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Orginal Article

Analysis of technical problems in modern super-slim high-rise residential buildings

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Abstract: The purpose of this paper is to present a new skyscraper typology which has developed over the recent years – super-tall and slender, needle-like residential towers. This trend appeared on the construction market along with the progress of advanced structural solutions and the high demand for luxury apartments with spectacular views. Two types of constructions can be distinguished within this typology: ultra-luxury super-slim towers with the exclusivity of one or two apartments per floor (e.g. located in Manhattan, New York) and other slender high-rise towers, built in Dubai, Abu Dhabi, Hong Kong, Bangkok, and Melbourne, among others, which have multiple apartments on each floor. This paper presents a survey of selected slender high-rise buildings, where structural improvements in tall buildings developed over the recent decade are considered from the architectural and structural view.

Keywords: tall residential buildings; development; slenderness; structural system; advanced materials; damping systems

1. Introduction

In the global race for the title of the world's tallest building, height is no longer the only valuation criterion. At present, records related to their slenderness are being set in the construction of tall buildings. A new generation of groundbreaking, slender structures that most often perform a residential function is growing worldwide. Latest skyscrapers are pushing slenderness to previously impossible levels.

Slender, tall buildings in large metropolises are becoming more and more popular because they allow to accommodate large volumes of space on a relatively small area, which is economically and environmentally beneficial. These buildings characterize with the smallest possible footprint.

The slenderness of high-rise buildings is defined by the height to width ratio at the building's base. According to the standards, buildings with slenderness greater than 10: 1 are considered to be slender. Table 1 lists the most slender tall buildings in the world.

Due to high land values and liberal zoning law, Hong Kong was once a pioneer in building pencil-thin (needle-like) towers [1]. For example, Highcliff, which was designed by Denis Lau & Chun Man Architects & Engineers studio and completed in 2003, features an extraordinary slenderness ratio of 20:1 (height to width). However, this was the only example of this type of residential tower, with a height exceeding 250 m and of such a slim design in Hong Kong. The trend of building very tall, slim apartment buildings began in New York. Skyscrapers One57, 432 Park Avenue, 56 Leonard, 30 Park Place, 53 West 53rd, and 111 West 57th Street put New York on top of the extraordinary slender high-rise building league table [2]. Eight residential towers in "Billionaires Row" reinforce the view that New York is a cosmopolitan city, with its residents coming from all over the world (Fig. 1). Inspired by New York's slender residential 80 to 100-storey towers, other buildings of this type have recently begun to pop up in Dubai, Abu Dhabi, Melbourne, Brisbane, Toronto, Mumbai, Moscow, etc. Besides Central Park in Manhattan's Midtown, the other key city that fulfilled its aspirations to become the capital of high-rise and slender buildings is Dubai. The remaining pencil-type buildings are spread across twenty-one other cities.

However, the type of needle-like buildings in New York differs fundamentally from the structures found in the other, abovementioned cities. The super-slender apartment towers of New York have a significantly lower girth as each floor is designed to contain only two apartments. In contrast, other tall, slender residential towers built worldwide contain more flats per floor. This multiplicity requires a larger floor space to accommodate extra elevators needed to handle the volume of traffic. They also require a large central core devoted to mechanical systems and shared hallways [3].

Tab. 1. The list of the world's super-slender tall buildings (developed by authors and based on [7].[8])

Building	Location	Slenderness ratio height/width	Structure	Function
111 West 57 Street	New York	24:1	steel/concrete	residential
Central Park Tower	New York	23:1	concrete	residential
125 Greenwich Street	New York	20:1	concrete	residential
Highcliff	Hong Kong	20:1	concrete	residential
150 North Riverside	Chicago	20:1 at base	composite	office
220 Central Park South	New York	18:1	concrete	residential
Collins House	Melbourne	16.25:1	concrete	residential
432 Park Avenue	New York	15:1	concrete	residential
MahaNakhon	Bangkok	13.6:1	concrete	residential/hotel
Burj Mohammed Bin Rashid Tower	Abu Dhabi	13:1	concrete	residential
Etihad Tower T2	Abu Dhabi	12:1	concrete	residential
Marina 101	Dubai	12:1	concrete	residential/hotel
53W 53th MOMA Tower	New York	12:1	concrete	residential
One Madison Park	New York	12:1	concrete	residential
Pearl River Tower	Guangzhou	11.7:1	composite	office
Ocean Heights	Dubai	11.5:1	concrete	residential
One Bennett Park	Chicago	11.5:1	concrete	residential
Neva Tower 2	Moscow	11.3:1	concrete	residential
Princess Tower	Dubai	11:1	steel/concrete	residential
Trump World Tower	New York	11:1	concrete	residential
Cayan Tower	Dubai	10.8:1	concrete	residential
30 Park Place	New York	10.5:1	concrete	residential/hotel
Elite Residence	Dubai	10.3:1	concrete	residential
56 Leonard	New York	10:1	concrete	residential
9 DeKalb Avenue	New York	10:1	concrete	residential/office/retail

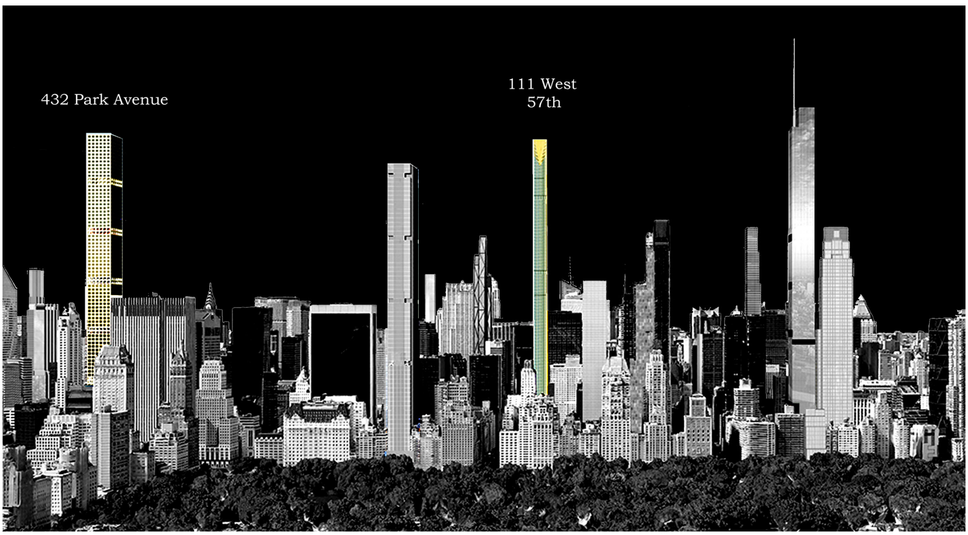

Fig. 1. Eight residential skyscrapers in "Billionaires Row" in New York (developed by authors based on [4])

Until the beginning of the 21st century, most high-rise buildings served as office towers. After 2010, the number of super-tall residential buildings increased rapidly. Since 2011, 262 buildings over 200 m height were built (Fig. 2).

The newly erected 111 West 57 Street (Steinway Tower) building in New York with slenderness ratio 24:1 is the world's most slender residential skyscraper. Following New York's lead, super-slender buildings are also being constructed in Australia. One example is a proposal for the "Magic" tower in Melbourne [5]-[6], a 330-meter tall super-slender, triangular-based construction with a slenderness ratio of 27:1.

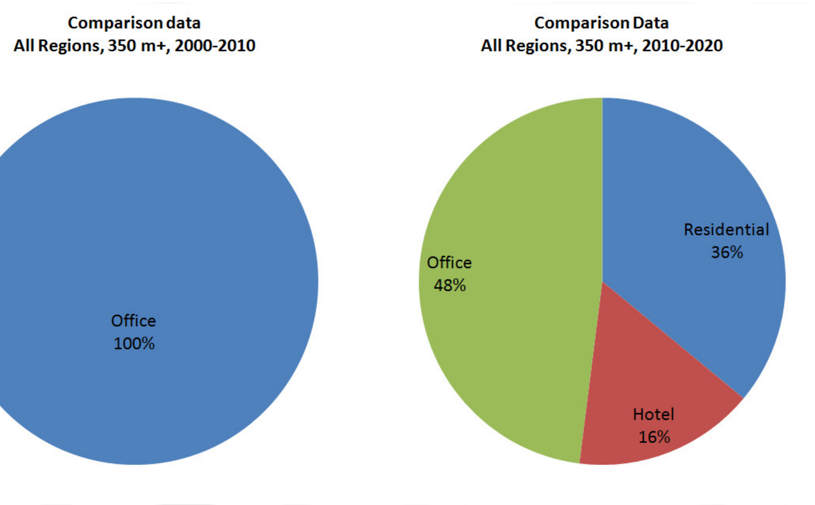

Fig. 2. Comparison of the percentage share of tall residential buildings over 350 meters in the years 2000-2010 and 2010-2020 (based on the global tall buildings database of Council on Tall Buildings and Urban Habitat)

2. Historical development of slender high-rise buildings

The history of building skyscrapers began in Chicago and New York in the late 1880s, not as a sign of lofty ambition, but as a commercial necessity. By the year 2019, a total of 1 521 buildings over 200 m height were built in 140 cities worldwide (database CTBUH). At the beginning of 2010, a new super-slender form of a skyscraper was initiated in New York. This was due to the increasing shortage of land, population growth, and a specific need for luxury apartments.

The first period of building slender high-rise buildings saw a rapid increase in height. At that time no municipal regulations limited the height of buildings. Completed in 1909, the Metropolitan Life Insurance Tower, of 213.4 m and 50 storeys, had a lot of only 22.9 m x 25.90 m.

The second period dates back to the 1920s. The first Zoning Law of 1916 states that the building's shape up to a certain height should have been the same and above it had to decrease. Moreover, the upper floors' building area could not be more than 25% of the bottom space.

The examples of this new characteristic cascade type of a New York skyscraper are the Empire State Building, Chrysler Building and 570 Lexington Avenue. At that time the skyscrapers only housed hotel apartments. Until 1929, apartment buildings were regulated by the New York State tenement house laws, which set their maximum height at 46 m. After 1929, a revision of the Multiple Dwelling Law allowed constructing higher apartment buildings. The San Remo and El Dorado's twin-tower form on Central Park West established a new standard of luxury living [10]. After 1961, a new zoning law [11], determined a maximum permitted total floor area for a building lot. The new formula defined Floor Area Ratio (FAR) as the sum of the total area of the above-ground part of the building to the plot area [12]. The law has established a principle that allows design and building without special control, whilst complying zoning rules and not exceeding the maximum FAR for a lot (Marine Midland, 277 Park Avenue, Home Insurance Plaza). Moreover, the air rights were introduced, which allow a building that has not used all of the FAR to sell unused air rights to the owner of neighbouring lots. This type of action referred to as "transferable development rights" allowed developers to combine plots to increase the FAR for a single building. Currently, all tall buildings use this method to obtain the maximum FAR.

Between 1969-1976, sky-living buildings' unprecedented heights became possible in Chicago when the mixed-use modernist tower, John Hancock Center and Water Tower Place, developed apartments on its upper floors [13]. There are currently 53 residential buildings above 150 m high in Chicago, but only two can be categorized as slender ones (Park Tower, One Bennett Park).

In New York, the next period of skyscraper residences followed with the rise of condominium towers, which saw a boom in the mid-1980s, which were especially centred around Fifth Avenue and 57th Street (Metropolitan Tower, City Spire). These towers were the first to use slenderness as a dominant strategy. Completed in 2001, Trump World Tower is an example of a new type of luxury, which grew in popularity in the 21st century due to New York's latest super-slender, super-luxury high-rise residential buildings.

During the years 2005-2010, several ultra-luxury, slender towers were built in New York, including 100 East 53 Street, Eight Spruce, 56 Leonard, 50 West Street, and One 57. Another common feature for these landmark buildings was that they were designed by world-famous architects (Norman Foster, Frank Gehry, Christian de Portzamparc, Jacques Herzog, and Pierre de Meuron).

Development of tall, slender residential buildings is rapidly increasing worldwide. As of November 2019, there were 94 residential towers above 250 m (database CTBUH), 23 of which are slender. New York boasts the largest number of super-slender tall skyscrapers [11], with others being built in Chicago, Dubai, Abu Dhabi, Melbourne, Guangzhou, Moscow, and Bangkok. In the next five years, developers worldwide are set to complete about 50 new super-slender residential towers, more than double the number currently standing. This boom underscores the growing desire among the world's super-wealthy to live "above it all". Hong Kong made a mark in the history of tall, slender residential buildings with the Highcliff building completed in 2003, which was the slimmest building in the world at the time. However, in the following years, Hong Kong stopped building such tall residential buildings.

3. Methods

The basic research method used in the paper includes identifying a group of super-slender tall buildings. The relations between the architectural form, the structural system, and the construction material used are significantly visible. The trend related to constructing high-rise, slender residential buildings involves two solid foundations: a technological and economic one. The authors try to analyze various aspects affecting the spread of this trend in global architecture. At the beginning of its development, the difficulties associated with creating slender residential skyscrapers were enormous due to the complicated design process, risks related to financing and commercialization, and the challenging organization of construction works conducted on a large scale on small lots. New York initiated the transformation of the existing office towers into slender residential towers, and became the reference city to analyze this problem. A city that can be considered a laboratory of architecture and urban planning. In the paper, the authors used a method that takes into account the following elements:

- The collection of information which concerns the creation of the slim residential towers in New York and other cities and the advanced technologies of their construction.
- The analysis and synthesis of the acquired information based on the literature search and own review experience.
- Conducting, according to a structured scheme, architectural and structural analysis of selected slender high-rise buildings that are the most significant of this type.

The authors' main intention was to present a new typology of tall buildings and the main factors related to their design. In the analysis, apart from touching upon aspects related to the strategy of slender buildings and the standard requirements for their construction, attention was drawn to some other elements, such as: characteristic load-bearing structure, which was adopted from earlier skyscraper solutions; foundations construction; use of ultra-strong concrete; the strategy of reducing wind action; damping systems. The collected source material and the presented characteristics allowed to indicate the main determinants of super-slender tall buildings.

Moreover, the authors' idea was to analyze sustainable construction features included in the designs of super-slender residential buildings, including reducing energy consumption in their construction and operation, the maximum use of daylight to illuminate rooms and minimize interference with the surroundings. The analyses of elements related to the design of slender tall buildings presented in the article, obtained from the synthesis of the collected data, may be an additional source of information about the design of tall buildings.

4. Characteristic of super-slender high-rise buildings

4.1. Requirements for the design of slender tall buildings

Super-slender skyscrapers are an expression of advanced technologies, modern building materials and tools to facilitate their design. Each project has individual features, and the main engineering challenge is related to the mitigation of wind action. The wind action is the basic variable load, and not only the variability in height is essential, but also asymmetrical loads in the plan, leading to a dynamic twist of building. Many years of experience enabled the construction of residential buildings to reach heights of over 400 m. Using innovative design solutions and often new intelligent materials, the form and function could be adapted to their residents' different needs [14]. Super-slender tall buildings are for developers' optimal real estate, guaranteeing high market value due to the high demand for residences with magnificent views [15].

General stability for this type of buildings is the most important element of the design. From the building statics' point of view, the computational effect caused by destabilizing loads must be smaller than the effect caused by stabilizing loads. Therefore, super-slender high-rise buildings should have adequate mass. The main material used in their construction to increase their mass is concrete.

The building design is based on the fulfilment of two limit states according to standard codes. The ultimate limit state is related to the strength requirements of structural elements and ensures adequate structural robustness. Serviceability limit state is related to the deflection of structure and floor slab acceleration on the acceptable level and provides the required comfort level to residents.

The following are the most important requirements for the designers of super-slender high-rise buildings:

- To counteract the impact of wind.
- To ensure stability, especially for the ground with low load-capacity and on unstable earthquake areas.
- To protect the building against a progressive and disproportionate collapse in the case of accidental impacts (internal explosions, human errors, terrorist attacks).
- To develop new construction techniques to reduce time and minimize costs.

4.2. Slenderness strategy

A critical aspect of the analysis of these types of buildings is slenderness strategy. This strategy strives to ensure that there are no large apartments on a typical floor and they are situated at a height where the view is undisturbed by neighbouring buildings. New York counts the most slender tall buildings. They constitute a separate category among all other slender constructions, i.e. the New York residential towers contain one or two units per floor with an area of 220 m^2 to 740 m^2. For comparison, in Dubai, the second city after New York with many needle-like buildings, the average number of units is 4 to 6. A summary of the number of apartments per level in the world's tallest slender residential buildings is shown in Table 2.

Tab. 2. The tallest residential slender towers in the world (based on the global tall buildings database of Council on Tall Buildings and Urban Habitat)

Building	Location	Levels	Residential Units Condo/Hotel	Completion Date
9 DeKalb Avenue	New York	73	417	2022
111 West 57th	New York	84	58	2020
Central Park Tower	New York	98	179	2020
125 Greenwich Street	New York	273	72	2020
220 Central Park South	New York	65	116	2020
Neva Tower 2	Moscow	79	814	2020
Collins House	Melbourne	60	298	2019
53W 53rd MOMA Tower	New York	77	145	2019
One Bennett Park	Chicago	67	345	2018
Marina 101	Dubai	101	506/281	2017
30 Park Place	New York	67	157/185	2016
56 Leonard	New York	57	146	2016
432 Park Avenue	New York	85	146	2015
Burj Mohammed Bin Rashid Tower	Abu Dhabi	88	474	2014
Cayan Tower	Dubai	73	495	2013
Princess Tower	Dubai	101	763	2012
Elite Residence	Dubai	87	697	2012
Etihad Tower T2	Abu Dhabi	80	387	2011
One Madison Park	New York	50	69	2010
Ocean Heights	Dubai	83	519	2010
Highcliff	Hong Kong	73	113	2003

The small floor area makes its core super compact. It contributes to reducing the number of elevators and appropriate service strategy. For example, the most slender skyscraper in the world (111 West 57 Street building, New York), which has 80 stories and 60 apartments, is served by two passenger elevators. Clearly higher than the average floor-to-floor height (up to 4.7 m) increases the sense of space and comfort. At 432 Park Avenue, New York, the architects and engineers elaborated special design that results in the thinnest profile and minimal footprint. The tower's lower floors without views are used for residential amenities, e.g. storage, pool, gym, and spa [16].

4.3. Advanced materials

The evolution of modern slender high-rise buildings is associated with the technological achievements of material engineering. Innovative and recently prevalent smart materials (such as phase change materials, shape memory alloys, magnetorheological liquids) enable creating a complex form and structure [17] as well as obtaining previously unachievable super height energy efficiency.

This type of buildings is designed using ultra-high-strength concrete. UHSC is made of high-quality cement with a low water-cement ratio using highly-effective chemical admixtures, such as shaping rheological properties (plasticizers and superplasticizers), mineral additives, especially micro-silica (spheres and silicon dioxide), as well as micro-fillers and fibres [18]. To reduce the hydration heat, fly ash is used to replace portions of the cement's content. Fly ash also provides better workability and less segregation due to its smaller particle size and lighter weight when compared to cement. Other raw materials, such as coarse aggregates and sand, are stocked in a shaded area with automatic water sprinklers to control their temperature. Polystyrene foam also plays a vital role in the curing of concrete. The foam's purpose is to achieve the same temperature in the top and middle layers of concrete.

Additives significantly increase the strength (above 150 MPa) and modulus of elasticity (50000 MPa), as well as accelerate the curing of concrete (low hydration heat, not to exceed 70^{o}C) and enable construction works in conditions with very high temperature amplitudes. Concrete reinforcing bars also have very high strength in the range from 280 MPa to 690 MPa.

The main advantages of concrete structures against the steel structures of tall residential buildings include:

- Less noise transmitted between floors.
- Less sway due to wind shear.
- Temperature is more consistent even though energy costs are typically lower due to thermal mass.

4.4. Foundation

The foundation of super-slender buildings should meet the higher demands concerning bearing capacity and sensitivity to different settlements. Its stability depends on the form and size of vertical forces which have a stabilizing effect. The phenomenon of instability can be compared to buckling due to which the structure can lean. In order to provide stability of the building against wind pressure and seismic forces, designers are forced to build underground floors. Due to the higher construction costs of underground rather than above-ground storeys, 2 to 3 underground levels are usually implemented. The method of foundation building depends on soil type and hydrological conditions. The best soil type is solid rock which occurs, among others, in Manhattan. If the load-bearing soils are at a greater depth, pile foundation is used. The piles are deepened to a considerable depth to layers of soil with high load capacity. The piles transfer loads from the building to the ground by friction between the side surface and the ground and the pile blade's pressure on the load-bearing layer. The pile system of various lengths and diameters is designed based on stress distribution under the erected building.

Another type of foundation classified as deep foundation is a slab-pile composite foundation [19]. It is a special type of pile foundation, in which its top cooperates with the piles, and its main purpose is to limit the settlement of the building. This foundation transfers part of the load directly to the ground under the slab and the remaining part to the piles [20], Fig. 3. Under the pressure of the slab, the ground settles directly under it together with the piles, as a result of which there is no sidewall resistance in the upper part. Vertical stresses under the plate cause additional horizontal stresses in the ground, which act on the piles, significantly increasing the resistance of their side surface in deeper layers. The distribution of forces between the slab and piles, as well as on individual piles, their sides and bases, is the result of a complex system of mutual interactions and cooperation of these elements.

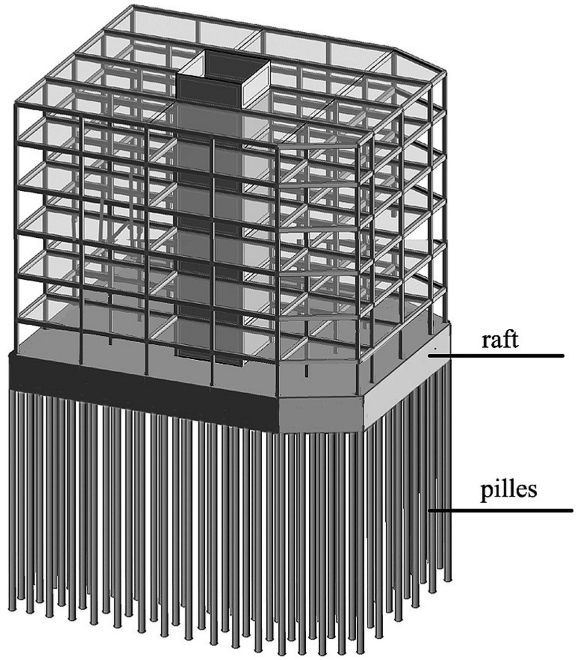

Fig. 3. The system of piled raft foundation (developed by authors)

The foundation design depends on many features of slender buildings [21]. The most important can be included

- Weight of building due to the transfer of vertical loads on the foundation.
- Second-order effect (P-Δ analysis), causing additional bending moments.
- Wind action causing large bending moments in the foundation system.
- Influence of cyclic wind impact in the lateral and vertical direction.
- Dynamic building response for higher modes of foundation vibration, when their natural periods can be excited by the wind.

4.5. Structural systems

With the increase of tall buildings with a high structural height and slenderness ratio, more attention is paid to the efficiency of structural systems. A super slender high-rise building's lateral stability is very often achieved through "frame-tube" structures with outriggers.

Frame Tubes was invented by Fazlur Rahman Khan in the 1960s and was used for the next two decades. However, its use was later limited due to the location of the perimeter columns and its impact on the façade form. However, this system was again used in slender buildings. The best examples are residential skyscrapers, such as 432 Park Avenue in New York and Marina 101 in Dubai (Fig. 4). For this type of buildings, the framed tube system is better integrated with the floor plan and façade system [22].

Fig. 4. Super-tall residential towers: a) 432 Park Avenue (New York, photograph by authors), b) Marina 101 (Dubai, developed by authors based on [28])

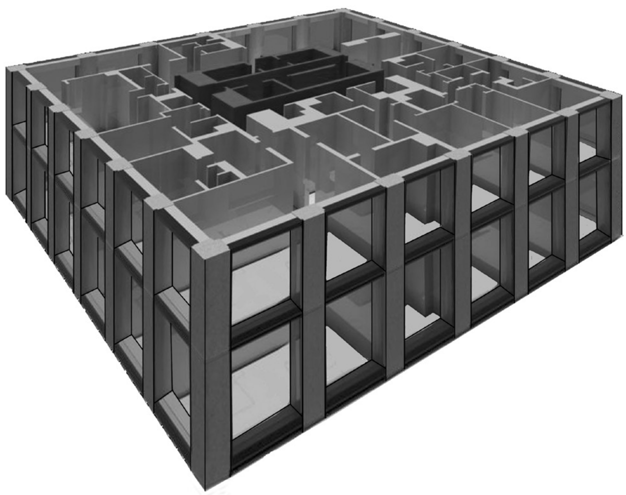

Fig. 5. Levels of a tall residential building whose floors are typically composed of many separate rooms (example of 432 Park Avenue, developed by authors)

A common system in super-slender, high-rise buildings is the outrigger frame system, which works by coupling together two structural systems – the rigid frame system on the perimeter and the core system to obtain the unified structural behaviour [23]-[24]. An outrigger performs the function of extending in the horizontal direction the core to peripheral columns. It is mainly designed in the form of a shear truss or shear walls (Fig. 6). They usually occupy one floor for the purpose of mechanical equipment and are characterized by high flexural and shear strength [25]. This structural system that increases the shear frame's rigidity is based on the action of a cantilever tube. It works by supporting the core and transferring loads to peripheral columns. In the case of a damped outrigger, the end of the outrigger is connected to the column via a damper. As the building sways under lateral loading, differential movement between the outrigger and column occur, resulting in a damping force [26]-[27].

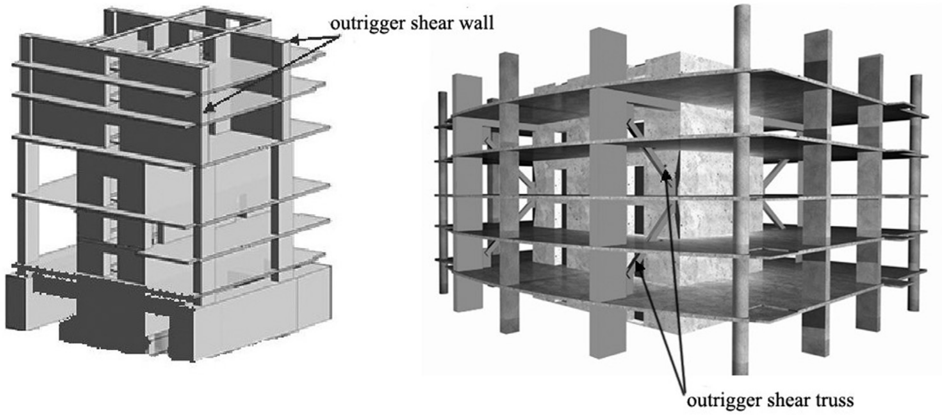

Fig. 6. Outrigger systems in slender high-rise buildings (developed by authors)

4.6. Strategy of reduction of wind action

The basic period of natural vibrations of a building is directly proportional to the slenderness ratio. Therefore, for buildings with large slenderness, this value is considerable. The critical load results from the difference between wind pressure on the windward side and suction on the leeward side for tall buildings. An additional load is also a perpendicular load acting with torsion. To comply with the serviceability limit state, the lateral displacement and acceleration of vibration must not exceed the limit value. Too large lateral displacements can cause damage to the structural and non-structural elements of the building. At the same time, excessive acceleration of vibrations affects the feeling of discomfort for its residents [29]. An important problem in the initial design phase is determining the required structural damping. For this purpose, an analysis of along wind action is carried out on the basis of pressure and load coefficients, assuming the average wind speed to assess the average load [30].

Crosswind effects can also be significant (Fig. 7). When the wind acts on a building, it induces vibrations, which results in an organized vortex shading pattern. From a structural point of view, the preferred mode of vortex shedding should be antisymmetric. The organized pattern of vortex shedding generates the largest forces in a perpendicular direction to the wind action [31]. These forces have oscillating character, and the load on the structure may increase as a result of resonance. The crosswind force depends on the geometry of the building plan and changes with height. In the case of slender buildings, which usually have a cuboid body with little geometric variation, the crosswind effect is particularly significant in the induction of motion. Torsional vibrations result from an eccentric loading and occur when resultant wind load coincides with the centre of the floor mass. Torsional-flexural coupling of vibrations can cause torsional motion of a building. Its response depends on the ratio of transverse to torsional frequencies. The occupants' comfort is crucial, and designers have to set the building's motion limits. Generally, in high buildings, the reinforced concrete core is the main load-bearing element and determines the rigidity. However, in slender residential buildings, it is very compact [32]. The designers' strategy to reduce these wind-induced motions consists of obtaining an aerodynamic shape (changing the building plan geometry, Fig. 8) and introducing vertical openings (atria) enabling the wind to penetrate the building to minimize the vortex shedding [33].[34].

Despite many countries developing codes for wind load assessment, they cannot accurately capture wind interaction with a high-rise building structure due to the gusty nature of wind and dynamic response of building [35]. In order to thoroughly investigate the problem, skyscrapers are tested in wind tunnels to accurately assess the response of longitudinal, lateral and torsional winds in a tall building, as well as to check how well the façade and other architectural elements work on breaking vortices. The building model and the layout of adjacent buildings and the most significant elements of the environment (dense greenery, different terrain levels) are placed in the tunnel and subjected to an air stream simulating wind.

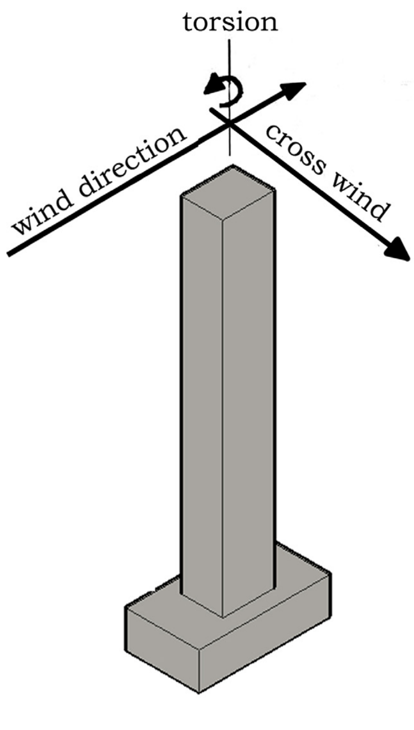

Fig. 7. Wind action on high-rise building (developed by authors based on [36])

One of the most important methods used in the wind tunnel is the High Frequency Force Balance Method (HFFB). Wind-induced loads are measured at the base of the building model. The analysis determines whether the building has uncoupled translational and uniform mode shapes under the action of averaged loads that are correlated with the measured loads [37]. The HFFB illustrates global wind impact on a building as a sum of static and dynamic interactions. From HFFB procedures applied in a wind tunnel, the wind-induced response in the building can be determined. Based on obtained results, some improvements in the building can be made in the following form: optimal building orientation, changing of height, changing the floor location for stiffening elements such as outrigger truss, application of damping devices, etc.

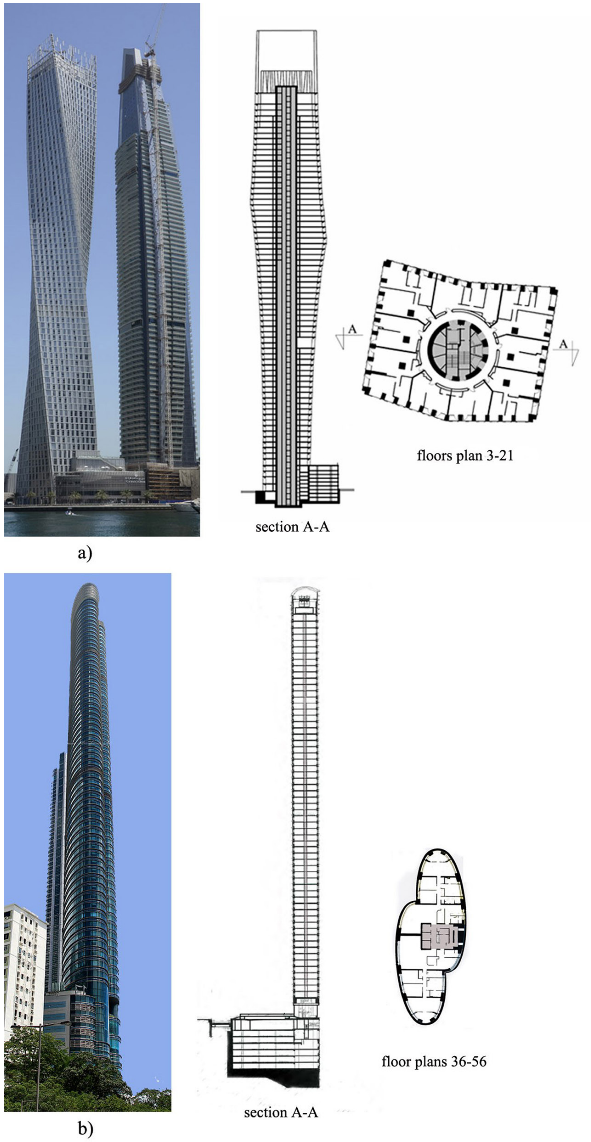

Fig. 8. Aerodynamic changing of plan geometry of residential buildings: a) Cayan Tower (Dubai, UAE); b) HighCliff (Hong Kong, China) (developed by authors)

In addition to experimental methods, computer programs based on fluid dynamic can simulate the impact of wind on the building. The most popular software programs created for this purpose are Fluent, Airpak, Tass, Comis, Trnflow, etc. However, despite technological advancement, which increases the possibilities of computer simulations, laboratory tests still give more accurate and reliable results.

Another method that allows vibration reduction is the use of special vibration dampers [38]. There is generally a distinction between active, semi-active, passive and hybrid dampers. The most popular types of silencers in slender buildings are tuned mass silencers (TMD), which are installed in the upper part of the building and use water tanks that act as counterweights, Fig. 9. Tuned mass dampers are designed to adjust their position when the building is moving [39]. Viscous dampers (VD) integrated with structural elements are another type of dampers used in slender tall buildings.

In addition, special antivibration pads that can transfer and absorb vertical and horizontal vibrations are used in the building's underground zone. As a result, the building under the influence of vibrations, moves in a snake motion; deviates from the centre of gravity in a controlled manner and does not go beyond the outline of the foundations.

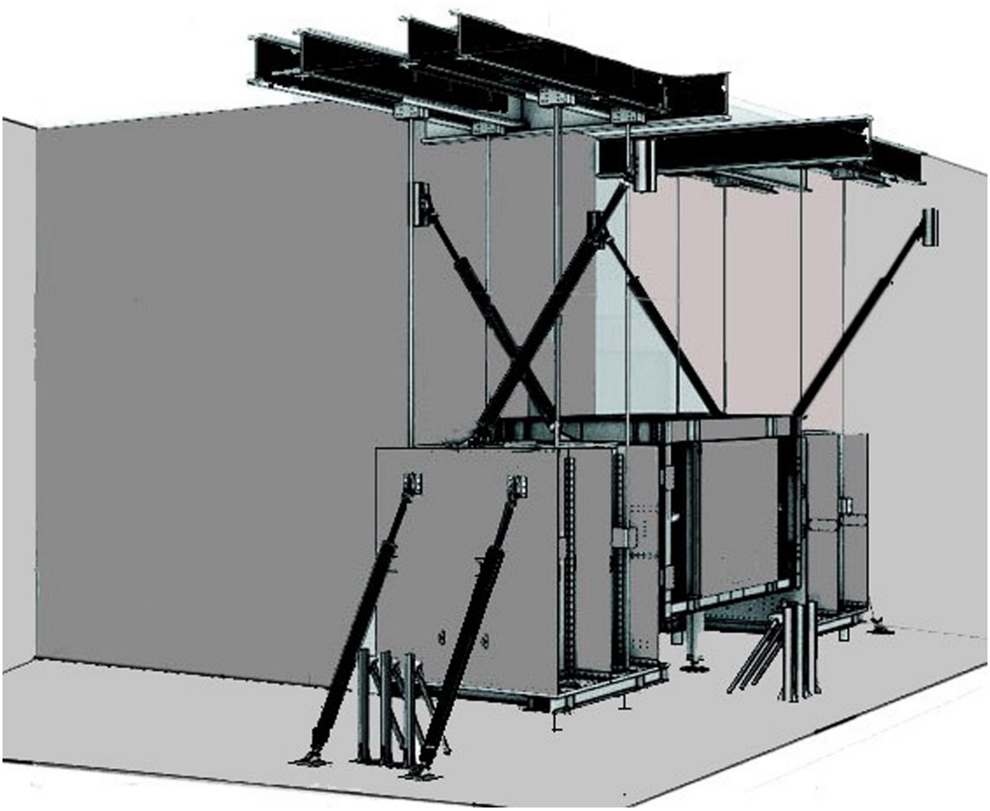

Fig. 9. Example of tuned mass damper installed in some slender skyscrapers (developed by authors)

4.7. Sustainability

The main goal of the design processes of high-rise buildings is to pursue the idea of low-energy construction. It involves the full use of renewable energy technologies. Due to buildings' verticality, more land can be allocated to public use in the form of squares, shopping centres, and recreation areas. The vital aspect of a sustainable tall building is the orientation and shape of its plan, which will allow the maximum advantage of daylight usage. The façade and the area given to windows are also of ultimate concern for determining the thermal insulation of the exterior walls and for gathering light. An example of an energy-saving element is a double-skinned façade with a ventilation system and a closed cavity type, whose operation involves creating a closed, empty space in which insulated glass units with two or three glass panes are mounted on the inside, and single glazing on the outside. Other passive low-energy strategies include natural ventilation, the location of service core, sun blinds, atrium, and smart materials. Low energy use is fundamental for sustainable development. The main issue can be seen as how this energy is generated. Active solutions that can be implemented through technical installations include solar collectors, photovoltaic panels, wind turbines, CHP system, fuel cells (PEMFC, PAFC, SOFC, AFC, MCFC), and a combination of heat pump technology with geothermal energy. Also, a computer-intelligent monitoring system plays a vital role in managing energy consumption. The building management system (BMS) is a centralized control system for managing various systems, such as fire protection, security, communication networks, elevators, HVAC systems, etc.

5. Examples of selected super slender high-rise buildings

The main criterion for selecting examples of slender residential skyscrapers was their super slenderness, an original geometric form designed by outstanding architectural studios (Jaros, Baum & Boles (New York); Rafael Viñoly Architects (New York); Bates Smart (Melbourne); Foster & Partners (London); Buro Ole Sheeren (Berlin), as well the geographical and historical aspect. In addition, an important element in analyzing the considered buildings was the preparation of the authors' photographic documentation. The super-slender skyscrapers presented in the article were created in competing metropolises as a result of the search for an original and revolutionary architectural and structural form, using the greatest technological achievements.

5.1. 111 West 57th Street (New York, under construction, 435.3 m)

The 111 West 57th Street building is a residential skyscraper with a steel and concrete structure designed by SHoP Architects. The tower has been erected in the courtyard of the former Steinway building designed in 1925. The world's most slender skyscraper is located between 6th and 7th Avenues on 57th Street in Manhattan. A remarkable aspect of the tower is that its location is almost perfectly aligned with Central Park's centerline. This will give future residents a very symmetrical view of the lush green space, the Upper West Side, and the Upper East Side [40].

Fig. 10. 111 West 57th Street (photograph by authors)

The building is 435.3 m in height and contains 84 floors at the above-ground level and one underground floor (Fig. 10). Because of its location in Manhattan, where bedrock is close to the surface, the foundation of the building is made up of conventional footprints with approximately 200 rock anchors that extend to 30.5 m [41].

The 111 West 57th was designed on a square shape plan with a dimension of 18.3 m, Fig. 11. From the south side, approximately two-thirds of building height gradually set back and taper the cross-section. The highest section of the building is steel frame structure situated at the level of 383 m with a high of 52.4 m. The architects were inspired by the famous skyscrapers from the golden era of Manhattan, namely the 30 Rockefeller Center or Empire

State Building. A fully-glazed curtain wall system with vertical strips of bronze was used in the north and south façades, and terracotta rain screen panels with glass and bronze ornamentation in the east and west. In the entire building, a crucial role is played by the façade structure, which supports the weight of terracotta tiles and gives the building a multiplied slenderness effect.

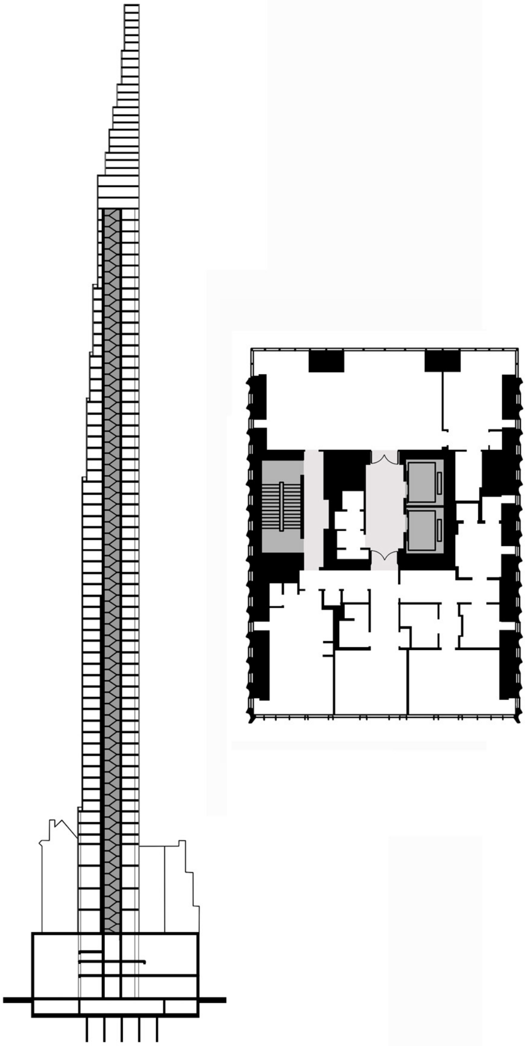

Fig. 11. 111 West 57th Street: plan and section (developed by authors based on [44])

5.2. 432 Park Avenue (New York, 425.7 m)

432 Park Avenue is a residential skyscraper with a concrete structure designed by the Rafael Viñoly Architects studio. The tower is located between Park Avenue and East 57th in

Manhattan. The building consists of 125 condominiums on middle and upper levels and amenities for residents and retail area on lower levels. The building is 425.7 m in height and contains 85 floors at the above-ground level and 3 underground floors (Fig. 12). 432 Park Avenue is designed on a square plan with a dimension of 28.5 m, Fig. 13. The main architectural attributes are symmetry and very simple geometry. The body of this building has a cuboidal form with large slenderness. 432 Park Avenue was built on the site of the demolished Drake Hotel from 1927. With a slim silhouette and a façade of regular rectangular division windows, the building gives the impression of being extremely lightweight. The original composition of the façade refers to a metal basket designed by Austrian architect Josef Hoffmann.

The foundations of the building are footings with 60 rock anchors that extend down from 18.3 to 21.3 m into Manhattan's bedrock [39]. The concrete for the foundation and part of the superstructure has a strength of 96.5 MPa. The tube-in-tube system [7] is a main load-bearing system that provides the tower's lateral stability. Internal concrete core with dimensions 9 m x 9 m is connected with the perimeter tube, which has a form of the concrete frame. The core wall is 75 cm thick. The 1.1 m wide exterior columns, spaced 4.7 m apart, are connected by spandrel beams to form exterior tube [45]. The dimensions of these elements decrease with the increasing height of the building. It was also applied large beams, at every 12 floors with double-story plant rooms, to connect the outer tube with a central core.

Using the highest strength concrete (100 MPa) enabled both the column sizes to be minimized and intruded into the usable livable area [46]. Because of the slenderness and to counteract wind-induced vibrations, the storey plant rooms are open, which allows the wind to flow through the building and minimize vortex forces.

Despite the lateral stiffness and open double-storey plant rooms, structural designers added extra mass to the upper levels by increasing the thickness of concrete floors from 25 to 45 cm. Moreover, two 650 tonnes tuned mass dampers were installed at the top of the building, and viscous dampers were integrated laterally with structural elements.

The 432 Park Avenue design can be considered sustainable, which uses renewable energy technology to be LEED-certified in the near future.

Fig. 12. 432 Park Avenue (photograph by authors)

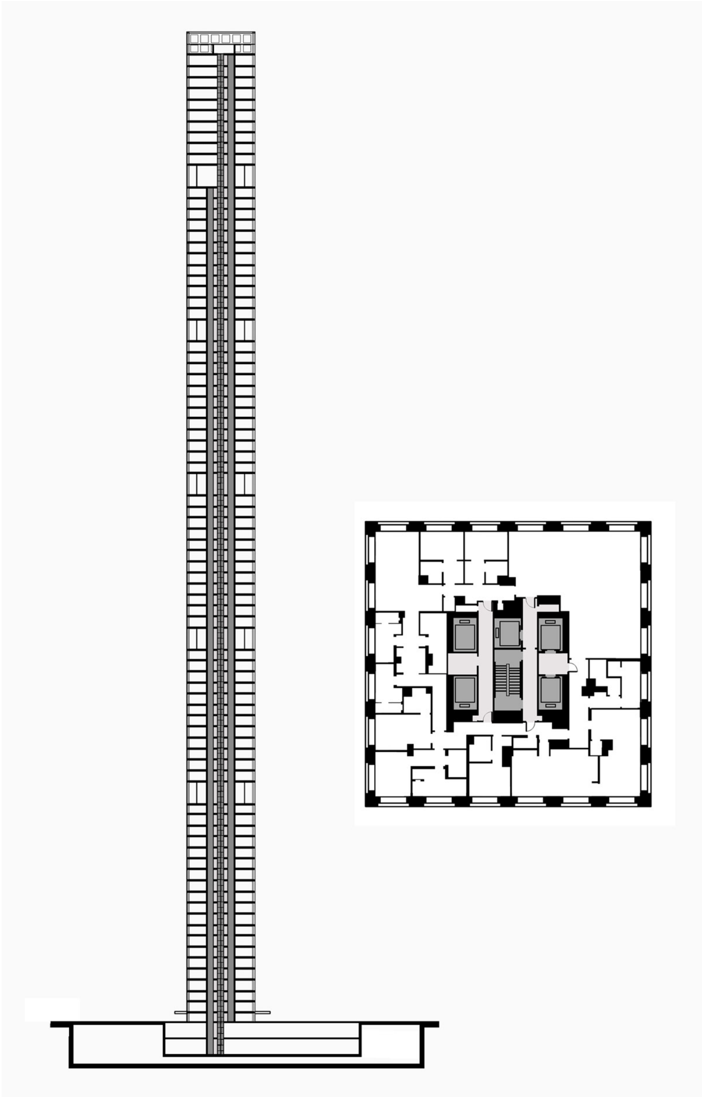

Fig. 13. 432 Park Avenue: plan and section (developed by authors based on [47])

5.3. Collins House (Melbourne, 189.6 m)

Collins House is a tall residential building with a concrete structure designed by Bates Smart studio. The building is located at the corner of Collins and William Street, in a very prestigious central location in Melbourne, which has a similar meaning to Fifth Avenue in New York. It is constructed on the top of an existing 3-storey Makers Mark building whose façades derive from the Art Nouveau period. Collins House is 183.4 m in height and contains 59 floors at the above-ground level and one underground floor (Fig. 14). Two top floors are occupied double-storey penthouses. The plan of this building has a rectangular shape with a dimension of 11.7 m x 40.0 m, Fig. 15.

Fig. 14. Collins House (Courtesy of Bates Smart)

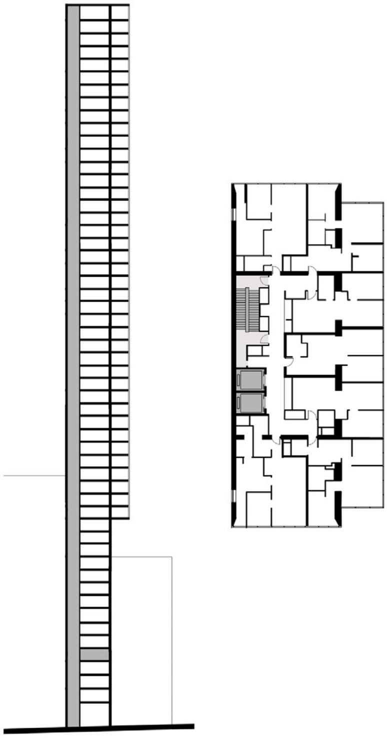

Fig. 15. Collins House: plan and section (developed by authors based on [50])

The tower is supported by a piled raft foundation. The load-bearing structural system is based on concrete shear walls on each side. The side walls are stiffened by two transverse walls forming a rigid box in H-section in the east-west direction [48]. No columns on the north and south elevations allow maximum daylight. Up to 14 floors, the building is constructed from monolithic concrete, while above these levels, designers applied Hickory's prefabricated elements [49]. As a result, the building became one of the tallest modular building in the world. The modular system allows a more flexible arrangement of units, which can be repeated on different floors depending on their function.

The building's façade is a system of a double-glazed curtain wall. On the eastern façade above level 14, the floor system is cantilevered out 4.5 m in the form of rizalit. In the north and south façades from 14 to 27 floors, there are axially wide loggias. Additionally, from 14 to 47 floors are designed a strip of narrow loggias. Openings in the building and shifted center of its mass results in a magnification of vibrations acceleration due to torsional effect. In order to counteract vibrations in north-south and east-west directions, two liquid tuned dampers, which are located at the plant room level, were used.

5.4. Burj Mohammed Bin Rashid Tower (Abu Dhabi, 381.2 m)

The Burj Mohammed Bin Rashid tower belongs to the World Trade Center complex, which comprises two tall buildings. The higher, residential and the lower, commercial tower, also known as Trust Tower offices. The Burj Mohammed Bin Rashid is a residential skyscraper with a concrete structure designed by Foster and Partners studio. The tower is located in a residential suburb of Abu Dhabi in Khalifa Area. The building is 381.2 m high and contains 88 floors at the above-ground level and 5 underground floors (Fig. 16). The tower was designed on an elongated quadrangle plan. Reflective façade has wave-like form and wraps the entire building in a regular pattern, Fig. 17. The glazed cladding creates a mirage effect inspired by the desert landscape phenomenon. As a result of the wavy form of the building, a unique floor plan was obtained, which allows arranging the space in many different ways.

Fig. 16. Burj Mohammed Bin Rashid Tower (photograph by authors)

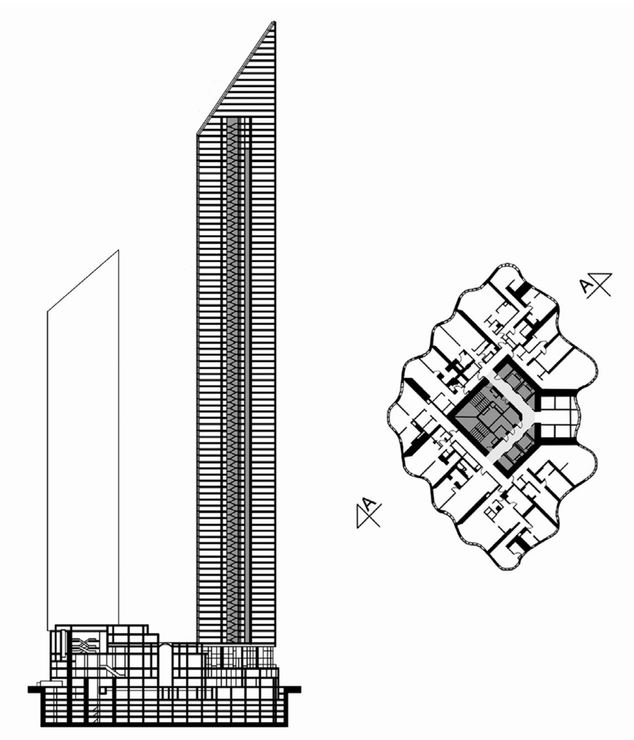

Fig. 17. Burj Mohammed Bin Rashid Tower: plan and section (developed by authors based on [51])

The Burj Mohammed Bin Rashid foundation consists of a pile-supported raft, where piles were utilized as settlement reducers. Reinforced concrete walls placed around the elevators and stairs in the tower's central core create a lateral load resisting system. The system forms a stiff spine, which resists lateral loads and provides the tower's torsional stiffness [51]. Reinforced concrete outrigger and belt walls are located at three mechanical plant floors over the height of the building. These outrigger and belt walls connect the core to the reinforced concrete perimeter columns, allowing the lateral overturning forces to be resisted by the entire width of the tower, even though there is essentially no structure around the perimeter. The wall-columns, which were designed to be thin and hidden in the room partitions, line the perimeter so that an absolute minimum amount of exterior perimeter is blocked by the structure. Many solutions based on renewable energy were used to increase the energy efficiency of the building (such as solar collectors, ventilated three-skin façade). Moreover, local building materials were applied to reduce embodied carbon.

5.5. MahaNakhon (Bangkok, 320.0 m)

MahaNakhon is a two function skyscraper (residential, hotel) with a concrete structure designed by Büro Ole Scheeren. The skyscraper is located in Bangkok's Central Business District. The literal translation of the name MahaNakhon is a "great metropolis". The building is 320.0 m in height and contains 79 floors at the above-ground level and 1 underground floor. (Fig. 18). With its distinctive sculptural appearance, MahaNahkon was carefully carved in order to present a three-dimensional "pixel" that circles about entire building, Fig. 19.

The seven-storey podium intended for a shopping center characterizes with many internal and external cascading terraces that resemble a mountainous landscape. The three-level restaurant has double-height spaces and a rooftop bar with an observation deck.

MahaNakhon is supported by mat foundation (8.77 m of height) and barrette piles (129 with a size of 1.2 x 3 m) which reach to a depth of 65 m below grade [53]. The central core wall provides structural stability to lateral loads. Its dimensions are the largest at the basement (23 m x 23 m) and gradually decrease towards the top of the building (23 m x 14 m). The gravitational loads are supported by 12 mega-columns surrounding the core along with its height. Lateral stiffness was strengthened by outrigger walls linking the center core walls to the mega-columns at transfer floors on 3 levels. The mechanism minimizes the fundamental period of vibration and the lateral drifts and accelerations, in turn lowering the risk of human discomfort.

Fig. 18. MahaNakhon (photograph by authors)

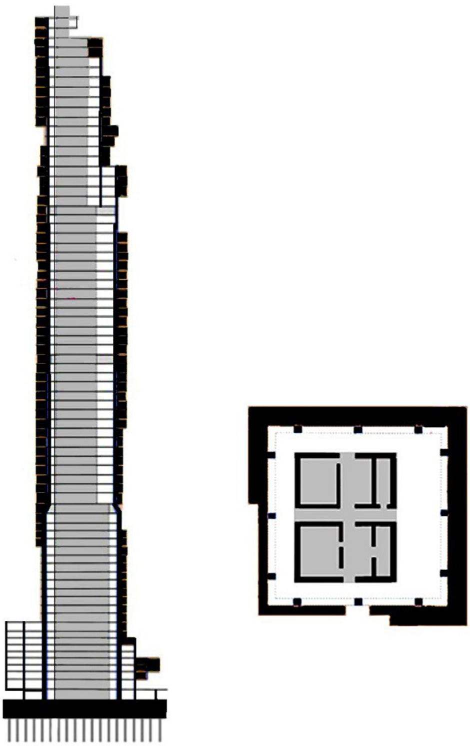

Fig. 19. MahaNakhon: plan and section (developed by authors based on [54])

The slabs consist of post-tensioned band beams with reinforced concrete flat slabs. Almost 30% of the floor slabs are cantilevered, creating the pixilation effect achieved through the stacked surfaces of cantilever terraces. MahaNakhon's floor slabs vary from floor to floor throughout the tower providing many different arrangements of units. The residences have ceilings of up to 3.4 meters high and floor-to-ceiling glass windows to provide expansive panoramic views. The MahaNakhon wall system is a unitized curtain wall comprised of large units of low-e double-layer glass and mullions and special hooks that lock the units together. The façade system was designed to be hung from the edge of each floor slab with special horizontal joints between panels.

In order to increase energy efficiency, the following elements were applied: independent controls for air, power, and water; lighting controls with modern LED technology, energy management, mechanical parking systems, and smart home automation.

6. Discussion

At first, the design and construction of tall and thin skyscrapers (also named pencil towers or needle-like towers) seemed completely economically unviable. However, currently, after completing several projects around the world, it can be seen that this form of the building has become a kind of trend among high-rise residential buildings. Due to the lack of land in desirable locations of various metropolises, and therefore sky-high property prices, developers are trying to integrate tall buildings into existing infrastructure on a small plot. New super-slender residential towers, which stand on very narrow footprints, offer more than just luxury residences with the iconic building's postal address.

Due to their slenderness and compact core, these buildings have one or two apartments per floor, which affects its spatial exclusivity. The crucial aspect of designing such buildings is that they provide astonishing views of the surroundings. For example, in New York, a city that pioneered this trend in architecture, panoramic views of Central Park are worth astronomical prices.

However, saving land by building upwards does not come without consequences – super-tall buildings cause severe shading. This issue roots a moral problem. An exclusive group of wealthy tenants having extraordinary views affects other residents' environment. Architecture critics, Aaron Betsky and architect Steven Holl, among others, have questioned the social aspects of such buildings. They criticized the developers who have been transforming Manhattan into a capitalist "holy land without space for the poor".

Tab. 3. The list of the most costly residential high-rise buildings (developed by authors)

Building	Location	Cost (Billions, USD)
Central Park Tower	New York	$3.00
Princess Tower	Dubai	$2.17
One57	New York	$1.50
220 Central Park South	New York	$1.40
432 Park Avenue	Moscow	$1.25
111 West 57th	Melbourne	$1.00
MahaNakhon	New York	$1.00
Neva Towers (1.2)	Chicago	$1.00

Slender skyscrapers are incredibly costly to build (Table 3). This is because of innovative materials and construction solutions, a small number of apartments and difficult construction conditions on a narrow plot. However, they are an attractive investment for developers due to high demand and popularity among affluent clients, especially in New York. The high prices of apartments enable the employment of the best architects and the most outstanding designers and engineers, as well as the application of the most sophisticated technology. The attractiveness of the investment means that these types of buildings are purchased by foreign investors, and as a result, they are hardly used throughout the year.

Designers aim to maximize interior space in slender skyscrapers; therefore, the structural support is more likely to come from the building's exterior. A mechanical floor with heavy equipment is usually located on the upper floors to stabilize the building and counteract the effects of wind. The main challenge for designers is to provide adequate lateral stiffness. In a tall building with a high slenderness ratio, ensuring human comfort is vital. The application of outriggers on a few levels is necessary to improve the stiffness of the tower by linking the center core walls with surrounding columns, where push-pull mechanism with axial forces is created. Outriggers counteract by bending under wind loads. The rigid belt surrounding the building causes external columns action. This mechanism minimizes the dynamic action of the wind loads, lowering the risk of the residents' discomfort.

It is currently possible to build higher buildings using structural elements of the same cross-sections by using ultra-high strength concrete. This undoubtedly contributed to the development of the trend of slender tall buildings. Recent formulations of concrete make the structure more rigid and strong enough to support heavier loads. Perhaps major problems that have to be solved are found in building technology, which relate to the use of cranes and construction platforms in a small space and at a very high altitude. The traditional procedure of placing the crane in the compact core of slender skyscrapers has many limitations and requires the use of special technologies, which are costly and require improvement. The use of computer technologies (CAD, BIM), as in other architecture fields, allows the logistical and economic development of projects.

7. Conclusions

The main factor influencing the development of slender buildings were economic considerations related to high construction land prices and the real estate market demand from wealthy clients. Another contributing factor was the search for an original, revolutionary geometric form made possible by technological progress.

The development strategies of super-slender towers evolved in New York over the past decade. These up to 100-storey high buildings contain luxury apartments with beautiful views of the city skyline. Because they comprise only one or two apartments per floor, they offer a view from three or four sides of the world. This fundamentally differs the New York skyscrapers from the traditional ones.

Following New York's footsteps, Hong Kong, Dubai, Abu Dhabi, Melbourne, Brisbane, Toronto, Mumbai, Moscow, etc. started constructing slender residential towers. Slender residential skyscrapers erected in the metropolis' centres on tiny plots become a global architectural trend. Zoning laws and high prices of land were important factors driving this type of structures. This fashion of pencil-shaped structures is associated with an incredibly high cost of construction.

Recently, advances in materials and engineering have made building both super-slender and super-tall possible. This is enabled by the following technical factors: applying ultra-high strength materials, advances in structural modelling, computing power, simulation, and aerodynamic shaping. Application of ultra-high strength concrete to a compact core with an outrigger system allowed designers to minimize the structural elements in the apartments, providing the possibility of flexible arrangement and preserving stunning, uninterrupted views.

Wind-induced vibrations in super-slender tall buildings have been reduced by increasing lateral stiffness and increasing total weight. The new use of the outrigger system provided additional damping to reduce wind load and vibration acceleration. Also, tuned mass dampers and aerodynamic building shape optimization were complementary auxiliary methods for their design.

There are mechanical and structural limits to how high-rise a building should be. Still, the higher a building is, more rigid and more robust should be its structure. There is no doubt that super-tall, slender buildings are the most technologically advanced constructions in the world. However, the question arises whether modern technologies and high expenditure make this architecture an outstanding work.

American architects Ali and Al Kadmany [55] believe that tall eco-friendly buildings may become the primary housing type of future. However, the main disadvantage of all skyscrapers, especially super-slender ones, is their elitism, resulting from very high constructional and exploitation costs. Moreover, the density of tall buildings in metropolitan centers causes shading of the terrain, which may be beneficial in countries with high sunshine, but unfavorable in countries with a temperate climate. Undeniably, however, ecologically sustainable high-rise buildings are the future of worldwide construction.

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Analiza technicznych problemów super smukłych współczesnych wysokich budynków mieszkalnych

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Streszczenie: Celem artykułu jest przedstawienie nowego typu wieżowca, która rozwinął się w ciągu ostatnich dziesięciu lat w formę bardzo wysokiego, super smukłego budynku mieszkalnego. Obecnie w wyścigu o światowy rekord nowym kryterium stała się smukłość. W centrach wielu metropolii ze względu na coraz mniejszą ilość dostępnego miejsca oraz bardzo wysokie ceny działek budowlanych, architekci zaczęli projektować wysokie budynki na niewielkiej powierzchni. Innymi czynnikami powodującymi rozwój tego trendu były względy ekonomiczne, wraz z zapotrzebowaniem rynku nieruchomości na luksusowe apartamenty z panoramicznym widokami, jak również postęp technologiczny umożliwiający wybudowanie super smukłych wieżowców. W ramach tej typologii można wyróżnić dwa rodzaje budynków. Ultra-luksusowe super-smukłe wieżowce z jednym lub dwoma apartamentami zaprojektowanymi na jednej kondygnacji, które są charakterystyczne dla dzielnicy Manhattan w Nowym Jorku oraz inne smukłe wieżowce w Hong Kongu, Dubaju, Abu Zabi, Bangkoku, Melbourne itp., które mają więcej apartamentów na poziomie jednego piętra. W artykule przedstawiono przegląd wybranych smukłych wieżowców oraz ich cech konstrukcyjnych i architektonicznych w odniesieniu do postępu technologicznego wysokich budynków ostatniej dekady.

Słowa kluczowe: wysokie budynki mieszkalne; smukłość; system konstrukcyjny; zaawansowane materiały; systemy tłumienia drgań