

**AIRPORTS AND THEIR INFRASTRUCTURE**

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**STRUCTURAL SYSTEMS OF HIGH-RISE BUILDINGS**<sup>1,2,5,6,7,8,9</sup>National Aviation University, 1, Lubomyr Husar ave., Kyiv, 03058, Ukraine<sup>3</sup>Kyiv National University of Civil Engineering and Architecture, Kyiv, 03037, Ukraine<sup>4</sup>National University of Life and Environmental Sciences of Ukraine, Kyiv, 03041, UkraineE-mails: <sup>1</sup>pershakov@nau.edu.ua; <sup>2</sup>beljatynskij@ukr.net; <sup>3</sup>vartist@ukr.net; <sup>4</sup>bakulin959@ukr.net; <sup>5</sup>poi220154@gmail.com; <sup>6</sup>bolotovgi@g.mail.com; <sup>7</sup>k\_imf@nau.edu.ua; <sup>8</sup>popovich\_ivanna1992@ukr.net; <sup>9</sup>reznik.oleksandr@g.mail.com**Abstract**

*The article is devoted to topical issues of researching structural designs as a component of high-rise buildings structural system, which form an architectural image and a volumetric three-dimensional structure, consisting of a set of interconnected structural elements that, working together, provide the strength of the volumetric structure, spatial rigidity and overall stability of the object. High-rise buildings use different structural designs, consisting of vertical elements (columns, walls, nuclei, diaphragms etc.) and horizontal elements (floors, beams, slanting belts etc.). Horizontal load-bearing structures of high-rise buildings, are, as a rule, of the same type and represent a rigid reinforced concrete disk (monolithic, precast-monolithic, precast). Horizontal structures carry vertical and horizontal loads and transmit them to load-bearing structures and foundations. To reduce wind effect, aerodynamically efficient cylindrical, pyramidal or prismatic shape of the building is chosen. The high-rise buildings designs have their own specificity, which greatly influences the three-dimensional planning and architectural and design decisions. These features include: significant loads on load-bearing structures; unequal loads on structural elements; high wind load as a horizontal component; problems of joint work of load-bearing structures made of steel and concrete; impact of natural factors (seismic, atmospheric, aerodynamic); influence of technogenic factors (vibrations, noise, accidents, fires, sabotage acts, local destruction); heightened requirements for fire safety and environment control systems; complex engineering and technical support.*

**Keywords:** structural designs and systems; high-rise buildings; frameworks of high-rise structures; frame systems**1. Introduction**

Compared to low-rise buildings, the high-rise buildings work mostly as a single integrated structure and it is the feature that affects significantly the designing process of such type buildings. The structural design of high-rise buildings forms some architectural image and certain spatial structure consisting of a set of interconnected structural elements providing the strength, spatial rigidity and overall stability of the object.

Any variant of structural system should ensure reliable operation of a high-rise building for at least 150 years, taking into account the warranty on its safe operation and maintenance in case of possible object's resource restoration.

Various structural designs consisting of both the vertical (columns, walls, diaphragms, etc.) and horizontal (floors, roofs, beams, braces and other elements) ones are used in structural systems of high-rise buildings. Horizontal bearing structures of high-rise buildings, as a rule, are of one type and usually

represent a rigid reinforced concrete disk (cast-in-situ, prefabricated cast-in-situ, or prefabricated one). Horizontal constructions take up vertical and horizontal loads and transmit them through one storey after another to the vertical bearing structures, which in turn transmit these loads to the foundation.

The main types of a high-rise building or skyscraper horizontal sections are 40x40, 50x50, 40x60 m, depending on its height. Such type restrictions are caused by predominant influence of wind loads on the stability of building taking into account the possibility

of resonant vortex excitation of its oscillations. That's why the floor area of even 80-100 storey skyscrapers does not exceed 2.0-2.5 thousand square meters [1].

In order to reduce the wind action, the aerodynamic forms (cylindrical, pyramidal or prismatic) of buildings are used (Fig. 1).

To increase the stability of the building, they resort to extending its cross-section area downward in one, two, three, or four directions (Fig. 1, b). The flexibility of the most high-rise buildings, that is, the ratio of their height to their width, is usually between one and eight.

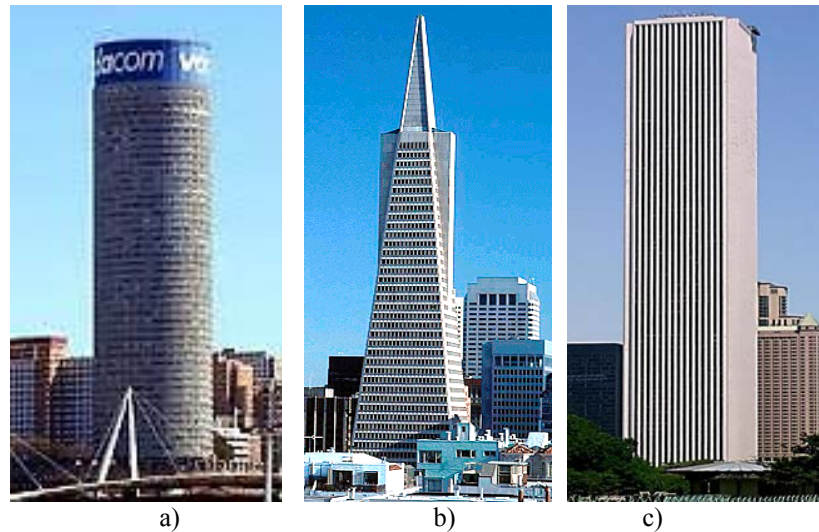


Fig. 1. Efficient aerodynamic forms of high-rise buildings:  
 a – 54-storey cylindrical Skyscraper «Well», 173 m high, in Johannesburg;  
 b – Transamerica Pyramid, 260 m high in San Francisco;  
 c – 83-storey tower "Aon Center," 346.3 m high in Chicago

The higher value of flexibility coefficient results in inadmissible lateral accelerations at the top of the building and therefore it requires using some damping elements to ensure normal building operation. The standard horizontal displacements of the top of the building should be for buildings up to 150 m high not more than 0,002 mm, more than 250 m - up to 0,001 mm. For intermediate heights, the standard value is taken by the interpolation method.

Moreover, high-rise buildings are provided with special construction measures to protect them from the progressive collapse during natural and man-made emergencies. These measures consist in reserving the strength of bearing structures.

Various structural peculiarities of high-rise buildings affect significantly their spatial-planning and architectural-designing solutions. There are the following peculiarities of such type:

- significant loads taken up by the bearing structures;
- different loading of structural components of buildings;
- great wind loading as a horizontal component;

- problems of joint work of steel and concrete bearing structures;
- the impact of natural factors (seismic, weather, wind);
- the impact of man-made factors (vibration, noise, emergency, fires, acts of sabotage, local destructions);
- increased requirements for fire safety and life support systems;
- complicated engineering and technical support.

## 2. History of development and modern concepts of high-rise house-building structural systems

A characteristic feature of high-rise buildings, in contrast to the ordinary-story buildings, is the significant impact of horizontal wind loading [1]. To ensure the strength and stability of high-rise buildings, various structural systems are used in the world practice, depending on the building's storey number, construction conditions, seismic activity of the object's construction area, engineering-geological conditions, atmospheric impacts, primarily wind loads, and architectural and planning requirements (Fig. 2).

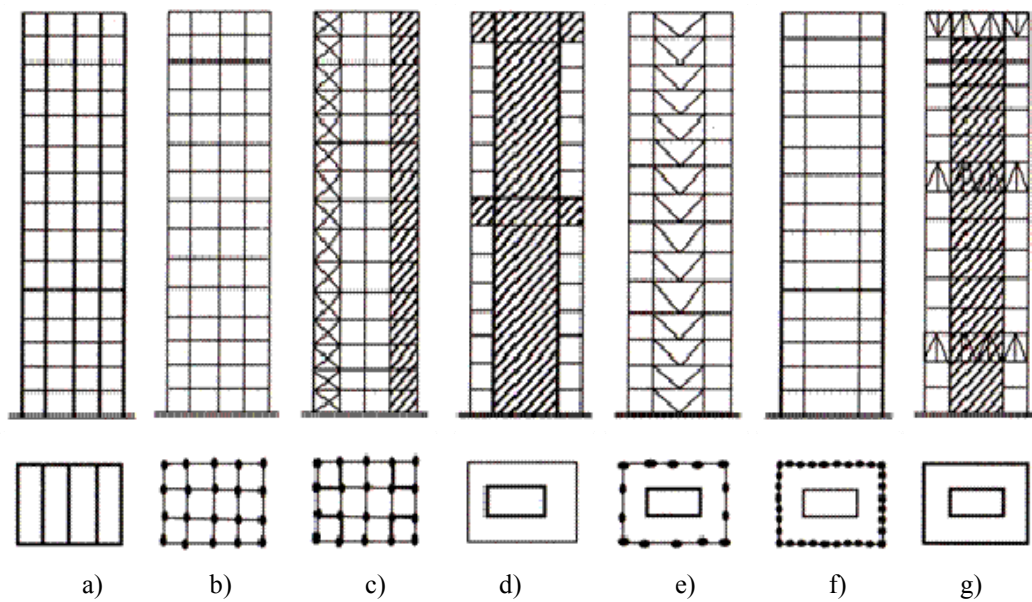


Fig. 2. Structural systems of high-rise buildings:

- a – with transversal bearing walls; b – frame-skeleton system; c – skeleton system with stiffening diaphragms;
- d – tube type; e – skeleton-tube type; f – box type; g – box-tube type

The frame-skeleton structural system was first applied by architect Raymond Hood during erecting the McGraw-Hill Building, Manhattan, New York

City (1929 - 1931). The thick out-walls are the main shortcoming of such type systems (Fig.3).



Fig. 3. Skyscraper McGraw-Hill Building, Manhattan, New York City

The frame-skeleton structural system is of various types (Fig.4).

### 3. Main results of the research

The “tube” type or “tube in tube” type structural

system, regardless of the material used for construction, steel or reinforced concrete, was first applied to erect the 38-storey administrative skyscraper “Brunswick Building” 145 m high in Chicago.

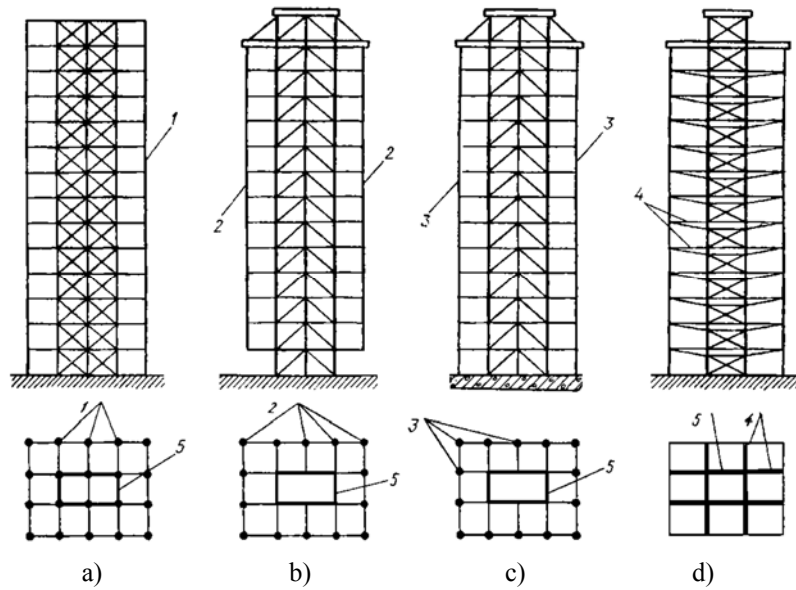


Fig. 4. Types of frame-skeleton structural system:

a – with external columns; b – with a suspension of floors along the perimeter of the building; c – with floors suspended by pre-stressed ropes; d – with cantilever beams; 1 – columns; 2 – cable stays; 3 – pre-stressed cable stays; 4 – cantilever beams; 5 – stiffening core

The particularity of the "tube" structural system is that the horizontal loads are taken by trunk of the building (its stiffening core), that enables to reduce

significantly its outer wall's weights, in contrast to the frame-skeleton structural system (Fig. 5).

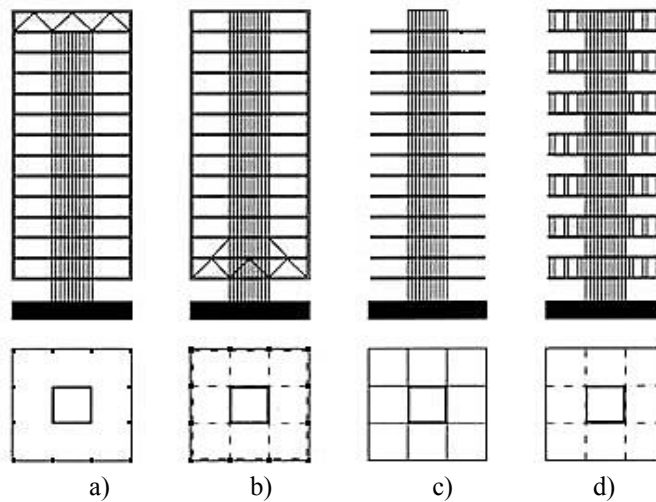


Fig. 5. The tube type systems:

a – hanging on the upper cantilever; b – resting upon the bottom cantilever; c – cantilever resting of floors upon the tube; d – intermediate location of bearing cantilevers

The "tube in a tube" system differs from the "cantilever" one by presence of the second internal load bearing system. Thus, in this structural system, all horizontal and vertical loads are taken up by the internal and external trunk systems. Joint operation of internal and external trunks under the horizontal loads is provided by grillages, located at the levels of technical floors. Due to the joint work of external and

internal systems, the rigidity of the building rises up to 30-50% compared with the frame-braced and braced ones.

The design solution of twin houses of the International Trade Center in New York, 417 and 415 m high, is based on box-type structural system where all horizontal loads are taken up by the spatial lattice of the outer walls.

The 100-storey administrative complex "John Hancock Center" 344 m high has been built in 1969 in Chicago. In this house the tube type structural system was used. However, it differs from the previous one, as the outer wall's lattice is without braces.

In general, the tube structural system is used in all the highest buildings of the world. They differ by their outer wall's lattices only.

The construction of a high-rise building of HSBC's headquarters in Hong Kong represented the creation of a new structural system, the so called "mega-spatial" framework where the vertical spatial truss is used as a main bearing structure of the building. The spatial framework of the building is formed by connecting vertical planar trusses of different heights and configurations. Thus, such spatial structural system is a structural combination of 54-meter space-frame modules with four-corner and one central supporting joints resting on the concrete columns. The main advantage of using spatial trusses is the economic efficiency of construction due to reducing the overall weight of structures, the number of columns, and the absence of concrete structures in the frame (Fig. 6).



Fig. 6. HSBC's headquarters in Hong Kong

Such structural system is sufficiently resistant to seismic and wind loads and can withstand a wind flow speed up to 89 km/h.

At the end of the twentieth century, the structural diagonal lattice, as an external bearing shell has become widely used for high-rise buildings. This technique has been used in the design of high-rise building of Puerto Europe or the Gates of Europe in Madrid, architect F. Johnson (Fig. 7).

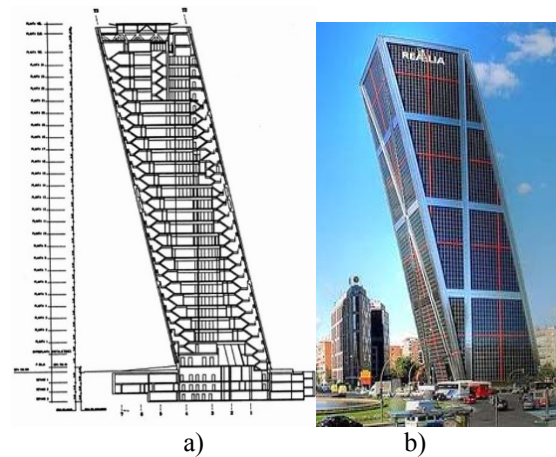


Fig. 7. The high-rise building «Gate of Europe»: a – the design of the building; b – the general view of the building

In order to increase the flexural stiffness of the bearing skeleton of high-rise buildings with the tube structural systems and their resistance to the dynamic horizontal loads, the outrigger structures (systems of diaphragm-outriggers), that have become widely implemented due to increased efficiency of taking up the wind loads, are used in the frame of buildings. The purpose of the system is to reduce the bending strains of the whole building. Such structural technique enables to avoid reducing the useful area of the building's premises, which is typical in case of traditional outrigger systems. A new design approach for connection joints of the outrigger beams with columns was developed - the "flat-jack" support. This system enables to monitor the bearing structures during the first three years of building operation and, if necessary, to stabilize the emerging deformation (Fig. 8).

In order to neutralize seismic loads and fluctuations arising under the wind action, the structural control system of buildings has been widely used. This system includes methods of active, resonant, frictional suppression of oscillations and a soft low-carbon steel technique.



Fig. 8. General view of "flat-jack" support

The method of resonant suppression of oscillation in the form of a passive swing damper was used in the structural design of the Taipei 101 office building, the official name is “Taipei Financial Center”, in Taiwan, Taipei, arch. Bureau “C.Y. Lee & Partners”. Damper (in the form of a ball) weighing 728 tons, 5.4 meters in diameter, suspended with cables in the upper part

of the building, between floors 92 and 88, is designed to suppress inertial oscillations. In ordinary conditions of operation, the damper provides the building’s top deflection within 10 cm, while under strong wind or earthquake impacts, it swings with an amplitude of up to 150 cm, ensuring the building swing within its safety limits (Fig. 9).

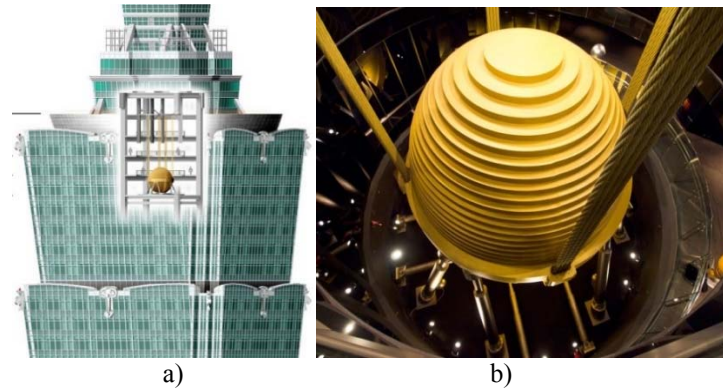


Fig. 9. Skyscraper “Taipei 101”:

a – location of the damper in upper part of the building; b – swing damper in the form of a ball

The 123-story Mega Skyscraper, 556-meter high “Lotte World Premium Tower” in Seoul has been developed by the “Kohn Pedersen Fox” architectural Bureau (Fig. 10, a). The problem of increased flexibility in this building was solved by installing a built-in water oscillation damper. It is a technical system located in the upper part of the building including a reservoir filled with water through vertical tubular lines, which enable to regulate the water level in the reservoir (Fig. 10, b). The water filling the reservoir has the ability to suppress the oscillations and limit their amplitude to the level acceptable for a comfortable stay of people.

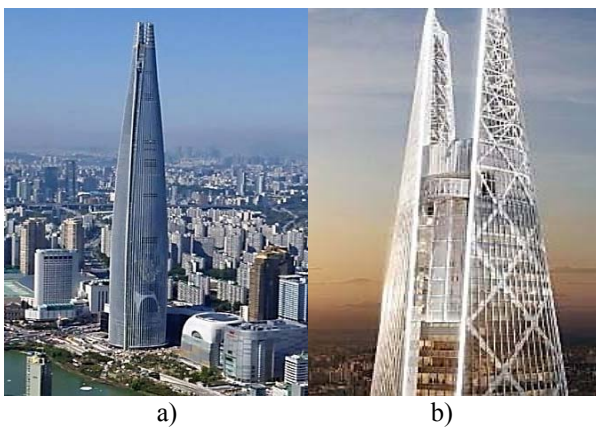


Fig. 10. Mega Skyscraper, “Lotte World Premium Tower”:

a – general view; b – location of the water damper in the upper part of the building

One of the main tasks of modern high-rise construction is to solve issues related to ensuring the reliability and safety of structures. Therefore the designer’s task is to create a building that will not collapse when some of its separate constructive components have collapsed.

#### 4. Conclusions

Summarizing the structural systems development of high-rise buildings in recent years, it is possible to note their main features:

- application of three main structural systems: tube, box, tube-box and variants of their combination;
- creation of new structural system – a mega-space frame;
- use of a diagonal lattice as a bearing element of the outer shell;
- introduction of systems: of active, resonant, and frictional oscillation suppression;
- introduction of design techniques for effective taking up wind loads by structural system of buildings
- outrigger structures;
- use of double ventilated facade.

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Стаття присвячена актуальним питанням дослідження конструктивної системи висотних будівель, яка утворює архітектурний образ і об'ємно-просторову структуру, що складається із сукупності взаємозв'язаних конструктивних елементів, які при сумісній роботі забезпечують міцність просторової структури, просторову жорсткість і загальну стійкість об'єкта. У висотних будівлях застосовують різні конструктивні схеми, які складаються із вертикальних (колон, стін, ядер, діафрагм та інші) і горизонтальних елементів (перекриттів, покриттів, балок, розкідних поясів та інших). Горизонтальні несучі конструкції висотних будівель, як правило, однотипні і зазвичай являють собою жорсткий залізобетонний диск (монолітний, збірно-монолітний, збірний). Горизонтальні конструкції сприймають вертикальні та горизонтальні навантаження і передають їх на несучі конструкції та на фундаменти. З метою зниження вітрових впливів вибирають ефективну в аеродинамічному відношенні циліндричну, пірамідальну або призматичну форму будівлі. Конструкції висотних будинків мають свою специфіку, яка значною мірою впливає на їхні об'ємно-планувальні та архітектурно-конструктивні рішення. До таких особливостей відносяться: значні навантаження на несучі конструкції; неоднакове навантаження на конструктивні елементи конструкцій; високе значення вітрового навантаження як горизонтальної складової; проблеми спільної роботи несучих конструкцій із сталі та бетону; вплив природних факторів (сейсмічних, атмосферних, аеродинамічних); вплив техногенних факторів (вібрації, шуми, аварії, пожежі, диверсійні акти, локальні руйнування); підвищені вимоги до пожежної безпеки та систем життєзабезпечення; складне інженерно-технічне забезпечення.

**Ключові слова:** конструктивні схеми та системи, багатопверхові будівлі, каркаси висотних споруд, рамні системи

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Статья посвящена актуальным вопросам исследования конструктивной системы высотных зданий, которые создают архитектурный образ и объемно-пространственную структуру, состоящую из взаимосвязанных конструктивных элементов, которые при совместной работе обеспечивают прочность пространственной структуры, пространственную жесткость и общую стойкость объекта. В высотных зданиях используют разные конструктивные схемы, которые состоят из вертикальных (колонн, стен,

ядер, диафрагмы т. д.) и горизонтальных элементов (перекрытий, покрытий, балок, раскосных поясов и т. д.). Горизонтальные несущие конструкции высотных зданий, как правило, однотипны и представляют собой жёсткий железобетонный диск (монолитный, сборно-монолитный, сборный). Горизонтальные конструкции воспринимают вертикальные и горизонтальные нагрузки и передают их на несущие конструкции и фундаменты. С целью снижения ветровых воздействий выбирают эффективную в аэродинамическом отношении цилиндрическую, пирамидальную или призматическую форму здания. Конструкции высотных зданий имеют свою специфику, которая влияет на их объёмно-планировочные и архитектурно-конструктивные решения. К таким особенностям относятся: значительные нагрузки на несущие конструкции; неодинаковые нагрузки на конструктивные элементы конструкций; высокое значение ветровой нагрузки как горизонтальной составляющей; проблемы совместной работы несущих конструкций из стали и бетона; воздействие природных факторов (сейсмичных, атмосферных, аэродинамичных); воздействие техногенных факторов (вибрации, шумы, аварии, пожары, диверсионные акты, локальные разрушения); повышенные требования к пожарной безопасности и систем жизнеобеспечения; сложное инженерно-техническое обеспечение.

**Ключевые слова:** конструктивные схемы и системы, многоэтажные здания, каркасы высотных сооружений, рамные системы

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