Shaping and structuring of high-rise office buildings in Europe

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The subject of the study were high-rise office and mixed-use buildings in Europe, with a height exceeding 150 meters and realized after the year 2000. The aim of the analysis was to examine the correlation between form and structure of the overground parts of this buildings. The skyscrapers were categorized according to the analysis of the core location and the form of the building. The article presents the results of analyses of skyscrapers with a single, inner core. The analyzed high-rise buildings' forms are highly varied. Although the skyscrapers of biaxial symmetry plans seem to dominate, one can observe the increasing forgoing of design forms with regular, repetitive floors. However, translating the projects with free-form shapes into the material form constitutes a significant problem. The most important parts of the skyscraper are the ground floor and the top part, which is often shaped as a structure between a flat ending and a spire. The structure of high-rise buildings in Europe almost always rely on the cooperation of the core with the peripheral supports. The cores, frames and ceilings are based on different material solutions, but the most common combination is the whole structure made of the monolithic reinforced concrete. The core is usually placed in the central part of the plan and its area on the average equals 23% of the ground floor's area. The dimensions and areas of the cores are mainly functionally conditioned, and they decrease as the height grows taller.

Key words: Europe, high-rise office buildings, skyscrapers, shape, structure, core

Introduction

High-rise buildings were a subject of a number of studies, however, the European projects are rarely researched. The specificity of the European examples requires a more thorough analysis, in particular of the latest projects and realizations.

The development of a high-rise building, which exceeded 100 meters was described in the twentieth century. After year 2000 the number and height of finished skyscrapers in the world increased significantly. Currently, the high-rise building researchers focus on the development of buildings higher than 200 meters [1]. In Europe, the majority of high-rise buildings is still in the height range of 100-200 meters. It can be assumed that the European high-rise buildings, which especially stand out compared to the rest of the continent, range between 150 - 200 meters.

Skyscrapers demonstrate progress, economic prosperity and economic strength as well as show the investor demand for a centralized and prestigious office space [2]. This is why office and mixed-use buildings constitute the largest group among the European high-rise buildings, especially among the highest and the most spectacular of constructions.

Tall office buildings are often the objects of original functional and spatial solutions. This results in. al. from the funds allocated for their implementation, the symbolism associated with their form and comfort, as well as the possibility of introducing variously arranged spaces. The original forms of the designed high-rise buildings pose a significant challenge to design and technology.

Material and methods

As part of the research an analysis of high-rise buildings was performed: both office and mixed-use buildings, with a height exceeding 150 meters. The scope of research was limited to objects realized after the year 2000. The data analyzed included: shaping and constructing high-rise buildings, their functional solutions, their transformation to convert the irregular forms of the architectural concept into a tangible form of a building, designed structures and their material solutions as well as the structural and functional role of the building core. The comparison of the objects was conducted according to the technical documentation that was used to determine and analyze the selected parameters.

The scrutinized skyscrapers were categorized according to the analysis of the core location and the form of the building. The basic division was to differentiate the two groups of high-rise buildings: single- and multi-core. Both groups were divided into building categories with their cores placed in the central part of the floor plan and those with their core situated on the outside contour of the body or at their periphery. The article presents the results of analyses of the most numerous of these groups, i.e. skyscrapers with a single, inner core (Table 1). Both the placement and the number of cores were marked as the basic criterion for the scheme since the core is an essential functional and structural component, common to all of the analyzed examples. In the analyzed European high-rise buildings, the core is not only the place of vertical service shafts, but also vertical transportation routes and exits, and at the same time it serves as a structural element. The European skyscrapers, which reach heights of 150 – 300 meters, are situated within the range where implementing the cores is necessary, whereas still the building heights are not as significant for the core to be too frail to perform the structural role [3], [4]. Furthermore, due to their function, the core is the least flexible element of the skyscraper, and its specific dimensions, geometrical solutions and verticality affect the form and space usage inside the building.

Figure 1: 30 St. Mary Axe Tower, London: a view – the form and the steel structure under construction
source: K. Foljanty and www.constructalia.com/repository/transfer/en/resources/ContenidoProyect/00919849Foto_big.pdf

Figure 2. Opernturm, Frankfurt: a view – the form and the reinforced concrete structure under construction.
source: commons.wikimedia.org/wiki/File:Frankfurt Opernturm_(Taunus anlage).jpg and www.skyscrapercity.com/showthread.php?t=1328795&highlight =frankfurt&page =2

Shaping the form of high-rise buildings

Today, high-rise buildings' forms are highly varied. However, the skyscrapers of biaxial symmetry plans as well as slightly disturbed biaxial symmetry plans seem to dominate (Fig. 1, 2). Such objects are beneficial for structural reasons [5]. The shape of the form in symmetrical structures allows for an even core load distribution and limits its deformation or twisting. Designing an efficient structure, however, does not require a perfect symmetry of the body's floor plan, it is enough to balance the system, for example, according to different spacing of the building's elements and controlling the moving of columns and the core [5]. Therefore, the buildings with impaired symmetry can be considered as structures working symmetrically, at the same time introducing deformations of forms allowing for a more creative design.

Although the majority of constructed high-rise buildings are still characterized by simple, geometrical forms, one can observe the increasing tendency of design forms with regular, repetitive stories. A body of the building formed in an original manner (Fig. 3-6, 9-10) becomes a visual asset of the skyscraper and a landmark of companies and institutions or the city in which the building was erected [2]. Unique forms arise due to the irregular shape of the building site and surrounding microclimate analysis, due to the vision of the designer or for other reasons. Some originally formed constructions take free-form shapes (Fig. 5, 10), most of them however, are highly geometrical (Fig. 3, 11).

Translating the projects with free-form shapes into the material form constitutes a significant problem [4]. The simplest designs are constructed as a combination of vertical or inclined straight columns and appropriately shaped ceilings (Fig. 3). In the case of more complex geometry, a division into straight or flat elements that change the angle only at the junctions, is introduced. Arches are approximated by catenary curves (Fig. 4), and multi-curved planes divided into diamond-shaped or triangular modules (Fig. 5). Replacing the free-formed, curved geometry with their rectilinear approximations facilitates the production of structural components, their assembly and finished interior and exterior, at the same time often being visually indistinguishable.

Figure 3. Carpe Diem Tower, Courbevoie: a view – the form and the reinforced concrete structure under construction.
source: www.ramsa.com/en/news/tour-carpe-diem-certified-leed-platinum-raising-ramsa-s-total-to.html and www.doka.com/web/newsroom/press/Tour-Carpe-Diem.me.php

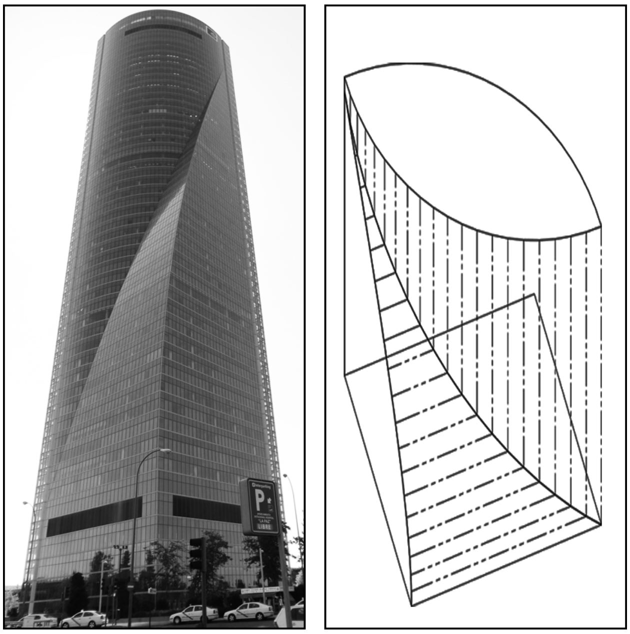

Figure 4. Torre Espacio, Madrid: a view – the form and a diagram showing the geometry of facade.
source: J. Pietrzak and own work

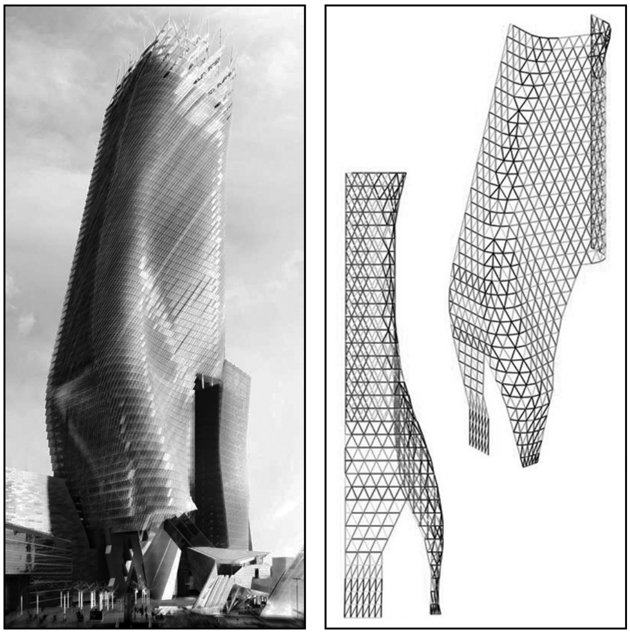

Figure 5. Tour Phare, Puteaux: a visualization – the form and a diagram of elevation's panelization.
source: www.archiscene.net/wp-content/gallery/archiscene/phare-tower-morphosis04.jpg and www.bformtech.com/services/m3-geometry/

Figure 6. Il Curvo Tower, Milan: a visualization – the form and a model of the structure.
source: saint-andres.blogspot.com/2010/06/milano-progetto-city-life-3-grattacieli.html and www.idealista.it/news/immobiliare/residenziale /2010/05/19/6292-ti-piacerebbe-vivere-in-un-grattacielo

The important parts of the skyscraper are the ground floor and the top part [6]. The entrance zones in the analyzed buildings vary from a dozen to 30 meters of height, and most of them were designed as completely transparent (Fig. 7, 8). The flat endings of the high-rise buildings are becoming less common; however, the trend to top the skyscrapers with spires in order to elevate their height is also not widespread.

Tapered buildings with still quite large areas at the top constitute a numerous group. On the last floors are commonly introduced: winter gardens, restaurants or viewpoints (Fig. 9, 10).

Figure 7. Taunus Turm, Frankfurt: a view – the form and the prefabricated concrete structure under construction. *source: www.hofmannnaturstein.com/files/taunusturm_frankfurt_03_neu.jpg and http://www.skyscrapercity.com/showthread.php?t=521026&page=22*

Figure 8. Warsaw Spire, Warsaw: a visualization – the form and the steel and concrete structure under construction. source: www.skyscrapercity.com/showthread.php?t= 596467&page=5and www.cbakkala.com/project/warsaw-spire-poland

Structuring and material solutions

The design of a high-rise building is determined by, among others, the safety of its users [7]. More and more attention is paid to the „redundancy" of the structure, which will be ready to carry the load in the event of the partial destruction of the structure. Additional elements are present also in order to ensure a proper users' comfort [6], especially to prevent swaying of a skyscraper. The elements improving only the rigidity of the building may be unsecured against fire.

The structure of high-rise European office buildings almost always rely on the cooperation of the core with the peripheral supports (Fig. 6, 11). The shell in the elevation line or the core rarely play the dominant construction role. The core of a typical construction bears the horizontal forces and stiffens the structure, the columns carry the vertical forces. Parts of vertical forces are transferred through the ceiling floors onto the core. Shell-shaped diagrid buildings [8] are an exception (Fig. 1, 9). The diagonal structure carries the wind force well enough, therefore only vertical loads are transferred on the shaft.

To stiffen the taller buildings extra trusses are used to impart the forces between the core and the supports. An efficient transfer of forces between the core and the columns requires connecting them to each other on one, two or three levels – evenly spread over the height of the building [9]. The transmission of large forces between the elements of design quite often requires the introduction of single- or double-story high-rise superstructures, which are typically located at the technical levels.

The designers sought to eliminate internal supports sharing the office space in the majority of the analyzed buildings. Only in a few cases a grid of 7 to 8 meters columns was applied. Such solutions can be seen particularly in multi-functional buildings, where the repeating floor and structure pattern is usually adapted to the function of a hotel or residential building. In such designs, there is a shift from square to round columns at the office floors.

Loads change in high building; therefore in order to make the structural solution efficient, the elements of the structure should also change. The variables are mostly: a cross-section, type of the material or the number of elements. The core changes the most - the thickness of the walls and / or area of the core decreases. As zoning the elevators is commonly used, the individual units end up on different floors, which allows for a gradual reduction of the core's area. Variable column sections and the spacing of peripheral columns are also used. In addition, in the composite columns the cross-sectional area of the steel element and / or concrete class is reduced, and in the case of steel columns and beams, the wall thickness of profile changes and the additional ribs appear.

Almost half of the analyzed skyscrapers have the highest part of the building made out of a steel structure which is independent from the main frame and the core. The observed tendency to place restaurants, winter gardens etc. at the highest single-space levels is associated with the more frequent crowning of the buildings with a wide-span steel roof (Fig. 9, 10). There can be also distinguished a group

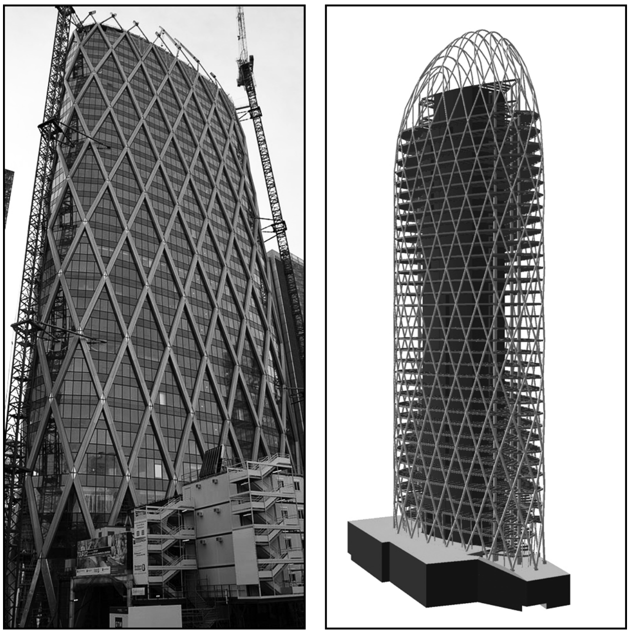

Figure 9. Tour D2, Courbevoie: a view – the form and a digital model of the steel structure.
source: fr.wikipedia.org/wiki/Tour_D2#mediaviewer/File: La_tour_D2_Le_1er _F%C3%A9vrier_2014.JPG and www. pss- archi.eu/forum/viewtopic.php?id=28 506&p=53

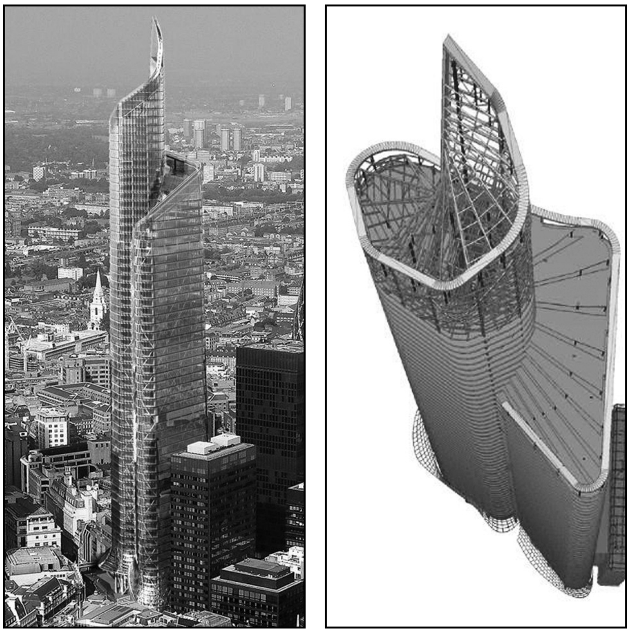

Figure 10. The Pinnacle Tower, London: a visualization – the form, a digital model of the steel structure.
source: www.skyscrapercity.com/showthread.php?t=2276 59 and www.masterbuilder.co.in/arup-and-tekla-bim-the-pinnacle-of-structural-design/

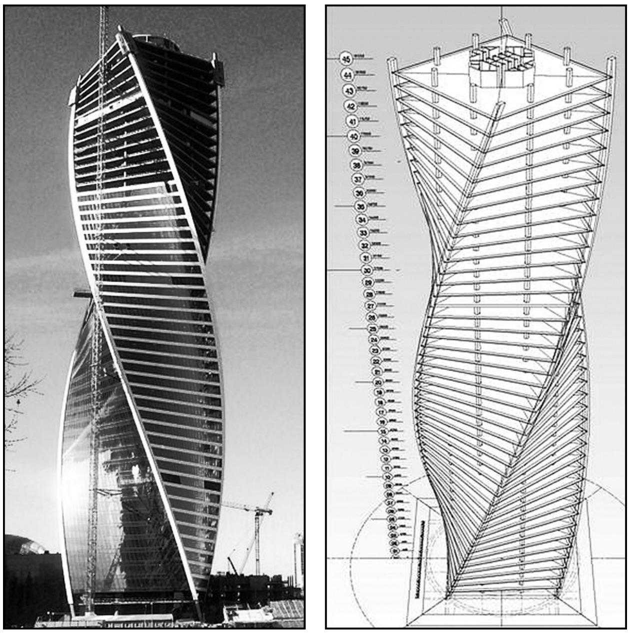

Figure 11. Evolution Tower, Moscow: a view – the form and a digital model of the reinforced concrete structure.
source: en.wikipedia.org/wiki/File:EvolurtionTower2014. jpg and forum.skyscraperpage.com/showthread.php?t= 188154

Figure 12. Mercury City Tower, Moscow: a view – the form and the reinforced concrete under construction.
source: www.skyscrapercity.com/showthread.php?t=351 203&page=178 andwww.schoeck.com/en/media-relations/reaching-the-sky-europe-s-tallest-building-incorporates-schoeck-thermal-break-technology-344?filter-active=1

of flat-ended buildings, with top ceilings covered by steel structures of facades (Fig. 8).

The cores, frames and ceilings of high-rise European office buildings are based on different material solutions that cannot be linked to a one, common way of shaping their bodies. The cores in the vast majority of the analyzed buildings are made of reinforced concrete. Load-bearing frame constructions are typically made of one material, wherein it is as often steel (Fig. 5, 8, 9, 10) as concrete (Fig. 2, 3, 4, 7, 11). Therefore, the most common combination is the whole structure made of monolithic reinforced concrete (Fig. 12). Buildings constructed only with steel constitute the smallest group (Fig. 1).

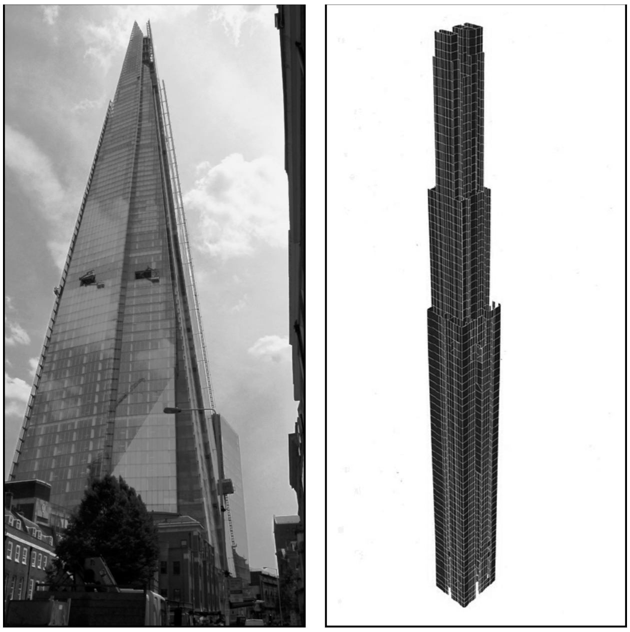

Figure 13. The Shard Tower: a view – the form and a digital model of the reinforced concrete core.
source: K. Foljanty and www.ctbuh.org/LinkClick.aspx?fileticket=hefxeNINiV 8%3D&tabid=1323&language=en-US

Figure 14: Torre de Cristal, Madrid: a view – the form and the steel and concrete structure under construction
source: J. Pietrzak and upload.wikimedia.org/wikipedia/commons/a/a1/Torre _de_Cristal_%28Madrid%29_03a.jpg

In high-rise European buildings are also implemented composite steel-concrete elements that form the entire frame or simply complement the reinforced concrete structure in high stress areas. The composite frame allows in. al. for a shortening of the construction time and eliminating of additional fire protection.

In buildings with reinforced concrete frames the ceilings are made of concrete. Typically, they are made of reinforced concrete slabs or pre-stressed concrete. Occasionally there are other solutions like prefabricated hollow core slabs or floors made according to the „bubbledeck" technology. On the other hand, steel and composite constructions complement the steel-concrete ceilings: fluted metal sheet is spread over the steel beams, and onto it is purred a thin reinforced concrete slab.

The structuring of the building and the aesthetic appeal

There are two approaches to integrating the form and the load-bearing structure of a skyscraper: hiding the structure inside the building in order to minimize its elevation divisions or exposing of the structural elements. The main structure is visible primarily in buildings with large-sized columns and frames situated in the surface of the facade.

The outer shell is exposed on the facade whenever it takes the form of the diagrid [8] (Fig. 1, 9). Structural components may also emphasize the form of the building and underline the window divisions (Fig. 2, 7).

While the structure can be „hidden" on the higher floors, it is usually not possible to conceal it at the level of the transparent ground floors [3]. Therefore, it is common to reduce the number of columns in the entrance zones. The supports come together in a V-shape (Fig. 8), they are replaced by mega-columns or disappear entirely on the floors above the ground, where the transfer of loads takes place (Fig. 7). It is also important for the designers themselves to reduce the cross-section of columns. More traditional buildings can also be mentioned, in which the arrangement of columns from the upper floors is continued on the ground floor, whereas the ground floor is distinguished by a higher story level.

Cores – the shaping and structuring

Upon the analysis of selected European high-rise buildings, no general relation between their shaping and structuring could be specified. Basing all the projects on cores that serve both functionally and structurally is the exception. The shape of the core, which is the backbone of a high-rise building, is in turn reflected in the final shape of a skyscraper (Fig. 6). The consequent part of the study was therefore devoted to the analysis of the cores, designed to determine the conditions influencing the core shapes and the principles thereof.

Table 1: Skyscrapers with a single, inner core: systematics of spatial forms, presented on chosen examples. Data in table: the given number (for more information about skyscraper see the number in Table 2), a view and a ground floor plan on which core is marked

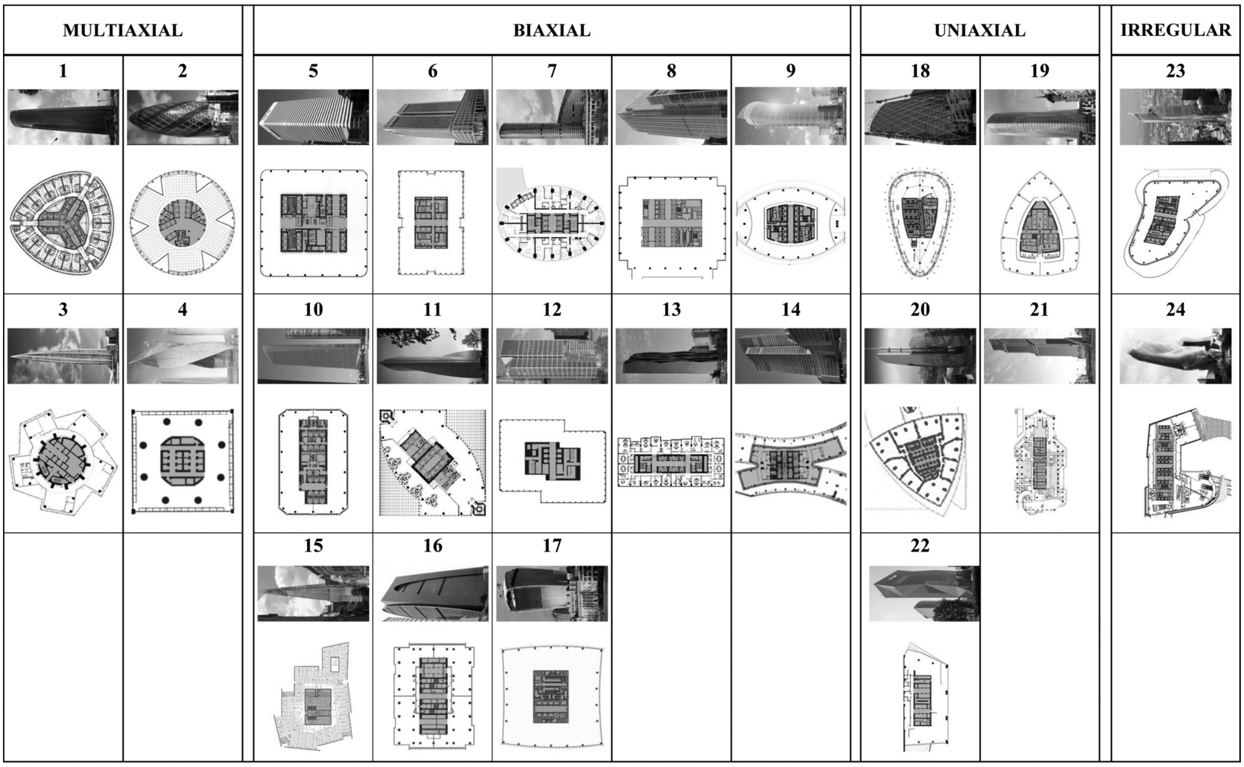

Table 2: Chosen examples of skyscrapers with a single, inner core presented in Table 1 – characteristic of core to floor area ratio.

Systematics	Nr	Skyscrapers name	Height [m]	Ground floor			Middle part			Top part		
				Floor area [m^2]	Core area [m^2]	Core to floor area ratio	Floor area [m^2]	Core area [m^2]	Core to floor area ratio	Floor area [m^2]	Core area [m^2]	Core to floor area ratio
Multiaxial	1	Sacyr Vallehermoso	236	1568	324	20,7%	constant					
	2	30 St. Mary Axe	180	1825	510	28,0%	1978	503	25,4%	1215	496	40,8%
	3	Lakhta Center	427	1978	514	26,0%	1453	372	25,6%	601	53	8,8%
	4	Evolution	255	2397	596	24,9%	constant					
Biaxial	5	8 Canada Square	200	2877	959	33,3%	no data			2877	353	12,3%
	6	Opernturm	170	1675	452	27,0%	constant					
	7	Sky Tower B2	212	1124	182	16,2%	constant					
	8	25 Canada Square	201	3307	843	25,5%	no data			3132	523	16,7%
	9	Warsaw Spire	220	2042	415	20,3%	1543	415	27%	2297	252	11,0%
	10	Torre de Cristal	249	2002	524	26,2%	1580	517	33%	1400	386	27,5%
	11	Torre Espacio	224	1797	377	21,0%	1295	287	22%	1208	196	16,2%
	12	Taunus Turm	170	1668	392	23,5%	constant					
	13	DC Tower I	220	1541	371	24,0%	1576	371	23,5%	1529	371	24,2%
	14	Palazzo Lombardia	161	2353	582	24,7%	constant			1266	265	20,9%
	15	The Shard	306	3703	605	16,3%	1336	245	18,4%	329	29	8,8%
	16	Imperia Tower	239	3721	961	25,8%	3514	572	16,3%	2090	268	12,8%
	17	20 Fenchurch	160	1875	536	28,6%	2802	536	19,1%	3151	536	17,0%
Uniaxial	18	Tour D2	171	1691	460	27,2%	constant					
	19	Torre Iberdrola	165	1824	451	24,7%	no data			1319	322	24,5%
	20	Vostok Tower	360	3318	461	13,9%	no data			2108	355	16,8%
	21	Mercury City Tower	339	3837	672	17,5%	1723	335	19%	827	91	11,0%
	22	Tour Carpe Diem	166	1547	348	22,5%	no data			1334	268	20,1%
Ir-regular	23	Pinnacle	288	no data		19,9%	no data		18%	no data		23,7%
	24	Tour Phare	298	3399	725	21,3%	3362	896	27%	1368	420	30,7%

In the analyzed objects, the cores are placed usually in the central part of the plan, therefore meeting the functional and constructional requirements most effectively. However, this causes the division of the floor plan. The plan of the core is typically a figure similar or close to the contour formed by the building body, and two forms are characterized by the same number of axes of symmetry (Table 1). The most common location of the core is in the center which allows for a better stiffening of the building and appropriate load dispersion [5].

However, the shape and dimensions of the core are determined mainly by its functional role, not structural. Even in high-rise buildings, which bodies are freely shaped, the cores are not very flexible and have a well-defined geometry. In addition, the use of cores as evacuation routes affects their design and material solutions.

More than 60% of the analyzed high-rise buildings are shaped very differently, however, their core area decreases as the height grows taller (Fig. 1, 4, 5, 10, 12, 13, 14). In contrast to the form of a skyscraper, which may be „continuous" or linearly varied, the core changes due to the offsets at the end point of the elevator shafts (Fig. 13). The geometry of the core is also closely defined: its walls are vertical, the dimensions correspond to their functions, and the plan is usually based on the right angle. Over 70% of the analyzed buildings have cores with a floor plan similar to a rectangle. Irregular, round cores are not very functional (Table 1).

In the analyzed building, the area of the core on the average equals 23% of the ground floor's area, independent of the body shape, the height of the building and the type of construction (Table 2). The dimensions and areas of the cores are mainly functionally conditioned and vary in proportion to the supported surface floors, which affect the number of required elevator and installation shafts, as well as stairwell dimensions.

Changing the area of the core at the height of the skyscraper rarely exceeds 50%. In the case of half of the buildings, the area of the top part of the core constitutes from 60 to 90% of its base, and generally is limited in the range of 70 to 80% (Table 2). It is easily noticeable that the areas of floors usually vary to a greater extent than areas of cores. In the majority of the skyscrapers the areas of floors and core decrease, and form tapers linearly. The change in the surface of the core allows for more efficient use of materials in this structural element, although this usually does not arise due to construction reasons.

Conclusions

The functional requirements of office spaces and cores are common for all the analyzed buildings. However, the spatial solutions used to meet these requirements and construction-materials vary.

The forms of many skyscrapers are still shaped in a simple and highly geometrical manner, although there is the assumption used on increasing basis in the design process of a high building that high office buildings are to be formed in an original and unique way, and its form is to become a recognizable symbol and asset on the real estate market.

Shaping the floor plans is often modeled due to the author's architectural concept and leads to a shaping a form manifesting the originality and uniqueness of a skyscraper. However, the structural and functional core present in current European projects must meet the standard requirements resulting from vertical technological shaft solutions and vertical routes. Due to their function, the core is the least flexible component of a skyscraper. Both the tall, simple-shaped symmetrical buildings as well as those with irregular forms have vertical cores, the geometry and dimensions of which depends on their function. The core is a rigid, central element of the composition in most high-rise buildings.

The freedom in forming the body surrounding the core is also strongly limited. The building forms are designed according to the accepted discipline so that they can be broken down into simple elements. The most preferred option is to introduce modules with the largest number of repetitive elements. The development of the construction technique and the cost of production of personalized elements do not yet allow for the free formation of such a large volume as skyscraper.

The selected structures and construction materials match the geometry of forms and meet the architectural requirements. However, because usually there are several possible solutions, the final choice depends on other premises than the correlation between form and structure. The general rule is, however, to design a construction system based on the co-operation of the core with the peripheral supports. It is the most effective solution for the European high-rise buildings.

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