TECHNICAL TRANSACTIONS | CZASOPISMO TECHNICZNE
ARCHITECTURE | ARCHITEKTURA

2-A/2016

DOI: 10.4467/2353737XCT.16.182.5793

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PROPOSALS FOR THE APPLICATION OF SPACE STRUCTURES IN THE DESIGN OF THE MAIN SUPPORT STRUCTURES OF TALL BUILDINGS

PROPOZYCJE ZASTOSOWANIA STRUKTUR PRZESTRZENNYCH W PROJEKTOWANIU GŁÓWNYCH SYSTEMÓW NOŚNYCH BUDYNKÓW WYSOKICH

Abstract

This paper contains several author's propositions for the shaping of structural systems for the design of high-rise buildings. The author has developed these structural systems as special types of space structures. The main goal in the processes of shaping these structures was to strive to enhance their rigidity by relatively simple means. Additionally, there was the aim to incorporate alternative evacuation routes in cases of emergency rather than only by vertical transportation means, which are usually located only in the central cores of tall buildings. The proposed structural systems of aboveground floors need to be highly resistant to the maximum values of horizontal, vertical, thermal and earthquake loads. These structures for high-rise buildings can be constructed from steel, reinforced concrete or they can be compound systems. Applications of these systems will considerably enrich the scope of the architectonic views of the tall buildings in which they are incorporated. The safety of tall buildings is to a large extent determined by the stability of their foundation structure particularly when they are located in areas with subsoil of small load capacity or areas that are at risk of earthquake. The paper also presents some proposals for the shaping of the foundation systems devised by the author and indented for heavily loaded objects including high-rise buildings.

Keywords: Space structure, High-rise building, Structural system, Foundation structure

Streszczenie

W pracy przedstawiono kilka autorskich propozycji kształtowania systemów konstrukcyjnych dla potrzeb projektowania budynków wysokich. Autor opracował te systemy konstrukcyjne jako specyficzne rodzaje struktur przestrzennych. Głównym celem procesu projektowania takich systemów było dążenie do nadania im większej sztywności za pomocą stosunkowo prostych zabiegów projektowych. Ponadto dążono do zapewnienia dodatkowych dróg ewakuacji nie tylko za pomocą środków komunikacji pionowej, które najczęściej są umieszczone w trzonach centralnych budynków wysokich. Proponowane systemy konstrukcyjne kondygnacji nadziemnych muszą bezpiecznie przejmować maksymalne wartości obciążeń poziomych, pionowych, termicznych oraz sejsmicznych. Takie systemy konstrukcyjne mogą być wykonane jako konstrukcje stalowe, żelbetowe bądź kompozytowe, a ich zastosowanie pozwoli na znaczące wzbogacenie zakresu form architektonicznych budynków wysokich, w których zostaną one zastosowane. Bezpieczeństwo budynków wysokich jest w przeważającej mierze uwarunkowane stabilną konstrukcją ich fundamentów, szczególnie wtedy gdy są one posadowione na gruntach o małej nośności lub na obszarach sejsmicznych. W pracy przedstawiono także autorskie propozycje kształtowania systemów fundamentowania i przeznaczonych dla posadowienia obiektów silnie obciążonych w tym także budynków wysokich.

Słowa kluczowe: struktura przestrzenna, budynek wysoki, system konstrukcyjny, konstrukcja fundamentu

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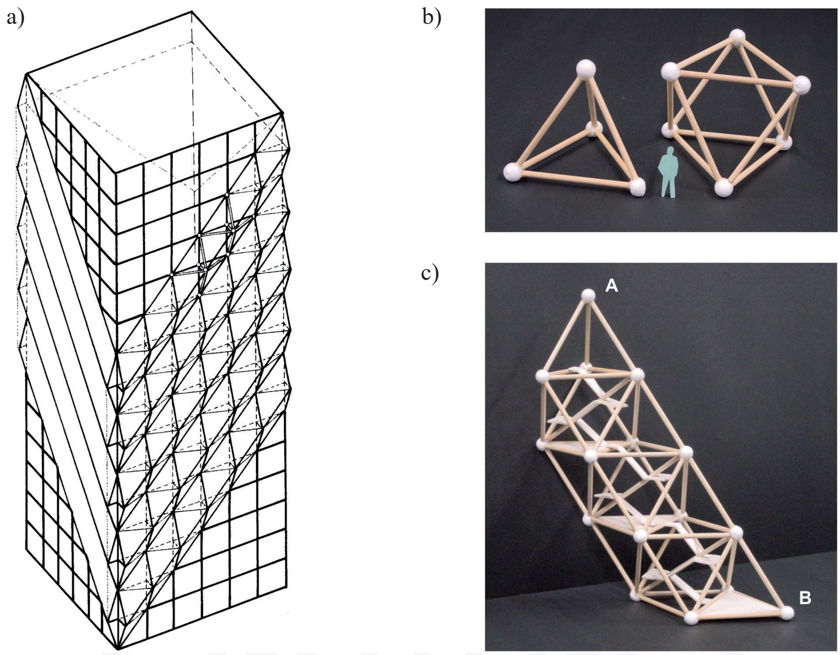
1. Introduction

Structural systems should provide tall buildings with a high degree of rigidity and with great stability even when under a very complex set of external loads. The bearing systems of tall buildings have to simultaneously provide two contradictory characteristics; on the one hand, they have to be very rigid but on the other hand, they have to offer some degree of flexibility [1, 2]. Both these features are characteristics for space structures defining as the bearing systems composed of members arranged in spatial way in their spaces where the force transmission is also done in a spatial way. The structural formula of these systems was formulated by Alexander Graham Bell and was later gradually developed by researches like Max Mengeringhausen, Zygmunt Stanisław Makowski and numerous others [3, 4]. Systems of space structures are applied mainly as the bearing structures of roof structures and can take various forms. Due to the advantageous features of space structures, many architects and engineers choose to apply them in the design of tall buildings. The bearing structures of high-rise buildings are designed and realised in certain structural systems such as framed tube, tube in tube, bundled tube, diagonal frame tube as well as in other types of systems [1]. These structural systems meet the satisfactory requirements of building safety, but in some extreme cases they turn out to be insufficient technical solutions. The terrorist attack against the USA on September 11th, 2001 and the collapse of the twin towers of the WTC in New York has led to the need for new considerations regarding the forms and structures of tall buildings. Of course, spatial rigidity, the resistance to all the types of possible, even the greatest values of various loads (horizontal, vertical, thermal or earthquake load) and the quick evacuation of people in cases of emergency remain the most basic requirements for the safety of high-rise building structures [5, 6]. The design of stable and safe foundation structures of heavily loaded objects remain a separate and very complex engineering task which is realised in various ways [7–13].

The structural formula of space structures has many promising features which encourage its application in the search for rigid and efficient types of structural systems for the aboveground parts of tall buildings as well as in the search for special shapes of foundation structures, the application of which make it possible to safely locate heavily loaded buildings on each type of subsoil. This paper presents some types of structural systems devised by the author as solutions to the above defined tasks.

2. Example of the basic form of structural configuration

Space frames, in the proposals previously provided by the author [14, 15], were vertically placed around the perimeter of the building. Their spatial rigidity is high, but this arrangement may cause the magnitudes of the force acting on some of its component parts to increase to an enormous degree. Even the subdivision of the perimeter space frame would be an insufficient solution to decrease the unjustified, excessive level of force acting on members of the space frame which are located in the boundary areas of that structure. On the other hand, the space of the perimeter frame could be used as the space



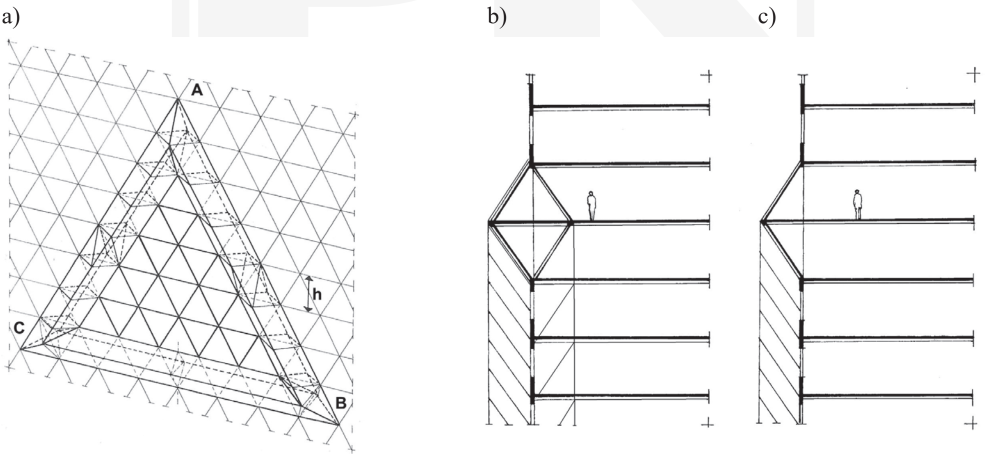
Ill. 1. Shapes of space structures proposed to be applied in multi-storey buildings

for another option for safe evacuation of people in emergency situations. Illustration 1a shows the result of the transformation of the space frame “square on square” being at the beginning the form of the circumferential space structure of a tall building. The number of structural members was reduced by the way in which the remainders of the initial arrangement created the skew spatial belts. The diagonal members, placed onto the main façade plane of the building, transfer the forces to all of the columns located along the perimeter of the building. The outer diagonal members transfer the horizontal forces in the same way except for the members located close to the corners. The spatial skew belts are not connected to the surfaces of the outer diagonals in order to focus the forces precisely along the corner columns. In the vertical cross-section of this part of the façade, one may notice the triangular, prismatic shapes of these belts. Of course, the space of all these skew belts and between them may belong to the inner space of the building due to appropriate arrangement of the curtain walls in the outer layer of the space structure, see the top left area of Illustration 1a. The geometrical dimensions of these skew belts should make it possible to design additional means of vertical transportation between particular storeys in these skew areas.

Inside the space of many spatial structures, one could easily distinguish the basic component parts that have tetrahedral and octahedral forms, see Illustration 1b. These are most often built by means of bars of equal lengths. When the bar length equals approximately four meters, the structure is habitable [16]. Both of these forms of bar units can create a very rigid space truss called a crystal space frame. If these bands are located along the edges of, for example, a huge octahedron then they will form a mega-octahedron and other types of habitable mega structures. These spatial mega-structures have high levels of rigidity and their inner spaces can be used for the arrangement of staircases (see Illustration 1c) or other means of vertical transportation beside the inner core. These alternative methods of evacuation will increase the safety of habitants in the event of dangerous situations.

3. Proposal of simple forms using prismatic structures

The localisation of these additional evacuation ways along the edges of the huge triangular fields of the façade will not unduly interfere with the functionality of space on each floor of tall buildings. In spite of these advantageous features the above presented arrangement may cause the appearing of the extremely big values of forces, which may act in some members of the space truss located in this way. Therefore, in order to keep the advantages and to display the jet forces along the main and single directions of edges of the huge triangular area of a façade and to avoid the disadvantage mentioned above, it is proposed to locate the band of that space truss in the manner shown in Illustration 2a. The other reason for such localisation is to endeavour to incorporate additional means of vertical transportation into the space. All of the mentioned reasons are of the equal importance. In order to include a staircase, the basic form of the space truss (see Illustration 1c) was supplemented by means of an additional number of the skew bars, see Illustration 2a. The bands, made as spatial trusses, may be located on the border between the inner and the outer space of a building (see Illustration 2b) or they can be put only onto the outer space of the façade, see Illustration 2c. In the vertical cross-section of the façade, one can notice the triangular, prismatic area of these space trusses [17] therefore it was assumed to call these types of the structural systems the prismatic space structures. It is supposed that the system can be applied relatively easily for the reinforcement of existing buildings of this type.

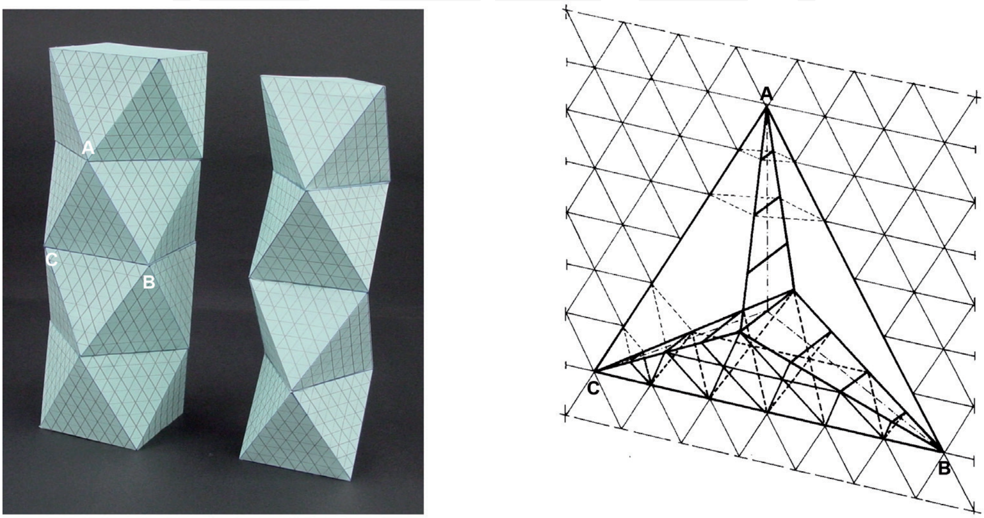


Ill. 2. Simple form of prismatic structure and its localisations into inner space of tall building

4. Star shapes of prismatic structures

The first of the proposed shapes for the prismatic structures is built my means of the space truss bands placed along the edges of a huge triangle. The basic form of the prismatic space structure may obtain various shapes of the huge triangular areas and they may be put, also in diversified manners in outer zones of the tall building. The proposed shape of the prismatic space structure can be placed onto every triangular side face of the forms of the buildings shown in Illustration 3 or it may be suitably arranged only for every second one of these triangular faces. The shape of the multi-storey building shown in Illustration 3a consists of vertically-orientated regular antiprisms with square bases and the shape presented in Illustration 3b is composed of regular antiprisms with triangular bases. This triangle can be the starting point for creating a gigantic prismatic space frame. Illustration 3c shows the basic shape of the huge prismatic structure. This shape consists of three tetrahedral solids, which are inscribed inside space bordered by outline form of e.g. the equilateral triangle. This can be described as a prismatic star-shaped structure. The general scheme of this form of prismatic space frame is presented in Illustration 3c, it is proposed for the design of tall buildings. Members are put onto all the faces of the prismatic structure which in this case creates triangular bar grids. The inner space of this gigantic module belongs to the inner space of the whole building. In these spaces, it is relatively easy to choose which areas are assigned to which functions with regard to the arrangement of additional evacuation routes. These areas can interpenetrate the space of the main building in the eliminated parts, what only in the limited degree can restrict the useful area of each floor [13]. With the example of this form of the prismatic space frame, it is easy to see that the resultant of the forces from its side faces will be concentrated along the side edges of this huge spatial structures.

a) b) c)

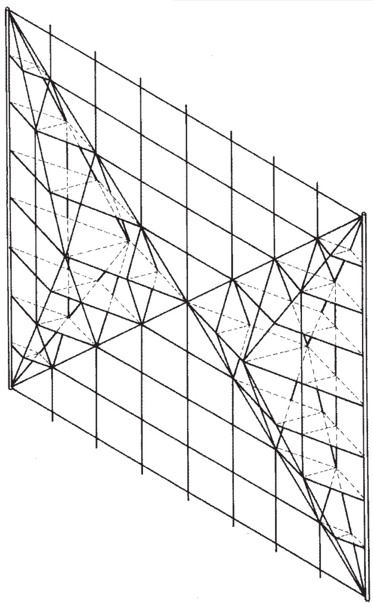


Ill. 3. Examples of shapes of tall buildings with triangular forms of façades together with example of the prismatic structure

The streams of forces are channelled along the designed lines which makes possible the simple and relatively easy transmission of force through the entire structural system.

The proposed form of the prismatic space frame is very rigid and has enough inner space in order to contain the installations necessary to arrange the alternative methods of evacuation in the chosen parts of the perimeter spaces of the building. For example, the staircases can be bound by means of translucent glass walls, which have to be fireproof and which may provide almost the unobstructed daylight to inner space of the floor. It may be that this form proves to be the best method to fulfil the requirements of a very safe and rigid structural system for high-rise buildings. The triangular forms of the prismatic space frames may be positioned in various manners to the facades of tall buildings. They can be installed for example, onto each of the triangular faces of the tall building forms shown in Illustration 3a or in Illustration 3b – a more economical option would be to position them suitably onto the every second of these faces.

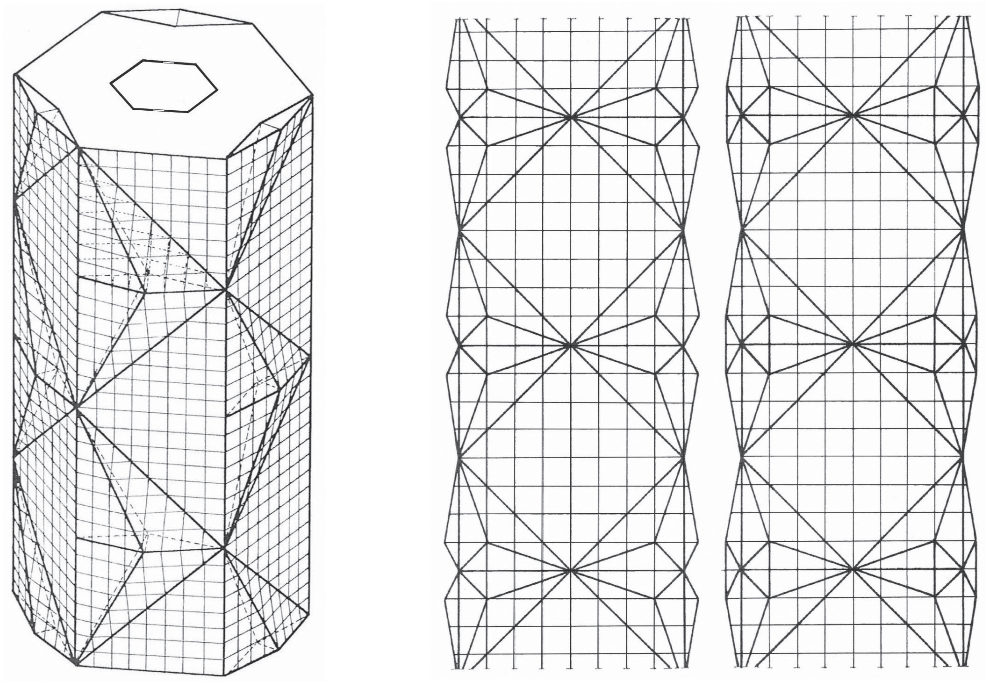
Another method of applying the proposed types of prismatic space frames into the structural systems of high-rise buildings is shown in Illustration 4. In this case, two prismatic frames are spaced between two main, corner columns of a high-rise building, they are opposite directed and joined in the central node, where two prismatic structures are connected together. In this way, a kind of the spatial girder of the structural system is built. A single unit of the star-shaped prismatic space frame can be arranged as previously on every second triangular field of the façade, see Illustration 5a. The basic form of the prismatic space frame can be adjusted to many various shapes. For instance, a single triangular form of the prismatic space frame can be located only in one of the corners of the basic square field of an elevation; the remaining three corners may be supplemented in the ways shown in Illustration 5b and in Illustration 5c, which show the only two examples of the architectonic views of the high-rise building façade possible to obtain by usage of this type of the proposed forms of the structural systems. The height of a single prismatic frame is in this particular case equal to the height of four floors.



Ill. 4. Double form of star-shape prismatic structure placed on vertical façade of tall buildings

Prismatic star-shaped structures can take various forms; one of these is the structural system which resembles the pattern of a simple vertical located truss with an X-shaped bracing system. The general concept of the structural system presents the model of the single spatial unit of it, see Ill. 6a. The height of the unit equals the height of several storeys. The structure is made by means of vertically arranging these units along every side of the building; in this way, an elongated version of the prismatic space frame is formed. In the middle, between the main columns, a simple vertical frame is located. It is the intention to arrange additional means of vertical transportation for the purpose of emergency evacuation in the vicinity

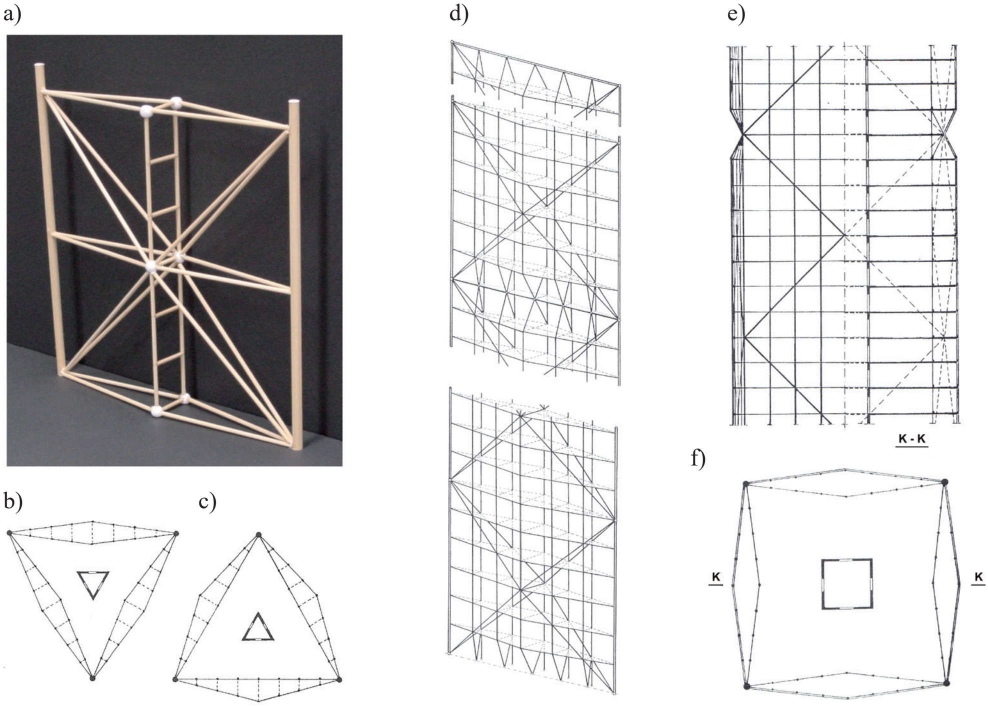
a) b) c)



Ill. 5. Proposals of arrangement of star-shape prismatic structures

of this frame. These facilities can be designed as foldable or retractable devices, for example, structures which may be hidden in the structures of floors. The spaces for these facilities can be separated by means of transparent glass walls and for everyday usage, they may serve as places of recreation. Striving to arrange there the alternative means of the vertical transportation, independent from space of the central core, is dictated by some reasons. One of the most important points is that the central areas of each side edge of the horizontal projection of the floors are usually the areas that are subjected to the smallest deformations of the structural system of the entire tall building.

In Illustration 6b and Illustration 6c, general schemes of two possible applications of the proposed solution are shown; the most basic and fundamental of these applications is shown in Illustration 6b, it is proposed that this design be applied to new buildings. The second scheme (see Illustration 6c) could be applied for the reinforcement of some types of tall buildings only on the condition that the structures of the floors would be able to take large magnitudes of horizontal forces which may appear in that structural system. This remark also refers to the structures of the floors in all the proposed systems, particularly in central areas of cross-bracing systems. The proper application of the proposed structure requires suitable arrangement of other component parts along the perimeter and the whole height of the tall building. Due to this arrangement, the system can be applied in the design of real buildings; however, the additional component parts make the structure somewhat complex.



Ill. 6. Another proposition of shape and possible application of star-shape prismatic structures

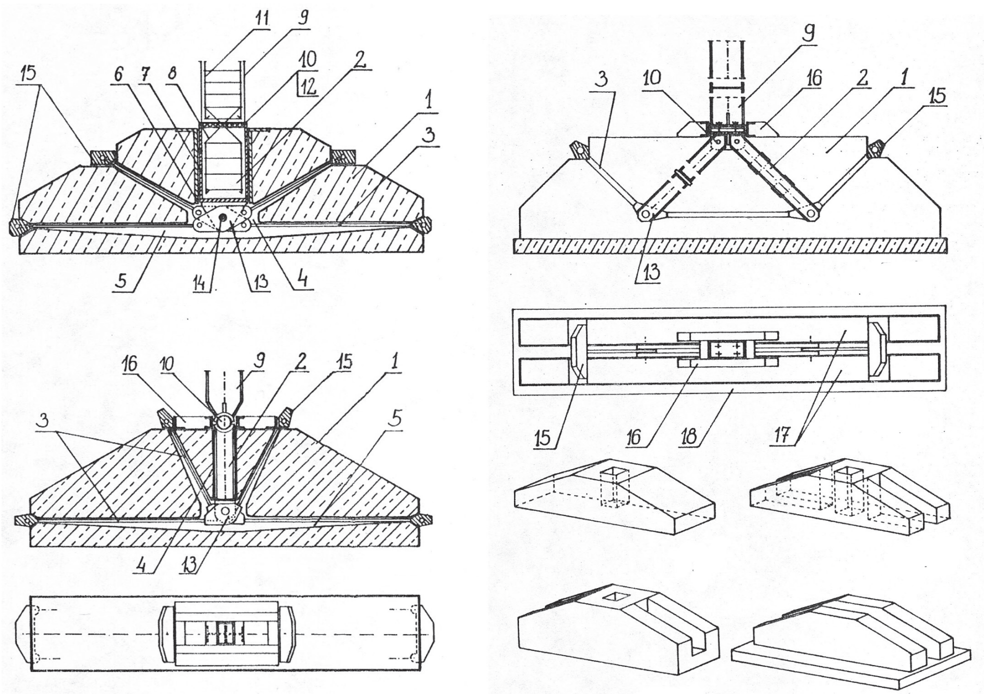
The necessity for the special arrangement of some areas of the system described above is caused by several factors such as the influence of the strains of the entire structure on the magnitudes of strains and forces appearing in its component parts. Thermal load, caused by the temperature differences between the outside and inner space of the building, is of importance to the structure of high-rise buildings. However, the most important factor in the case of this shape of support structure is the asymmetrical way of load of the intermediate columns, which are arranged between the main columns located in the corners areas of the tall building. The inner intermediate columns will be subjected to loads several times greater than the columns designed along the perimeter. In order to decrease the influence of all these elements on the levels of the strain values and on the force sizes acting on particular component parts of the whole system, it is proposed to the scheme which is presented in Illustration 6d. General schemes of an example form of a tall building designed with the incorporation of the proposed system are shown in Illustration 6e and in Illustration 6f. The entire structure is divided into some parts in the vertical direction. The height of a single segment is equal to, for example, the height of a set of three square units with an X-shaped bracing system. The two adjacent segments are connected together on levels where they have common nodes placed onto the central vertical plane of the elongated prismatic structure. Because the inner columns are subjected to greater loads than the perimeter columns, they run in the uninterrupted way to the foundation, being especially large along the perimeter of the building. The eccentric shape of the prismatic space structure causes increasing levels of force to act on the intermediate columns but it should allow to decrease values of force acting in many other component parts of the system, which may be caused by the bending of the whole building. It could be also a good enough technical solution regarding the influence of the thermal load. The huge X-shaped bracing system can also be located onto a single central and vertical plane of the prismatic structure, but in this case, it is necessary to arrange an additional system of short members in the chosen parts of its inner space in order to decrease buckling lengths of members creating the basic bracing system [17].

5. Required structural features of foundation systems

A safe and stable foundation structure is one of the crucial factors for all objects, including tall buildings. The significance of this statement is more crucial when the building is located on ground of a small carrying ability, for instance, in areas with mining damage or in areas subject to earthquakes. When the ground conditions are insufficient, the application of a lightweight support structure for high-rise building is advantageous, but on the other hand, lightweight structures are very sensitive to vibrations caused by wind loads or induced by earthquakes. It would be very favourable if the structural system was able to absorb energy caused by dynamic load and significantly reduce all vibrations. A satisfactory technical solution can be received by the suitable application of structural formula of the space structures. Two proposals for the solution of this complex problem are briefly presented below.

6. Basic form of combined foundations

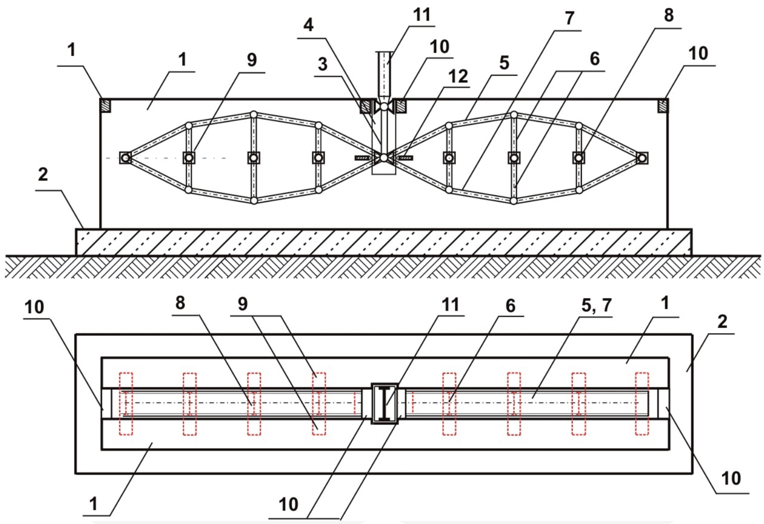
A large foundation surface area makes it possible to decrease the levels of stresses evoked by a heavy load. The tendency to increase the surface area of traditional foundation systems is restricted by the basic principles of the theory of structure. In order to significantly enlarge the foundation surface, the author decided to apply the formula of truss systems and later, the formula of space structures in the process of designing the foundation systems. Schemes of the first patented structural solution of combined foundations are presented together in Illustration 1 [18]. The point of structural concept of this system is to pre-stress long horizontal beams (1) by the own weight of the building transmitted by vertical columns (9) to the intermediate compression members (2), which transfer further the load forces to tension members (3) connected to the anchorage nodes (15). All the intermediate components are precisely arranged in the inner space of the designed foundation and their structure enables small strains independently to the deformation of the main beam elements (1) of the system. In other words, the intermediate component parts are suspended inside the space of the whole foundation and by means of the anchorage nodes, vertical force components are transmitted through the beam material to the ground, while horizontal components of these forces pre-stress the main beams. It is obvious that unobstructed small strains of component parts should be provided by their appropriate juxtaposition and by their stable, reliable and simple structure. There are several varied mutual arrangements and interconnections between components of other shapes within the basic structural configuration of the system.



Ill. 7. Examples of structural solutions defined in the first author's patent

7. Final structural configuration of combined foundation

The most important anchorage nodes of the basic form of the combined foundation are now placed in the extreme upper areas of the beams (1), where their displacements are the largest. Because the smallest dislocations are found in the neutral axis of a beam, the main nodes are distributed along the neutral axes of the main beams in the final structural solution of the combined foundation [19]. Moreover, these nodes have to be arranged uniformly along the possibly long beams. The structural concept of the final shape of the combined foundation system is presented in Illustration 8. The outer load force is transmitted to the two inner lenticular intermediate structures by means of a short strut, which has one degree of freedom of movement only along vertical guides, where it is precisely located. The uniform arrangement of the load forces is ensured by presence of a special intermediate structure, which consists of two sub-systems. The first sub-system consists of set of the rigid tension members located along the broken line of convexity directed up. Suitable nodes of this system are connected with the main foundation nodes by means of short vertical compression members. These main nodes are uniformly distributed along the neutral axes of the main beams (1). The second sub-system has a very similar form but the broken line having convexity directed down. If patterns of both sub-systems are symmetrical placed towards the neutral axis of the beam, the horizontal components of the reactions in the



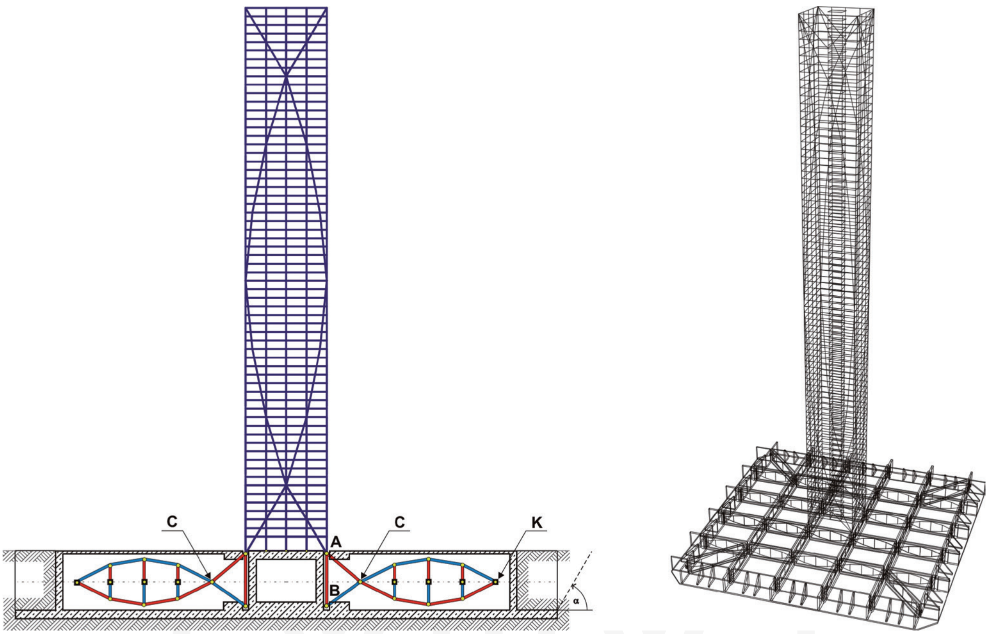
Ill. 8. Shape of one of the possible technical solutions defined in the second author's patent

extreme nodes are of the same value but they are directed in the opposite manner. Therefore, in the final shape of this structural system, only the vertical components of the reactions are applied to the main nodes (9) of the system. The shape presented in Illustration 8 consists of two lenticular modular units of the combined foundation. These units can be multiplied in various ways within the space of the designed foundation – this indicates that the surface of this type of foundation system is theoretically unlimited, which further implies that the very heavily loaded building can be located on subsoil with an extremely small load capacity.

8. Example of the application of a combined foundation

The effective length of the lenticular units of the foundation structure can be slightly enlarged by the application of a triangular set (ABC) presented in Illustration 9a. In this case, nodes of the type represented by node C have to be disconnected to the matter of the main beams – this is a key requirement of this technical solution. The number of instances of replication of the lenticular units in both directions is optional – this means that the horizontal surface of the foundation system is also optional, see Illustration 9b. When a multi-storey building is supported on the proposed type of foundation and a suitable type of the lenticular girder (see Illustration 9) is applied inside its aboveground structure, then the whole bearing structure is referred to as the combined structural system of the tall building [20–22]. In the boundary nodes of the combined foundation (K), are acting the vertical reactions having big values, which reactions are directed down, what is considered as disadvantageous of such forces. In order to stabilise these zones, it is proposed to form a kind of scoop, which is shaped by help of a suitable connection of the beam endings with the base slab.

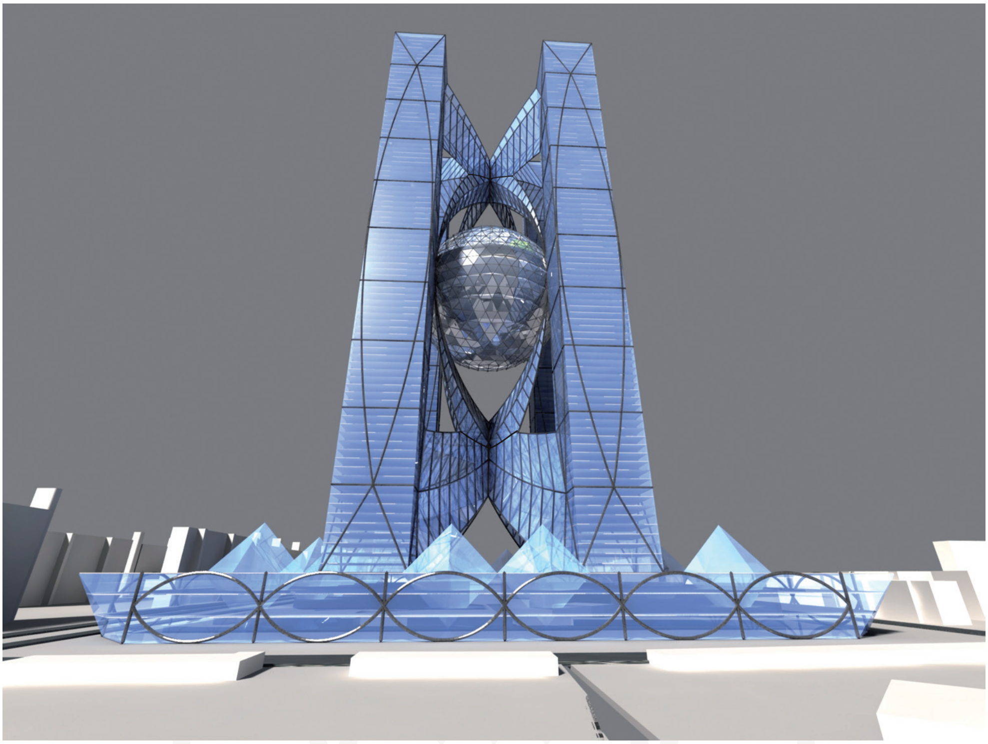
a) b)



Ill. 9. Scheme of vertical cross-section and general view of combined structural system of a tall building

As a result of this shaping, a certain part of the ground placed in the soil wedge would press down on this area of the foundation structure. Moreover, additional anchor piles can be placed directly underneath the boundary nodes. There are some other structural solutions to this problem. Due to the appropriate arrangement of components in the space of the proposed combined system, it is able to absorb a part of the energy vibration induced by dynamic loads. This ability can be enhanced by special technical devices such as electronically controlled hydraulic jacks purposely designed as integral parts of the intermediate foundation structure.

The proposed combined structural system was applied in the design of the building complex of GeoDome Sky Towers, see Illustration 10 [23]. The complex is situated in a typical urban area. It consists of four tower buildings which are rectangular prisms containing eighty storeys each. These towers have a square form of base projection and side lengths of thirty-six meters. These towers, each with a total height of around 382 meters, are put on a common broad base designed according to the rules of combined foundation, inner space of which contains three technical storeys The main four towers are connected by means of specific spatial structures in the form of huge arches running from halfway up the tower to suitably selected lower and upper parts of these towers. Moreover, these four main buildings are connected together by means of a central building having the form of a geodesic sphere which joints each tower halfway up.



Ill. 10. Perspective view of the GeoDome Sky Towers

9. Conclusions

The structural formula of space structures can be successfully applied in the process of designing tall building systems including those of their foundations. All the proposed types of the structural systems should be subjected to many comprehensive analyses in order to evaluate their practical suitability. The high-rise buildings, due to the application of the proposed structural system, can provide interesting and unique architectonic views.

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