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EXPOSURE OF THE LOAD-BEARING STRUCTURE IN THE DESIGN OF EUROPEAN HIGH-RISE BUILDINGS

Summary

A significant spatial element of the high-rise building is its load-bearing structure. Both concealment and exposure of the load-bearing elements requires deliberate decisions. Their sizes and geometries do not allow them to be located freely or easily "masked". Although in high-rise buildings of the European scale the aesthetic expression can be independent of the structure, some designers prefer solutions where the load-bearing structure is dominant. On the one hand, in many projects, the load-bearing structure only partially influences the aesthetics of the form (being a purely functional component), and on the other hand, the search for the original architectural expression of a skyscraper leads to an emphasis on structural logic in creating the architectural expression. The article discusses the possibilities of concealing and exposing the load-bearing structure depending on the designed structural systems and a different approach of designers to the use of the load-bearing structure for aesthetic expression.

Key words: high-rise building, tall building, skyscraper, Europe, load-bearing structure, aesthetic expression, exposed structure.

Introduction

The load-bearing structure is a significant element of a high-rise building. Designing a skyscraper requires a reference to its structure, especially when it is exposed (externally and internally). Both concealment and emphasis of the load-bearing elements requires thoughtful decisions, because their dimensions do not allow for their arbitrary placement.

The American designer Fazlur Kahn came to the conclusion that in a high-rise building there is no balance between the form and the structure, and that the optimal design of the load-bearing structure results from structural logic, not from function or aesthetics, hence he criticised the addition of decorative elements to the elevations. He emphasised that they were not related to the nature or structure of a high-rise building and resulted only in waste of

natural resources (Kahn 1982). Fazur Kahn's development of new structural systems and his modernist aspiration for simplicity were the basis for the development of the Structural Expressionism style. In the period of domination of Postmodernism, the principles of this style were not used in the design of European skyscrapers. However, at the end of the 20th century such thinking became the basis for the search for new aesthetics of high-rise buildings, and Structural Expressionism meant the dominance of the structure on the facades of the buildings and in architectural expression (Al-Kodmany, Ali 2016).

The ongoing search for the original architectural expression of skyscrapers increasingly leads to a reference to the "sincerity" and "true nature" of high-rise buildings. Instead of concealing the elements of the load-bearing system the structural logic shapes the skyscraper (Billington 1983). The aesthetic expression results from the coherence of the spatial form and the load-bearing structure, the revealed structural correctness without stylistic embellishments (Al-Kodmany, Ali 2016). This philosophy is also consistent with the tendency to imitate organic forms. In nature, the organism is identical to the structure, which is its integral part (Trzeciak 1976). The load-bearing structure becomes one of the key elements of the spatial composition also because the dimensions and geometry of the structural elements make their concealment almost impossible.

The article discusses the possibilities of concealing, exposing and the use of the load-bearing structure for aesthetic expression. The structural systems used in European projects of high-rise buildings are presented and briefly characterised. It takes into account the main load-bearing elements, their location and dimensions, which determine the possibility of their exposure or concealment. The influence of these systems on the design of the form of the building is also discussed. At the end, the paper discusses a different approach of designers to the exposure of load-bearing structures in the body (elevations) of skyscrapers and in their interiors.

The design of load-bearing structures in European high-rise buildings

The classic structural system adopted in European high-rise buildings is the core-frame system. Usually the designed buildings have a single, centrally located core. There are also buildings with several cores, also located outside of the outline of the floor plan. The other main structural elements are the columns located on the perimeter of the building and the floor slabs, sometimes also intermediate supports. In each building, the core and perimeter columns are connected through the floor slabs. However, this arrangement does not allow for an effective transfer of wind loads. Therefore, especially in taller

buildings, outriggers (massive elements connecting the peripheral columns with the core) are used (Choi et al. 2014). The transmission of large forces often requires the introduction of outriggers with a one or two storeys height. Effective "cooperation" of the core and columns requires connecting them on one, two or three levels.

In some taller or more slender buildings, in order to achieve the necessary stiffness, both the core and elements located on the façade must work in unison, creating a tube-in-tube or hull and core system (Pawłowski, Cała 2013). In buildings with such a system, the core is always located in the central part of the building. Intermediate supports are usually not necessary, unless they constitute a "closure" of the core.

In a few European skyscrapers the tube systems were used, designed as a braced tubes or diagrids. The braced tube is created by designing widely spaced columns and connecting them with massive bracing. The characteristic diagonal elements or X-shaped grids form large-scale divisions visible from a distance (Al-Kodmany, Ali 2016). The diagrid is a series of triangular fields (made up of elements less massive than those used in braced tubes) and horizontal rings of beams. Since the diagonal elements carry both the vertical and horizontal loads, this system is devoid of vertical elements (Boake 2014). In general, no structural core is required, and the supports in the central part of the plan transfer only the gravity loads.

Moreover, some solutions of spatial forms introduced by architects resulted in modification of the classical systems or even individually designed, atypical load-bearing structures which are difficult to classify.

The influence of the structural system on the exposure of the structure

Currently the most commonly used core-frame system can be adapted to many skyscraper forms with a certain degree of complexity and irregularity. In such buildings it is not necessary to add bracing to resist wind loads (Pawłowski 2012), and all structural elements may remain hidden inside the building, hence the façade can be shaped freely. Vertical cores are most often placed in the central part of the plan, while the columns are moved away from the elevation so as not to disturb its expression. The only structural elements affecting the aesthetics of such a building can be the floor slabs, the levels of which are visible as divisions of the elevation (illustration 1a). Despite the vertical form of the skyscraper, its horizontality is emphasized. Columns with more "dense" systems are usually located at the edges of the floor slabs. In that case, the horizontal and vertical structural elements visible on elevations of tall buildings can also be hidden within the grid of windows (illustration 1b). In

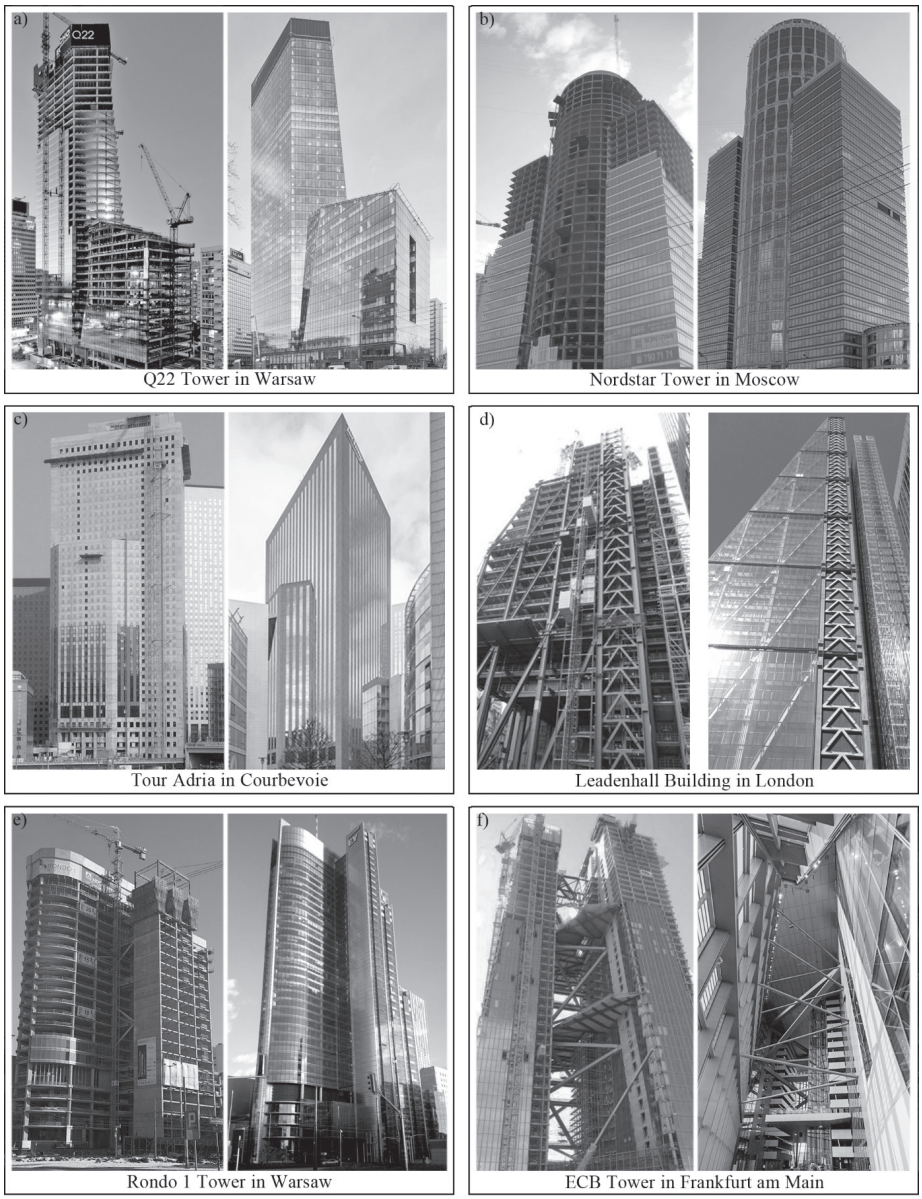
taller high-rise buildings with slender forms the core-outrigger structures are required. The additional structural elements are usually located on technical floors. As a result, the outriggers are not visible and do not interfere with the functional layout of the skyscraper.

In buildings with tube-in-tube structures, the central core is "hidden" inside and influences mainly the functional solutions. Typically, no internal supports are designed. The biggest constraints are the external partitions – shaped like traditional walls with window openings (only one building was designed with a steel diagrid). The geometry of the tube strictly defines the elevation surfaces, and their massiveness, transparency or divisions all depend on the adopted structural and material solutions. In some projects there are only small perforations and the elevations are defined by strong neutral planes (usually vertical or slightly inclined), whose final aesthetic expression depends on the adopted finish. When using larger window openings, an orthogonal, regular mesh is created, and the designer decides whether to emphasize the vertical or horizontal elements (illustration 1c).

In tubular structures the tube defines the aesthetics of the building, distinguishing its appearance from the "classic" building. The form is identical to the shape of the tube, and the structural elements located in the elevation plane are always exposed. The buildings are perceived as coherent, "light" and original. First of all, the diagonal elements become visible, and as they cannot be hidden in the divisions of windows and floor slabs levels they become exposed (illustration 1d). The structural logic of the high-rise building and its relation to the distribution of forces acting on the skyscraper are perceivable. Although the core does not stiffen the braced tube or diagrid structure, it is designed for functional reasons. Its location can be decided upon based on functionality or other considerations. Often the tubes are accompanied by external cores, even self-supporting ones, which are an important element of the spatial composition of the building, emphasizing its verticality (illustration 1d).

A group of atypical structures among the European high-rise buildings should also be mentioned. Their load-bearing structures are difficult to classify in an unambiguous manner. Their original structure is associated with the introduction of external structural elements that define the character of the building and become its hallmark (illustrations 1e, 1f).

Illustration 1. Load-bearing structure exposure in buildings with: a-b) core-frame structures; c) tube-in-tube structure; d) tube structure; e-f) an atypical structural solution



Source: a) – (www1) and (www2); b) – (www3) and (www4); c) – (www5) and (www6); d) – (www7) and (www8); e) – (www9) and (www10); f) – (www11) and (www12).

The load-bearing structure and the aesthetic expression of the building

Commonly, the design objective is to minimize the impact of the structure on the aesthetic of a building, sometimes by concealing the structure (illustration 2a). The masses of contemporary skyscrapers give the impression of being "carved" from a single piece of crystal, while the uniformly designed elevations constitute a "skin" stretched over the structural elements. Usually, however, the designers refer to the hidden structure, by highlighting some, subjectively selected elements of the regular horizontal or vertical grid on the elevation (created by columns and floor slabs). Emphasizing the horizontal divisions at floor levels balances the verticality of the skyscraper by connecting it with the ground, while a reference to the verticality emphasizes the slender form. The designers can change the perception of the building by emphasizing all or only selected divisions. Balanced, neutral compositions are those in which all the divisions are marked. An interesting solution is to highlight only the selected floor slabs or supports. Larger "fields" are clearly visible from a distance, and the proportions of the skyscraper's divisions resemble those observed in lower buildings.

Another approach to the design of a high-rise building is to refer to structural expressionism (illustration 2b). In some objects only (or additionally) the structural elements representing the folds of the elevation planes are accentuated. The external load-bearing structure or its selected elements indicate the planar changes on the façade and at the same time the geometrical divisions of the façade accentuate the shape of the load-bearing structure.

By revealing the "true" structure (the load-bearing structure) the designer can obtain original expression of the form. The design of the structure dominates in creating the aesthetic expression of a skyscraper. This approach emphasizes the structural logic over the additional or decorative elements. This creates an interesting effect as the exposed structural elements do not duplicate the classic "grids". In tube or atypical structures, the elements located on the façade are difficult to mask out and because of that, they are often deliberately exposed, although this causes various problems, e.g. related to thermal bridges. The exposed elements follow the shape of the building's form. The columns, beams and diagonal braces are visible, which introduces additional, characteristic divisions on the facades of skyscrapers. Structural details become one of the elements determining the aesthetics and the quality of architectural solutions. The exposed large-scale divisions on the elevation contrasted with the small divisions created by windows merge into one plane. In particular, the introduction of diagonal elements visually distinguishes the object from the surrounding buildings. On the other hand the external cores

emphasize the verticality and cause a visual breakdown of a skyscraper's form into several blocks.

The problem of the exposed structure also applies to the interiors of high-rise buildings (illustration 2c). In most skyscrapers, interiors are designed so that the divisions "mask" the structural elements. On the rentable floors the structure is usually covered with suspended ceilings, and only the columns are visible, especially in open space offices. The columns can be "hidden" only with partition walls, as in hotels and residential buildings. However, it is not possible to mask the diagonal elements on the elevation. It is also achievable to hide the structure in the enclosure of rooms which do not require natural lighting, but structure is usually visible in the zone of the glazed ground and top floors In addition, while striving to obtain the maximum spans the dimensions of the bearing elements increase. In rooms whose dimensions exceed the standard spatial divisions in the building, hiding the load-bearing structure may be difficult. In atriums, halls, etc. the floor slabs and sometimes even the core or diagonal bracing elements are visible and the exposed structural elements also determine the expression of these interiors.

Conclusions

The classic structural solutions used in European high-rise buildings are the core-frame, core-outrigger, tube-in-tube and tube systems. In addition, many original spatial forms required individually designed load-bearing structure.

In the case of the typical core-frame (and core-outrigger) systems, the "aesthetics" of a high-rise building are often just a "costume" rather than its "true nature". The structural skeleton of the building usually remains "hidden" in its interior, hence it is also possible to shape the façade quite freely. Usually, only the floor levels are visible in elevations. However, in some projects, the divisions and structural elements are visible in the elevation, so they determine the aesthetic expression. In facade compositions there may be an emphasis on horizontal or vertical directions, or, a more honest solution – with the whole network of structural divisions shown.

In the tube and atypical structural systems the elements located on the external part of the façade are difficult to mask. Often the exposed elements "follow" the shape of the building's body –– the form and the load-bearing structure are one and the same. In extreme cases the structure is the dominant element which creates the aesthetic expression of a skyscraper. The obtained expression, thanks to the originality, "raises" the quality of the skyscraper. Aesthetics justify the creation of more complex and expensive structural solutions like massive cores, spatial structures or diagonal elements.

Illustration 2. Load-bearing structure and the aesthetic expression of a high-rise building: a) different design of elevations with "hidden" load-bearing structure; b) elevations with the load-bearing structure exposed; c) interiors with exposed load-bearing structure

Sources: a) – (www13), (www14), (www15), (www16), (www17); b) – (www18), (www19), (www20), (www21), (www22); c) – (www23), (www24), (www25), (www26), (www27).

Although, in general, the designer's intention is to hide the internal structure in some projects, especially in buildings with atriums and many cores, the display of structural elements also creates the aesthetic of the interiors.

In the European high-rise buildings the aesthetic expression may be independent of the structure, nevertheless, some designers prefer solutions which emphasize the load-bearing structure – with the type of the structure, the structural elements and their locations being responsible for the final effect. The emphasis on the unusual form of a skyscraper results not only from its height, but also from the necessity of applying appropriate and technologically advanced structural solutions. Although in many designs, the structure is used mostly for its functional purpose and doesn't affect the building's aesthetics to a large extent, creating the building's aesthetics based on its verticality and the large scale elements seems to be a natural way of expressing authenticity in the designs.

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Ekspozycja struktury nośnej w kształtowaniu europejskich budynków wysokich

Streszczenie

Znaczącym elementem przestrzennym budynku wysokiego jest jego struktura nośna. Zarówno „ukrycie", jak i podkreślenie elementów nośnych wymaga przemyślanych decyzji, ponieważ ich gabaryty i geometria nie pozwalają na ich dowolne zlokalizowanie, a nawet na ich zamaskowanie. Chociaż w wieżowcach o europejskiej skali wyraz estetyczny może być niezależny od konstrukcji, to niektórzy projektanci preferują rozwiązania powodujące dominację struktury nośnej. Z jednej strony w wielu realizacjach struktura nośna tylko częściowo wpływa na estetykę formy (stanowiąc komponent czysto funkcjonalny), a z drugiej poszukiwania oryginalnego wyrazu architektonicznego wieżowca coraz częściej prowadzą do podkreślania logiki inżynierskiej kształtującej wieżowiec. W artykule omówiono możliwości ukrywania i eksponowania struktury nośnej w uzależnieniu od projektowanych ustrojów konstrukcyjnych oraz odmienne podejście projektantów do wykorzystywania struktury nośnej w kreowaniu wyrazu statycznego wieżowca.

Słowa kluczowe: budynek wysoki, wieżowiec, Europa, struktura nośna, wyraz estetyczny, kształtowanie, ekspozycja konstrukcji.

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