introduced in 1968, and the Law of Urban Renewal (Toshi Saikaihatsu-Ha) was introduced in 1969. All these laws aimed to improve conditions in built-up areas.

Japan's rapid economic growth continued until the first oil crisis in 1973. It had an influence on the development of urban centers around railway stations and the construction of many lines radiating outward from Tokyo. After the crisis, another stage of urbanization took place from 1970-1990. Tokyo's urbanism can be seen in terms of its architecture, with almost the whole city being completely rebuilt after the Second World War. This rebuilding is characterized by the fact that many of its original buildings were designed by architects from around the world. The landscape of Tokyo was largely transformed by technological development. It was a transition from its architecture that in the past appreciated the natural landscape to its present architecture that consumes natural resources and intervenes in the natural landscape. In recent years, the trends to preserve natural resources and ecological solutions have become a priority.

The panorama of Tokyo contains many skyscrapers, of which six form the basis for further architectural and structural analysis.

Tokyo is a modern city with a modern and traditional character. Its aesthetics include both western and Japanese styles. Although at first sight Tokyo appears chaotic and fragmented, all parts of it form a well-functioning organism. It has the original form of a polycentric metropolis that was

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developed under the influence of modern technology and a rich heritage of tradition and culture with different scenarios coexisting in symbiosis.

## II. The History of Tall Buildings in Tokyo

When analyzing the history of the architecture of Tokyo until the end of the 20th century, it can be said that it has undergone three stages of transformation. The first phase was after the earthquake in the Kanto region in 1923, the next phase was during the American air attacks during the Second World War in 1945, and the following phase was during the Olympic Games in 1964. The fourth phase, which began in the mid-90s, continues to this day, and most importantly transforms the city of low-rise buildings into a city of skyscrapers. Since 1868, when Emperor Meiji ordered the city's name to be changed from Edo to Tokyo, the city has been subject to constant change. An important moment in the history of Japan was in 1859 when the port of Yokohama was opened to trade with foreigners. This resulted, not only in the acceptance of foreigners, but also in the adoption of Western models.

As a result of the earthquake in 1923, three-quarters of the city was damaged or completely destroyed [1]. At the time, the tallest building in Tokyo was the 12-storey high brick building of Ryounkaku. This building, having survived the previous quake of 1894, was considered to be resistant to earthquakes. However, this time it was destroyed, and as a result bricked architecture was questioned as to whether it is quake-resistant, which was manifested in the failure to build any high-rise buildings for the next few decades.

The American raids during World War II brought a second wave of destruction that ruined Tokyo in 1945. During this period, Tokyo's future was dubious, but Japan was a strategically important place for the American army. Later, the war in Korea and Vietnam and the high demand for Japanese goods contributed to the revival of Tokyo's architecture due to Japan's spectacular economic growth. From 1953 to 1973, Japan transformed from an agricultural country into one of the most industrialized countries in the world. This economic expansion was the result of unprecedented government investment in infrastructure. In the whole area of the Japanese archipelago, in particular Tokyo, Osaka and the Ise Gulf, express roads, railway lines, ports, dams and artificial harbors were expanded. During this period, the construction industry became one of the main industries and accounted for 30% of Japan's total gross expenditure. The economic recovery enabled Tokyo to build the Tokyo Tower in 1958, Japan's first high structure with a height of 332.5 m, whose prototype was the Eiffel Tower. Tokyo Tower was the starting point in the urban process that affects the present appearance of the city. The first image of Tokyo as a high city appeared in the post-war period with the direction of Metabolism in architecture. An important part of the Metabolism vision is the mega-constructions inserted into the existing urban structure. An example of such constructions is the Tower City building designed by Kiyonori Kikutake in 1963 and a residential building designed by Octa Kenji Ekuan in 1965. These visions later became a trend in the development of high-rise buildings in the city. The organization of the Olympic Games in 1964 was a breakthrough for Tokyo. After the end of the post-war period, the city implemented a road development program that involved a basic reconstruction. Several new hotels, intended for participants of the Olympic Games, were located near the Imperial Palace. The highest of them, New Otani in Akasaka, became the tallest building in the city with 17 floors. Until 1963, Japan's law on construction standards limited construction to 31 meters. It was not until 1968 that the first Kasumigaseki office tower, 147 m high and with 36 floors, was completed. In the following years, the height record changed many times. In 1970, the World Trade Center was built in Hamamatsucho with a height of 150 m and 40 floors, and in 1971 the Keio Plaza hotel was built and had a height of over 200 m. Three years later, the Mitsui building with a height of 220 m and 55 floors was erected. The highest skyscraper of the first generation was built in 1978 and was the Sunshine building in Ikebukuro. It was the tallest building in Tokyo until 1992.

The first boom in building high-rise buildings came to an end in 1979. The best example of such architecture was the district of West Shinjuku, which became a reflection of Manhattan and had seven buildings erected in the years 1971-1979 that exceeded 150 m in height. In the next decade, despite a strong economy, there were few significant architectural projects. In the years 1980-1989, only four buildings with a height of over 150 m were completed in central Tokyo. These buildings were no longer in the Shinjuku district, but were instead designed in the Minato-ku district. The most interesting example is the Ark Hills city center built in 1986 in the Akasaka district, which marks a new type of urban development in which the developer Minoru Mori built a tower complex for office and residential use.

In the 1980s, land prices in Tokyo increased sharply, initiating the so-called bubble economy. At the beginning of the 1990s, when a significant number of high-rise building projects had already begun, Japan fell into an economic recession. Paradoxically, despite the recession, their construction accelerated. In the 90s, a total of 19 buildings over 150 m were built in Tokyo - more than the general height structure from the 60s, 70s, and 80s of the 20th century.

At the beginning of the 21st century, the Urban Revitalization Act further softened the regulations regarding the construction of skyscrapers, initiating a radical transformation process that led to the current state of the city. Over the next 12 years, 73 buildings exceeding 150 meters were built in the center of Tokyo. Until the end of 2010, in addition to Tokyo Tower and Sky tree, there were 556 buildings in Tokyo with a height of over 100 m, and 106 in the city center with a height of over 150 m. This means that Tokyo is currently fourth in the world in terms of the number of skyscrapers, behind Hong Kong, New York and Dubai.

At the beginning of the 21st century, for the first time in history, a significant number of foreign architects with extensive experience in designing office high-rise buildings were invited to cooperate with local architectural studios.

Among their projects are examples of tall buildings that set precedents for future development. Atago Hill Mori Tower and Forest Mori Tower designed by Cesar Pelli were erected in the Roppongi district in 2001. The corporate center developed by Minoru Mori Roppongi Hills was designed by the New York architectural studio Kohn Pedersen Associates in 2003. In 2007, Tokyo Midtown Tower, designed by Skidmore, Owings and Merrill, was opened.

An interesting example of the further development of Tokyo to solve the problem of the still growing number of inhabitants is the project Next Tokyo 2045. The central building of this project is the 1600m Sky Mile Tower, designed by Kohn Pedersen Associates and Leslie E. Robertson Associates. The skyscraper will be located on a man-made island near the coast of the Tokyo Bay. The main challenge for the designers was to protect the building against the threat caused by the occurrence of typhoons and earthquakes. The project used a solution in which sea waves that are dangerous to the construction would be broken up by hexagonal objects arranged around the Sky Mile Tower. The building will also house utility functions such as water tanks or places for plant cultivation. At present, this project can be treated as futuristic, however, it is included in the report of organization dealing with high-rise buildings (Council on Tall Buildings and Urban Habitat).

## III. Vibration Damping Systems Used in High-Rise Buildings in Japan

Buildings in Japan are designed in such a way that they are resistant to seismic activity. An essential aspect of designing tall buildings is their dynamic reaction to earthquakes and counteracting wind vortices. Moreover, high buildings are sensitive to wind-induced vibrations, and the impact of such vibrations becomes dominant for buildings higher than 200 m. According to Japanese standards, the following three average wind speeds are considered when analyzing the wind impact at the level of 10 minutes and the recurrence frequency of 1 year, 100 years and 500 years. Fulfilling the last case ensures that the building's response is almost completely elastic.

While the strength of building materials, such as steel, has doubled in the last few decades, its stiffness has not increased significantly. This has led to an elastic-based approach to design in which lateral deflections and accelerations are the dominant structural constraints for tall buildings. Vibrations can be partially damped by the structure itself. Increasing the stability of the structure causes an increase in the natural frequency. According to the numerical simulation of the construction response to wind, if the natural frequency is greater, the maximum acceleration decreases approximately in proportion to half of the natural frequency.

The light steel structure used in high-rise buildings has little natural damping or natural dissipation of energy and is sensitive to dangerous accelerations in conditions close to resonance. The dynamic reinforcement of load conditions can be reduced by redistributing stiffness in order to avoid resonance, or by the implementation of a damping system in the building. The need for motion control has led to the development of various methods and devices for dissipating energy. Damping devices can be passive, which do not require additional energy supply, or active (AMD), which suppress the reaction with input energy, usually through the use of actuators [2]. Although there are many effective applications for active dampers, the increased complexity, maintenance and cost, and lower reliability of passive dampers means that they are more often used. Passive damping systems are divided into three categories: hysteretic dampers, viscous dampers, and mass dampers.

Hysteretic damping uses SD and SJD steel vibration absorbers, as well as viscoelastic dampers (VED), lead dampers (LD) and friction dampers, which are used to reinforce material interactions at the FD connections. Steel vibration absorbers dissipate energy through cyclic inelastic deformation of materials. These damping systems are often designed in the form of a triangular plate or are X-shaped. Due to this shape, plastic deformations appear in a much larger area, which leads to a more efficient dissipation of energy. This system was used in the Ohjiseishi Building in Tokyo (1991), Art Hotels Sapporo in Sapporo (1996), and Kobe Fashion Plaza in Kobe (1997).

In friction dampers, energy dissipation occurs as a result of friction between two solids moving in relation to each other. For example, friction dampers were used in the Sonic City Office Tower in Ohmiya (1988) and Asahi Beer Tower in Tokyo (1989).

Viscous dampers (VD) and oleo-dynamic dampers (OD) use viscous materials in which the resistance force acting on the body moving in the material is proportional to the speed of the body.

In this case, high viscosity chemicals such as silicone oil are used. The thermal effect is also significant. Viscoelastic dampers were used in the TV-Shizuoka Media City buildings in Tokyo (1967) and the Torishima Riverside Hill Tower in Osaka (1999) to counteract the vibrations caused by extremely large earthquakes.

When these devices do not provide sufficient energy dissipation, significant damping can be added to the structure through the use of tuned mass dampers (TMD) [3]. A TMD is an additional mass, usually in the order of two percent of the total weight of the building, which is attached to the structure by means of springs and dashpots. The inertia force of the mass is damping the reaction of the building. However, TMDs are mostly effective only when they are excited by the resonant frequency for which they have been designed. This type of damper was used in Fukuoka Tower in Fukuoka (1989), Higashimyama Sky Tower in Nagoya (1989) and Huis Ten Bosch Domtoren in Nagasaki (1992).

Another type of mass damping system is tuned liquid dampers (TLCD). This damping system uses the movement of liquids in special containers to absorb the energy of building vibrations. TLCD vibration frequency can be controlled by the water depth and the size of the container. TLCDs are preferred because of their simplicity, low maintenance price and the possibility of including water for emergency fire protection. The TLCD system was used in the Rokko-Island P & G

Building in Kobe (1992), Crystal Tower in Osaka (1992), and Sea Hawk Hotel & Resort in Fukuoka (1998).

In recent years, hybrid dampers have appeared, which are a combination of a mass damper with an additional active element, which aims to improve the efficiency of passive damping. The forces from the active actuator increase the effectiveness of the mass silencer and are very effective in the event of changes in the dynamic characteristics of a structure. The hybrid system was used in the Landmark Tower building in Yokohama (1993) and in the Ando Nishikicho building in Tokyo (1993).

## IV. Architectural and Structural Analysis of Selected Skyscrapers

Tokyo is one of the most interesting cities in Japan and is referred to as the largest agglomeration in the world. This metropolis consists of 23 wards (Fig. 1) characterized by a very high density of population and buildings. In many aspects it differs from European cities, which is manifested, among other things, in the fact that addresses are based on a territorial system that defines particular areas in a hierarchical system. Tokyo urbanism is a dense cluster of buildings with centers and sub-centers located at metro and rail stations, which define the spatial structure of the city. Each ward has its own unique cultural and architectural specifics. In this paper, high-rise buildings from the wards located in the very center of Tokyo, i.e. Minato, Chuo, Shinjuku, and Sumida located in the eastern part of the city, were selected for analysis.

Minato ward is the main business center of Tokyo, located southwest of the Imperial Palace and bordering the districts of Chiyoda, Chuō, Kōtō, Shinagawa, Shibuya and Shinjuku. In this area there are many foreign corporations (Google, Apple, Goldman), domestic corporations (Honda, Mitsubishi Motors Corporation, NEC, Sony, Fujitsu, Toshiba) and embassies. Many large commercial complexes with hotels, conference centers and office skyscrapers are concentrated in the following districts: Roppongi (Roppongi Hills Tower office building), Toranomon (Toranomon Hills Tower office building), Akasaka (Midtown Tower) and Shiodome (Dentsu Tower).

The Chūō ward is located in the center of Tokyo and surrounded by five wards: Chiyoda, Minato, Taitō, Sumida and Kōtō. Chūō ward is divided administratively into three zones: Nihonbashi, Kyobashi and Tsukishima. Nihonbashi and Kyobashi are mainly shopping areas on the east side of Tokyo station, in which there are the districts Ginza and Tsukiji. Ginza is a luxurious district in which there are branded department stores (Mitsukoshi, Matsuya), boutiques, restaurants, cafes, as well as the Kabuki theater (a few-floor podium of the skyscraper Ginza Kabukiza). Tsukishima is a separate island in the Gulf of Tokyo dominated by residential skyscrapers.

Shinjuku ward is the largest commercial and entertainment area in Japan, located around Shinjuku Station and surrounded by six wards: Chiyoda, Bunkyo, Toshima, Nakano, Shibuya and Minato. The Tokyo Metropolitan Government building is located near the Nishi-Shinjuku district, where many high office and residential buildings are located in its western part. In addition, the skyscraper Mode Gakuen Cocoon Tower was built in this district, which is the educational center.

Sumida ward is located in the north-eastern part of the Tokyo metropolis. Sumida and Arakawa are the main rivers that form part of its borders. This ward is surrounded by five wards: Katsushika, Edogawa, Taitō, Chūō and Kōtō. The area of this ward is considered to be an old city, although recently a large number of high-rise residential buildings have been started in its area. The Skytree observation tower, which is the second largest building in the world, was built in the Oshiage district.


Fig. 1 Administrative division of Tokyo into wards (red color means wards in which the analysed skyscrapers are located)

### A. Dentsu Headquaters Building

The Dentsu Headquarters Building is an office high-rise building with a steel structure. The building is 213 m high and contains 48 floors above-ground level and 5 floors underground, Fig. 2. The skyscraper design was made by the architectural studio Jean Nouvel. This large complex, located in the center of Tokyo, is mainly used as the headquarters of the largest advertising agency in Japan and one of the largest in the world, Dentsu Inc. The skyscraper occupies the area of the old railway line, near the Tokyo station, and is part of the extensive reconstruction of this area. In order to ensure functionality and an original appearance that corresponds to the beginning of the 21$^{st}$ century, three aspects were considered during the design and subsequent implementation of the building: 100 years of operation, symbiosis with the environment and energy saving. In accordance with the urban plan for SIO-SITE (a comprehensive urban development project), the Dentsu building not only provides office space, but also attractive amenities for visitors that integrate commercial and cultural facilities. In the building is located a restaurant, cafe, theater, library, museum and specialist stores. In order to realize the main concept of "100 years of usability", the design aimed for a highly functional, very durable building that would ensure safety from wind and seismic forces.

The building is designed on a triangular plan with an internal atrium and is approximately 120 m long on its longer side and 41 m on its shorter side, Fig. 3. The communication part was located along the north façade and in the central part parallel to the obtuse sides of triangle.

The height / width ratio is 5 for the shorter side and 1.7 for the longer side, which classifies this building into that of a slender profile. The interior of the building is a massive steel structure with a series of atriums that are characterized by curvature and extensive surfaces [4]. Atriums are located on the north side, while its main façade is oriented from the south. The tower is divided into ten floors, showing the location of various companies. Vertical movement is implemented by panoramic public and office elevators. The elevator battery runs through the entire building, but only reaches the level of the passage. These transition zones determine the main levels of the various atriums. The levels have their own set of elevators for the ten floors occupied by each sector. The facade of the building is fully covered with ceramic printed glass, which not only emphasizes the landscape, but also significantly reduces air-conditioning loads and saves energy. In addition, the light that diffuses and passes through the ceramic printed glass helps daylight to be used with less glare. From the south side, in the façade, ceramic glass with 12 shades from white to gray is used, which creates a very diverse view.

The key element of the design of the structure was to determine the method of deformation control in the transverse direction, where bending is greatest. The main load-bearing structure of the building is a steel mega-frame. These frames are resistant to seismic vibrations and use two types of vibration dampers that are installed in the upper part of the building, controlling lateral and bending deformation. For the asymmetric configuration of the building, a steel shell filled with concrete with a strength of 80 MPa was used. In the atrium for the frame construction, fire-resistant steel with a maximum thickness of 80 mm was used. The foundations of the skyscraper were built on granite rock, which was also exposed in the interior of a six-storey space with stone walls and waterfalls.

The Dentsu skyscraper was designed based on the concept of coexistence with the global environment in which energy saving was a priority. In particular, the focus was on using natural energy and increasing energy efficiency resources. The building has at least 35 major architectural and hardware innovations that have effectively contributed to increased energy efficiency and reduced $CO_2$ emissions. At the time of completion, the building was about 30% more efficient than conventional constructions of the same scale.

Fig. 2 Dentsu Tower

*B. Kabukiza Tower*

Kabukiza Tower is an office and culture skyscraper with a steel structure. The building is 145.5 m high and contains 29 floors above-ground level and four underground floors, as shown in Fig. 4. The skyscraper design was made by Mitsubishi Estate Company and Kengo Kuma Associates. The Kabukiza theater was designed for floors 1 to 4, while floors 7 to 23 are intended for office use. Two intermediate floors (5 and 6) between the theater and the office space are occupied by the mechanical room and a public floor with a gallery and garden. Kabukiza Theater is a fifth-generation building, which is the renovation of the fourth generation building from 1924 designed by Yoshida. Kabukiza Theater includes an auditorium and a stage space spread over four floors and configured as a large atrium. It covers an area that is twice as large as the office part. Under the theater is Kobikicho Plaza, which serves as a municipal square and is connected to the metro station.

The skyscraper is designed on an elongated pentagon plan with dimensions of longest sides 70 m x 33 m, as shown in Fig. 5. The communication shaft has rectangular plan and is located in the south-eastern corner. On the north side of the building, the office space has a span of 20 m without columns [5]. The south façade of the upper part of the building above the theater is finished with panels of prestressed concrete with a window motif characteristic of traditional Japanese architecture.

The Kabukiza skyscraper has a steel frame structure that is used to provide resistance to seismic activity. Between the office part and the theater, two mega-trusses with a height of 13 m and a span of 38.4 m were placed in order to support 23 columns of the office part of the building. It is one of the largest multi-layer structures that have ever been used in Japan to build a skyscraper. In the bottom part of the theater, a steel structure is used that needs to support all the external elements remaining from the previous fourth generation building. An important construction role in this part of the theater is played by the columns that support mega-trusses and reinforced concrete beams with large cross-sections. The skyscraper has a raft foundation that cooperates with reinforced concrete piles.

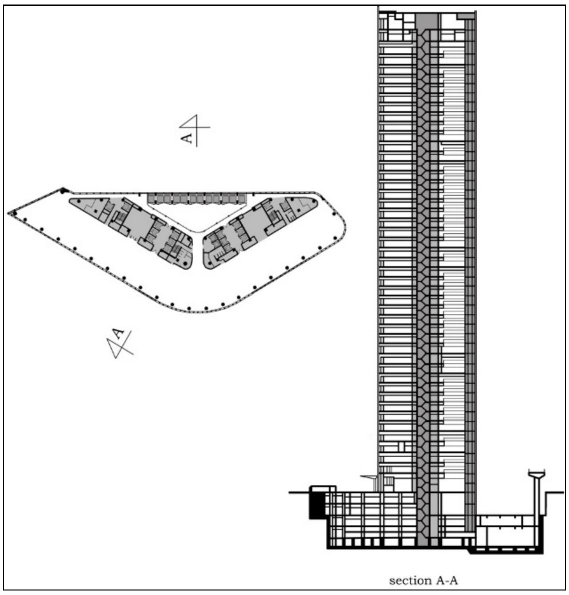


Fig. 3 Dentsu Tower: floor plan and section

Fig. 4 Ginza Kabukiza

The upper part of the skyscraper has a high bending strength due to the steel frame construction and steel columns that are filled with concrete. It uses hysteretic and viscose dampers to ensure safety in the case of seismic interactions. In the lower part, to counteract deformations, resilient steel stabilizers are installed, the strength of which is 490 MPa.

### *C. Mode Gakuen Cocoon Tower*

Mode Gakuen Cocoon Tower is an educational high-rise building with a steel and reinforced concrete structure. The building is 203.7 m high and contains 50 floors above-ground level and four underground floors as shown in Fig. 6. The building design was made by the architectural studio Tange Associates. 50 renowned architectural studios participated in the competition for its design and over 150 proposals were submitted. Mode Gakuen Cocoon Tower is an innovative educational center where three educational institutions are operated: Professional Fashion School (Tokyo Mode Gakuen), Special College of Technology and Design (HAL Tokyo) and Higher Medical School (College Shuto Iko). In terms of the height of the building, it is the world's second tallest educational building after the Moscow State University (239 m), and holds about 10,000 students. It is located between the most frequented Tokyo train station Shinjuki and the central business district.

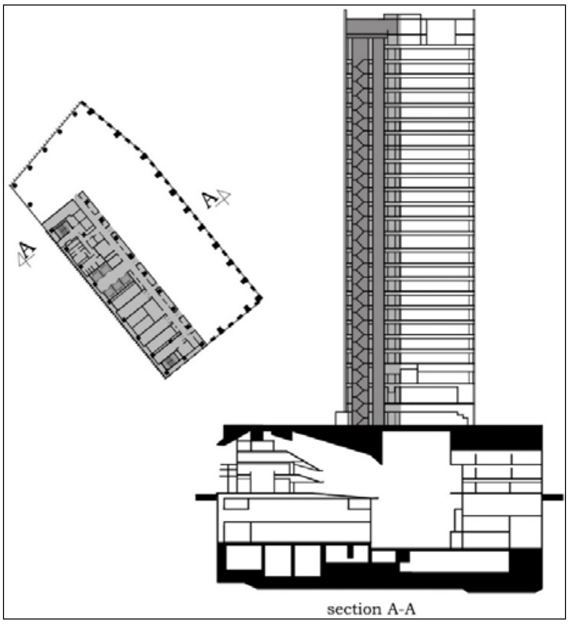


Fig. 5 Ginza Kabukiza: floor plan and section

The Mode Gakuen Cocoon Tower is designed on a circle plan, with a central communication shaft on a hexagon plan and three extended arms form three axes between which classrooms were arranged on a rectangular plan [6]. These three rectangles are rotated by an angle of 120 degrees in relation to the core, as shown in Fig. 7.

Each class has a width of 24 m. The depth of the classrooms varies with height, because the vertical section is an elliptical curve. From the $1^{st}$ to $50^{th}$ floor, the class rooms are arranged in a curved form. The internal core in the building consists of staircases and elevator shafts. The spaces between the classrooms are student rooms and are directed in three directions: east, south-west and north-west. Each of these rooms have a three-story atrium with a view of the surrounding landscape. The building has a sectional façade with a dotted print, creating intersecting stripes in various angles. Composite elements were applied to the façade in the form of fluted strips coinciding with the diagrid structure in classrooms.

A lower building with a height of 30 m, which houses two large auditoria and retail outlets, is adjacent to the high-rise building. Both buildings have the same four-story underground structure, which is used as a car park and retail space.

The main entrances were placed from the north and south side in the vestibule connecting the high-rise building with a ball-shaped building.

The Mode Gakuen Cocoon Tower has a raft foundation with a thickness of 3.8 m that cooperates with reinforced concrete piles. The main load-bearing structure of the tower consists of three peripheral elliptical diagrid frames and an internal frame core. The building has relatively high shear deformations in the middle floors due to the bending of each frame. Because the three frames are rigidly connected to the base and the upper part of the construction, the structure can be treated as a portal frame. The perimeter frames have a width of 24 m, with intersections of 4 m at each floor level, and are curved vertically in the shape of an ellipse. Their task is to transfer transverse forces and overturn moments from the action of wind and seismic effects. In addition, to reduce these impacts on each floor from 15 to 39, 6 viscoelastic dampers were used.

Fig. 6 Mode Gakuen Cocoon Tower

The height of each floor is adapted to the elliptical curve, which allows the diagrid elements to cross at the same angle on each floor. The floor beams in the classrooms are the load-bearing element for the storey and connect in a horizontal diagrid frame and the inner core, preventing the buckling of these frames from out of the plane. In the student rooms located in a three-story atrium, the glazing of the façade is three storeys high with a maximum width of 20 m. Vierendele double arched trusses were used to transfer the weight of the façade glass and counteract wind action. Vierendeel trusses are suspended on beams located above, so that no structural element would obstruct the view on any storey. Unlike many other tall buildings in Tokyo, the Gakuen Cocoon Tower does not have a flat roof. This is very important due to the fact that the cleaning system and the provision of space for helicopters is an essential requirement for a high building in Japan. Therefore, in order to fulfill these conditions, a sliding roof was used. A gondola hanger with a cleaning system is installed under a floating roof and moves on "Y" shaped rails with a rotating table in the middle. The hanger is able to provide the gondola to the entire outer surface of the building by extending and turning the arm at each end of the rails. The Mode Gakuen Cocoon Tower has a cogeneration system that generates 40% of energy, which increases the operational efficiency of the building, as well as reducing energy costs and greenhouse gas emissions. The elliptical shape allows for even distribution of sunlight and the aero-dynamic scattering of strong wind streams.

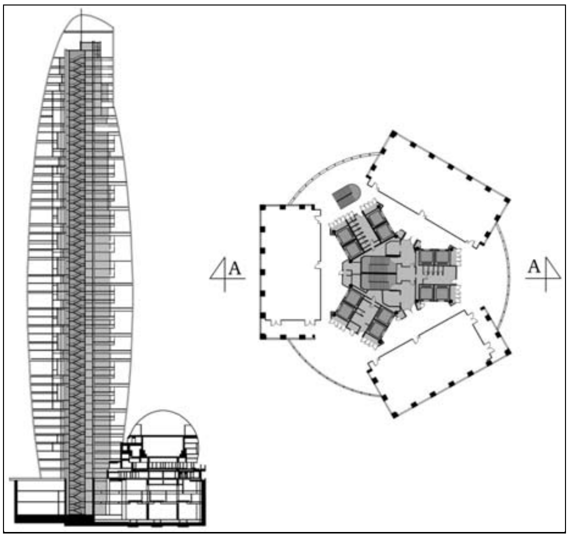


Fig. 7 Mode Gakuen Cocoon Tower: plan and section

*D.Roppongi Hills Mori Tower*

Roppongi Hills Mori Tower is a multi-functional skyscraper with a steel and reinforced concrete structure. The structure is the central point in the mega-complex that comprises office buildings, apartments, the Grand Hyatt hotel, the Asahi television studio and an amphitheater. The creator of this complex was the potentate of the building market Minoru Mori, who realized his vision of a global city. It is one of the largest urban complexes in Japan, which has been transformed from small building plots and surrounded by lush greenery that is combined with various urban functions.

Roppongi Hills is 238 m high and contains 54 floors above-ground level and six underground floors, as shown in Fig. 8. The building was designed by a team led by Eugen Kohn, William Pedersen and Paul Katz from the architectural studio Kohn Pedersen Fox Architects. The usable area of the skyscraper, when compared to this type of facility, is one of the largest in the world. The building is designed on a concave-convex octagon plan with a central communication shaft on a square plan. On the first six floors, there are shopping facilities and restaurants, floors 7-48 serve as offices of various corporations (Apple, Basf, Lenovo Japan, Google Japan), and the Mori Art Center is located is located on floors 49-54. The central element of this center is the Mori Art Museum located on the 53$^{rd}$ floor, which was designed by Gluckman Mayner Architects. The observation terraces were designed on floors 52 and 54. The form of the building was implemented in accordance with traditional Japanese architecture. In the facades, horizontal and diagonal lines have maximized the amount of glass and steel, just like in the folds of a paper origami sculpture.

Fig. 8 Roppongi Hills Mori Tower

The skyscraper has a raft foundation that cooperates with reinforced concrete piles. The main load-bearing structure of the building consists of steel frames, steel columns filled with concrete and an internal frame core as shown in Fig. 9. In order to counteract seismic actions, semi-active viscoelastic oil dampers and steel anti-buckling stabilizers with a low yield strength were used [7].

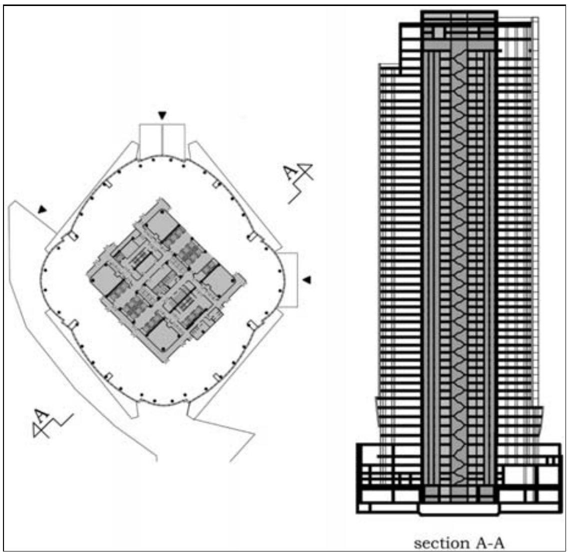


Fig. 9 Roppongi Hills Mori Tower: floor plan and section

### E. Tokyo Skytree Tower

Tokyo Skytree is a radio-television and observation tower with a steel and reinforced concrete structure as shown in Fig. 10. The tower is the highest in the world with a height of 634 m, exceeding the Canton Tower (600 m, Guangzhou, China), and is the second tallest structure after Burj Khalifa (829 m, Dubai, UAE). The tower was designed by the architectural studio Nikhen Sekkei. The main function of Tokyo skytree is the transmission of terrestrial digital signals for television. Due to the numerous tall buildings in the center of Tokyo, rising to a height of 200 meters, it became necessary to build a new tower higher than 600 meters. The previous Tokyo TV tower is 333 m tall. In the initial design, the height of Skytree was set at 610 m. However, from the beginning it was planned that it will be the world's highest freestanding radio and television tower. The decision on the height of 634 m was related to the symbolic meaning of this number. The pronunciation of the number 634 in old Japanese is "musa-shi", like the old Musashi province, which occupied a large area covering Tokyo, Saitama and part of the Kanagawa prefecture. The building at the base was designed on a triangular plan, which at the top goes into a circle. In addition to office space, shops and restaurants, there are also two observation terraces located here. The first one is located at a height of 350 m and is covered with 5-meter thick glass that enables a 360-degree panoramic view. The second observation terrace is located at a height of 450 m. Tokyo Skytree is designed in the original color of the brightest shade of Japanese traditional indigo blue, which gives a delicate pale blue glow that is reminiscent of white celadon porcelain.

Tokyo Skytree is located on the banks of the Sumida River, where the surface layer is soft silt. The foundation of the tower consists of steel piles filled with concrete, and also reinforced concrete walls with a thickness of 1.2 m that are located at a depth of 35 m on the load-bearing layer under the surface of soft silt as shown in Fig. 11. A set of cylindrical steel and thin-walled piles reaches up to a depth of 50 meters [8]. This system of rigid foundation construction and vulnerable ground uses a relative displacement that is used to damp vibrations. Moreover, the foundation must not only ensure horizontal stiffness, but also vertical stiffness, as well as counteract the overturning moment.

The tower's structure consists of two separate parts, one of which is a steel truss, the other an internal reinforced concrete core. Both parts can move independently. To minimize seismic energy, a central core or so-called shinbashira, utilized for centuries in traditional Japanese architecture in pagodas, was used. The core has a diameter of 8 m, a thickness of 6 m, a height of 375 m and operates on a stationary pendulum that balances seismic waves by reducing vibrations. Additionally, the elements supporting the reduction of vibrations are viscous oil dampers attached to the upper part of the core. An independent steel truss structure with a circular hollow tube section is placed on the core. The truss is not only light and strong, which is necessary from the design point of view in seismic areas but is also effective in a wind-resistant construction, reducing the frontal area and not causing an unstable aerodynamic reaction due to the absence of an external wall. There are two types of steel structure in the tower. One structure is a truss, and the other one is a mega truss with a lattice core and girder, known as the Kanae truss. The coexistence of two steel structures occurs in the area where there are shops.

To minimize the impact of wind in the upper part of the tower, a system of tuned mass dampers was installed. In practice, this is characterized by two massive ballast weights, weighing 25 and 40 tons, which were supplied by Mitsubishi Heavy Industries and hung close to the top with large springs and vibration absorbers. As in the case of structures with a reinforced concrete core and an external truss, these two counterweights work on shifting any lateral movement.

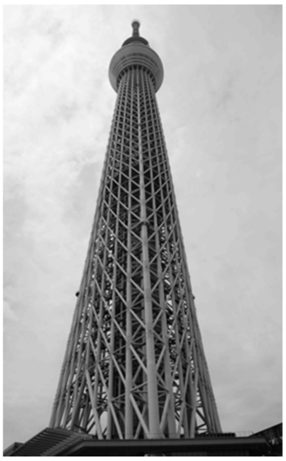

Fig. 10 Tokyo Skytree Tower

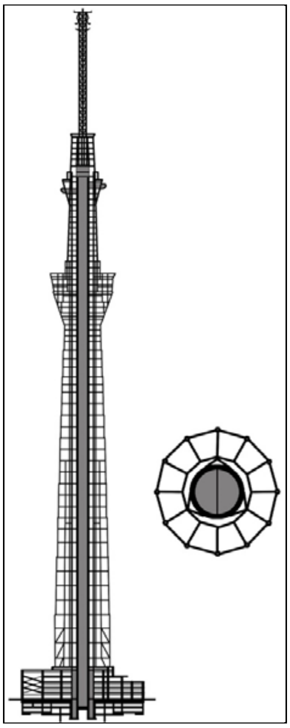

Fig. 11 Tokyo Skytree Tower: floor plan and section

### *F. Toranomon Hills Residential Tower*

Toranomon Hills Mori Tower is a multi-functional skyscraper with a steel and reinforced concrete structure designed in the Toranomon Hills complex, the creator of which, as with Roppongi Hills, was Minoru Mori.

The building is 247 m high and contains 52 floors above-ground level and 5 underground floors, see Fig. 12. The building was designed, by the architectural studio Nikhen Sekkei, on an elongated hexagon plan with two rounded opposite corners and with a central communication shaft on a rectangular plan. In the underground part there is a car park, on floors 1-3 commercial buildings, floors 4-5 occupy a conference center, floors 6-35 are intended for offices, floor 36 includes a spatial truss structure, floors 37 to 46 occupy the living spaces, and the hotel Andaz occupies the above floors. The skyscraper was designed around the new communication Loop Road 2 connecting Toranomon and Shimbashi as part of the loop around Tokyo. The Loop Road 2 that runs underground connects the eastern side of the building with a tunnel at the second underground level [9]. The road runs through a tunnel structure, which was built independently of the building's structure. In order to avoid the impact of road traffic vibrations on the building, the building's structure is isolated from the running structure by the introduction of material damping vibrations. Noise is reduced with the use of a Sylomer mat (polyurethane elastomer).

The skyscraper has a raft foundation that cooperates with reinforced concrete piles. The main load-bearing structure of the above-ground part of the building is a steel frame structure with steel columns filled with concrete and a central reinforced concrete core, see Fig. 13. The underground part has a mixed construction consisting of steel and reinforced concrete frames. The podium construction on the Loop Road tunnel consists of prefabricated reinforced concrete slabs with a thickness of 1 m. In the corners of the part of the building that has sharp angles, which are located in the north-west, south-east and south directions on floors 8 to 13, there is a system of inclined two columns, which intersect and pass into one column on the floors below. In the locations of this passage, there is a steel connection with a weight of 20 tons, which allows the load to be transferred from two columns to one. Due to the change of the structural layout in the sector above the 35th floor and the introduction of columns at a distance of 9 m from the outer edge of the building, on the 36th floor, a spatial truss with a height of 1 m was used. The crowning of the skyscraper is a steel structure inclined towards the east-west in the shape of shifted pyramids. In order to transfer forces from the roof to the building, two Keel trusses were used. The longest diagonal roof element has a length of 30 m and is covered with reinforced concrete slabs in order to increase its stiffness in the plane.

The use of a steel mega frame in the construction of the skyscraper effectively counteracts deformations coming from the bending of the entire building. Additionally, viscous oil dampers, buckling stabilizers in the form of diagonal braces and friction dampers as devices controlling shock and vibration reactions were used.

Fig. 12 Toranomon Hills Residential Tower

### G. Midtown Tower

Midtown Tower is a multi-functional skyscraper, the tallest of six buildings in the new Tokyo Midtown urban complex [10]. With the transfer of the headquarters of the Japan Defense Agency to the Ichigaya district, a great project to rebuild the area located in the center of Tokyo, containing an extensive range of greenery with the Hinokicho park, has begun. The project of the skyscraper was made by the architectural studios Nikken Sekkei and Skidmore, and Owings & Merill.

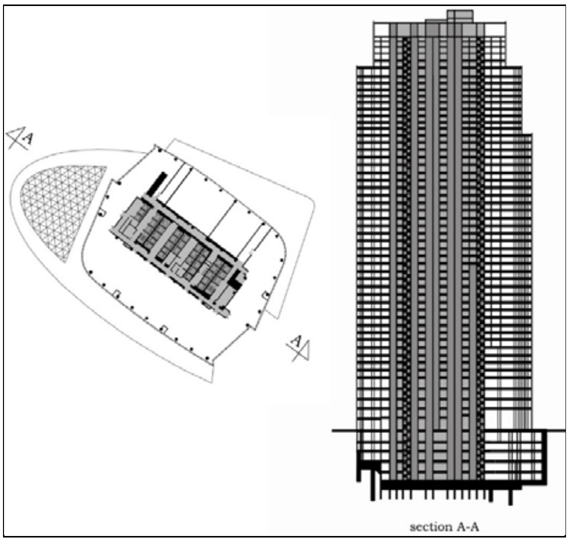


Fig. 13 Toranomon Hills Residential Tower: floor plan and section

The building is 248 m tall and contains 54 floors above-ground level and four underground floors, see Fig. 14. The Midtown tower is designed on a rectangular plan with a central communication shaft. In the underground part of the building there is a car park, while above-ground there is a shopping center (floors 1-3, Coppola's Vinoteca, Dean & DeLuca), conference center (4th floor), Tokyo Midtown Design Hube gallery and design office (floor 5), Medical Center (6th floor), commercial offices (floors 7-44, Cisco Systems, Nikko Asset Management, Yahoo Japan, Fuji Film) and the Ritz-Carlton hotel (floors 45-53). Unlike similar skyscrapers in the area, such as the Roppongi Hills Mori Tower, the top of the 54$^{th}$ floor of the Midtown Tower does not have an observation deck for visitors. Instead, the floor is occupied by a machine room.

Fig. 14 Midtown Tower

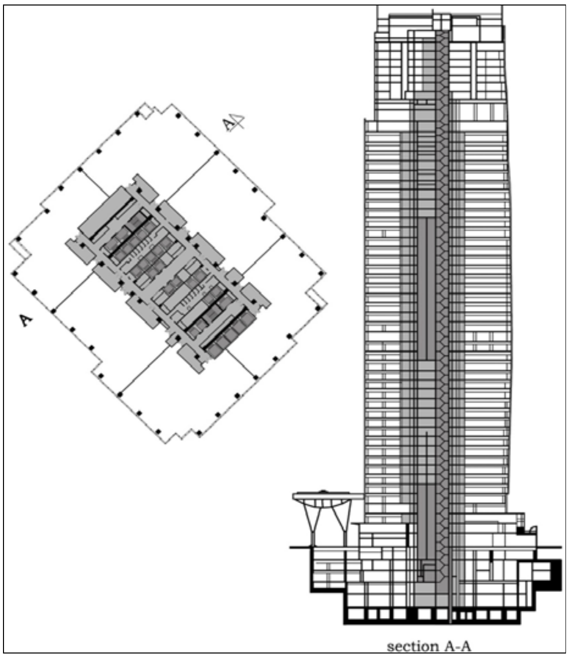


Fig. 15 Midtown Tower: floor plan and section

Three buildings in the Midtown Tower complex are located on a massive foundation slab with a length of 230 m on each side. The main load-bearing structure of the tower consists of steel frames, steel columns filled with concrete and an internal frame core, see Fig. 15. In order to counteract seismic impacts, buckling stabilizers and viscous oil dampers were used.

## V. Conclusion

Due to seismic actions, Japan is a country with very difficult conditions to build, especially high-rise buildings. Historically, traditional construction was characterized by light wooden constructions, usually skeletal and insensitive to slight deformation, with brick buildings being less frequent. Characteristic buildings of Japanese architecture were tall and slender pagodas, in which the structure is loaded from above with a massive wooden stake to ensure stability. Currently, traditional residential buildings are being replaced by multi-storey buildings with a higher communication shaft. Contemporary architecture adopts a global character, where high-rise buildings are a characteristic feature. Undoubtedly, the least-resistant construction for an earthquake is a skyscraper, which is a certain paradox in comparison with their number in Japan, and especially in Tokyo, which in this respect has the fourth most in the world. Since the Kobe earthquake in 1995, Japan has become a world leader in building new buildings, as well as modernizing old ones so that they can withstand rapid seismic quakes. The most modern skyscrapers in Tokyo are able to withstand earthquakes of over seven degrees on the Richter scale. Of course, more forces affect a building with a larger earthquake, and its construction therefore experiences larger displacements. A building's response to earthquakes are vibrations in the form of sinusoidal motion. In order to counteract both these forces and the impact of wind, apart from a rigid construction, very advanced technologies of damping devices are used. For example, the foundations of these buildings (Maison Hermes Tokyo) are mounted with a system of spring or elastomer vibration dampers, due to which tectonic movements affect the upper part of the building to a lesser extent. In addition, as presented by the characteristics of high-rise buildings, viscous oil dampers (Mode Gakuen Cocoon), anti-buckling steel stabilizers (Midtown Tower, Roppongi Hills, Kabukiza Tower) and tuned mass dampers (Tokyo Tree Tower) are used in various levels of these buildings. When using all these supporting elements, it is most important that the location of the center of gravity of the building does not change during earthquakes. The main load-bearing structures of the presented skyscrapers are steel mega-frames with steel columns filled with concrete and an internal frame core.

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