SHAPING OF STRUCTURAL SYSTEMS OF HIGH-RISE BUILDINGS

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Abstract: *Design of an efficient and suitably rigid support structure of a tall building is constantly a challenge for architects and engineers. Recently this challenge is enormously increased by the safety requirements conditioned by numerous emergency reasons. Among others one should mention here about effects of fire or a terrorist attack. The complex forms of structural systems have to be examined in many ways. Comprehensive analyses of these systems are carried out by application of suitable numerical models of these systems. The paper contains examples of shapes of structural systems proposed by the author together with definitions of their numerical models prepared in the programming language Formian.*

INTRODUCTION

The shaping of the structural systems for the high-rise buildings belongs to the two main streams of the research activity of the author [3-11]. The terrorist attack against USA in September 11th, 2001 and the collapse of the twins of the WTC in New York have caused the new perception of the form and the tasks of the tall building structures. The stiffness of a high-rise building structure is one of the crucial criteria for an estimation of a chosen system as the main support structure for that kind of the building. Various forms of space frames are of very rigid spatial rigidity. Certain types of space frames are for years proposed in the design of the tall buildings. Some of presented here have their counterparts in the systems proposed for or already used in the real tall building structures. Several of them are unique and they have not their counterparts in the forms of these structural systems. The main goal in the presented processes of shaping of them was the endeavour to give to the structure the possible great rigidity by means of relatively simple means. At the same time it was aimed to make possible the evacuation of the people, in cases of emergency, not only by the vertical transportation means, which are usually located only in the central cores of these tall buildings. The proposed structural systems should be very resist all the maximum values of the horizontal, vertical, thermal and earthquake loads. They could be designed as the steel systems, the reinforced concrete systems or the compound systems for the designed high-rise buildings. The paper presents the brief description several of chosen forms structural systems proposed by the author and numerical models of them defined in programming language Formian [2].

SYSTEM OF CIRCUMFERENTIAL VERTICAL SPACE FRAME

Certain types of the space frames, due to their inner build, can be applied as the habitable mega-structures [1]. The diagonal-orthogonal space structure, called in the author's papers by abbreviation as the {D – O} space frame [3, 4], and its double form called as 2x{D – O}A structure, belong to this group of space frames, which can be adopted to many useful purposes. The both forms of space frames have a comparatively great capacity of the arrangement of the necessary habitable functions inside them. Moreover they have enough spatial rigidity, which could be increased by means of small number of additional members located in the crucial areas of the designed structural system. These additional parts of a system may be placed inside them in the manner that they will do not bring serious obstacles about the useful area of each floor of a multi-storey building. Therefore the form of {D – O}space frame is taken as the basis of transformations made in order to shape new forms of the structural systems for high-rise buildings. The proposed form of the building system can be composed of vertically and horizontally located layers of this type of space frame, see Figure 1.

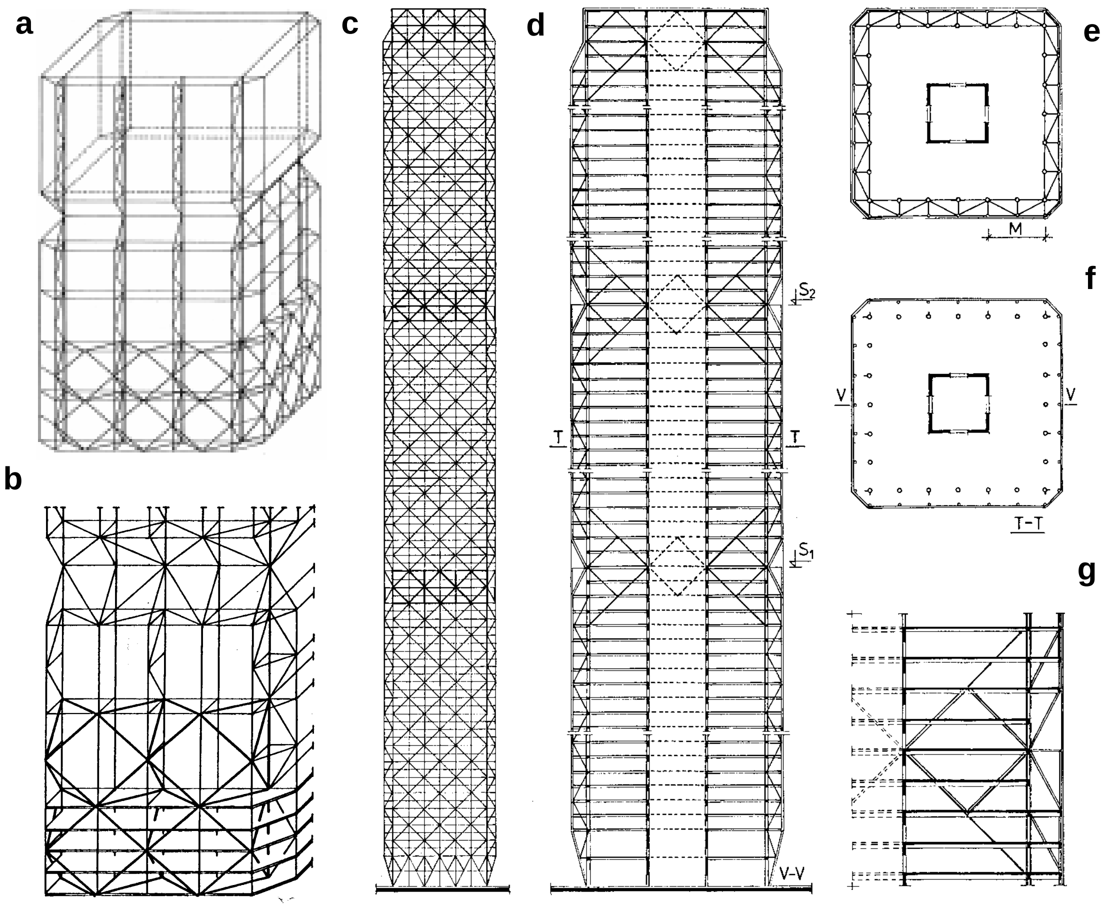

Figure 1. General schemes of the structural system of a tall building having the perimeter support structure of the form of vertically positioned {D –O} space frame, a) overall view of localization of two segments of a circumferential structure, b) detail of arrangement of sets of typical storeys, c) elevation, d) the main vertical cross-section, e) horizontal cross-section of the main structure, f) horizontal cross-section on level of the typical storey, g) vertical cross-section of a boundary area between two vertical segments

The considered form of a double-layer space frame is proposed as the main vertical support structure of a multi-storey building, see Figure 1a. The orthogonal grid of the structure is placed on the same vertical surface of the perimeter located horizontal beams and the main vertical columns of the building. The vertically positioned space frame is arranged around the perimeter of a tall building and it is of the height of a certain number of typical storeys. In this manner is shaped a single perimeter segment of the main support structure. Inside the space of the building one could arrange inner columns and a central vertical core. The core can be a part of the building structural system, which usually contains the means of vertical transportation and other technical equipment. The entire tall building system is composed of a few segments of the circumferential structure. These segments are located vertically each on other. The division of the whole system of the circumferential structure into several segments is motivated by the endeavour to decrease an impact of strains of single segments on strains of the segments adjacent to this one. Between two segments is horizontally located double form of {D – O}space frame, called 2x{D –O}A space structure [3, 8]. It plays the role of a horizontal disc of the entire system. Spaces of these triple-layer forms of space frames are devoted for needs of technical storeys of the building.

The unit M of the example shape of the {D –O} space frame equals in this case the height of four typical storeys, see Figure 1b and Figure 1e. The structural elements, in the outer layer of the circumferential space frame, do not create a continuous form of a grid but the curtain wall may run in the straight vertical lines due to the arrangement of additional secondary components. These additional elements should be suitable placed along the perimeter and around all the intermediate horizontal discs, see Figure 1g.

Chosen vertical parts of the perimeter circumferential structure could be distinguished and separated from the main space of the building by means of walls made of special glass and these spaces can be devoted as additional staircases or means of vertical transport in emergency cases. The example form of that kind of the building is composed of three segments, see Figures 1c-g. These particular segments are vertically located each on other and the height of them is equal respectively, from the top to the ground level, to the 38, 36 and again 36 storeys. Therefore the entire building is of the height of 110 storeys. Between two neighbouring segments are designed horizontal discs having the forms of the 2x{D –O}A space structure. Their spaces will be devoted for the needs of the technical storeys. In the perimeter zones of the storeys, located close to these technical storeys, are arranged additional skew members, see Figure 1g. Their presents will somewhat disturb in the usage of the full area of those storeys but they are located there in order to increase the rigidity of the whole system. The curtain walls will be displayed around the outer perimeter of the vertically located segments of the {D –O} space frame. They may run in the straight lines along of almost all the height of the building without distinguish the borders between two segments. It will be possible in case of designing of additional structural members in the areas of their mutual connection. These members can be located onto and below the level of the middle layer of the 2x{D –O}A space frame, see also Figure 1g., being the structure of the horizontal discs of that system.

For this type of the tall building and its perimeter space structure it was prepared Program 61, published below, written in the programming language Formian, which defines the numerical model of this spatial configuration, but restricted only to the two vertical segments. It was done in order to obtain a relatively clear picture of the system composed in this case of a very large number of the components. Particular stages of this program are illustrated in successive parts of Figure 2.

Program 61

01. m=3;(*)Number of modules in the horizontal direction(*)
02. n=6;(*)Number of modules in the vertical direction(*)
03. k=2;(*)Number of vertical segments(*)
04. K1={[0,0,0;0,-1,1],[0,0,0;1,-1,0],[0,-1,1;1,-1,0]};
05. KM=lamis(1,1)|lamis(1,1)|K1;
06. SD={[0,0,0;2,0,0],[0,0,2;2,0,2],[0,0,0;0,0,2],[2,0,0;2,0,2]};
07. mod1=KM#SD;
08. scian1=rinis(m,n,2,2)|mod1;
09. P1={[0,-1,1;0,-1,3]};
10. PP=rin(3,n-1,2)|P1;

11. P2=lam(1,m)|PP;
12. PH=lam(3,n)|rin(1,m-1,2)|[1,-1,0;3,-1,0];
13. TST={[0,-1,0;1,-1,0],[0,-1,0;0,-1,1],[0,-1,0;0,0,0]};
14. naroza=lam(3,n)|lam(1,m)|TST;

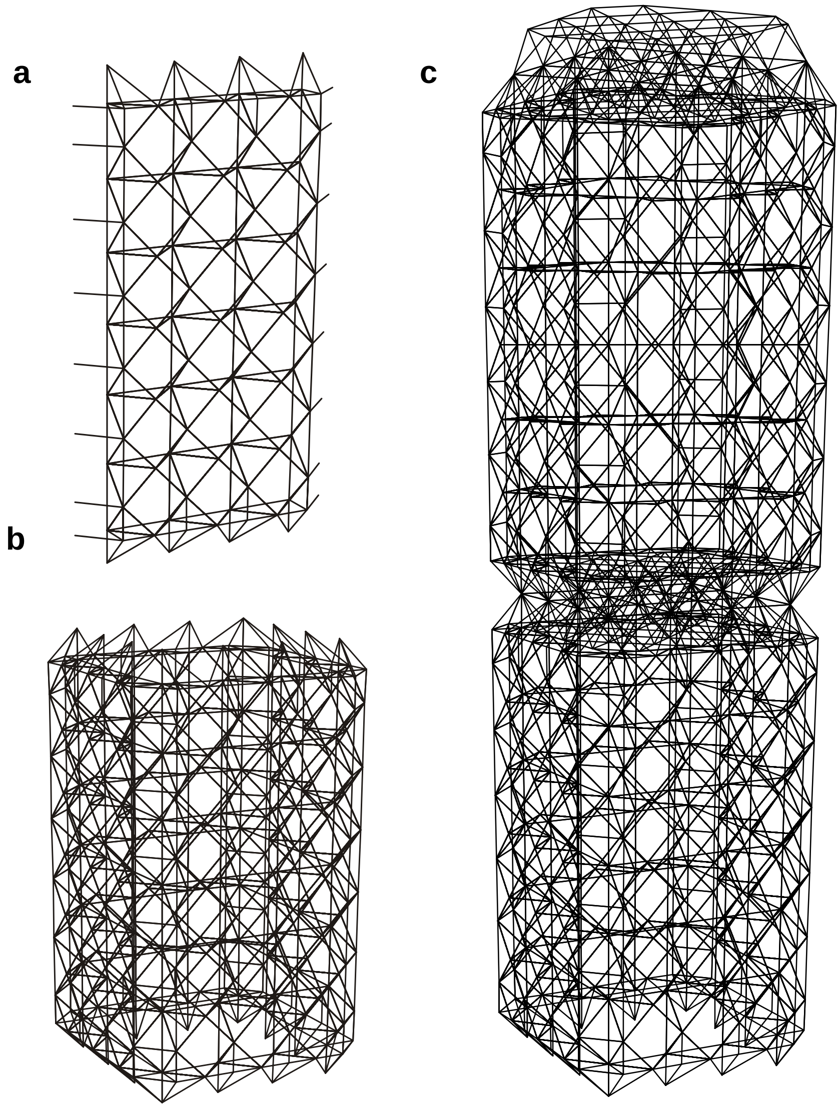

Figure 2. Visualization of the execution of the Program 61

15. prukosn1=lam(1,m)|rin(3,2,2*n)|[-1,0,0;0,-1,0];
16. prukosp2=lam(1,m)|rin(3,n,2)|[-1,0,1;0,-1,1];
17. scian2= P2#scian1#PH#naroza#prukosn1#prukosp2;
18. PD1={[0,0,0;0,0,-1],[0,0,-1;0,-1,0],[0,-1,1;0,-1,0]};
19. DDpr=lam(3,n)|rin(1,m+1,2)|PD1;
20. ddkrz=lam(3,n)|rin(1,m,2)|{[1,-1,0;0,0,-1],[1,-1,0;2,0,-1]};
21. goscian=rin(3,1,1)|scian2#DDpr#ddkrz;(*)Single façade, see Figure 2a(*)
22. segm1=rosad(m,m)|goscian;(*)First, the lower segment, see Figure 2b(*)
23. strnosn1=rin(3,k,2*n+2)|segm1;(*)All vertical segments(*)

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24. P={[0,0,0;2,0,0],[0,0,0;0,1,1],[0,0,0;1,0,1],[0,1,1;1,0,1]};
25. PM=rosad(1,1,4,-90)|P;
26. SDO=rinid(m,m,2,2)|PM;
27. StrDO=pex|SDO;
28. pradd1=[1,0,1;3,0,1];
29. p1=rinid(m-1,2,2,m*2)|pradd1;
30. p2=rinid(2,m-1,m*2,2)|[0,3,1;0,1,1];
31. s1=StrDO#P1#p2;
32. str2=lam(3,0)|s1;(*)Single horizontal disc(*)
33. str2obn=tran(3,-1)|str2;(*)Horizontal disc on ground level(*)
34. przepon1=tran(3,2*n+2)|str2obn;(*)Single horizontal disc on requested position(*)
35. przepwsz=rin(3,k,2*n+2)|przepon1;(*)All horizontal discs(*)
36. Building=przepwsz# strnosn1;
37. use &,vm(2),vt(2),lw(0.1),vh(-20,-50,7,0,0,0,0,0,1);
38. draw Building;(*)see Figure 2c(*)
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This program defines a numerical model only for the circumferential support structure of this example shape of the tall building system. The commend placed in the row number 21 determines localization of the basic form of the space frame onto the vertical surface. The form of a single segment of the circumferential structure is finally determined in the row number 22. The whole shape of the considered structural system is defined in row number 36. The Formian's program determines this structural shape can be of more concise form than Program 61 but in this one presented here one can easy notice each particular and important stage of the process of preparing of a numerical model.

SYSTEM OF FRAMED POLYHEDRON

The typical form of the framed tube system consists of vertical columns and horizontal beams located onto the surfaces of each façade of a tall building. The columns and beams create together an orthogonal grid of the main support structure of the building. The height of a single storey usually equals the distance between two nearest horizontal beams of that kind of the perimeter structure. The rigidity of the entire system is mainly the resultant of the rigidity of all connections of theses component parts in the suitable designed and produced nodes of that type of the frame grid. These type of connections and nodes are usually expensive and relatively difficult to made on the building site. The great spatial rigidity of the multi-storey building may be obtained by application of the proposed structural system called framed polyhedron, see Figure 3, [8, 10, 11].

The triangular form of a bar grid is the best pattern of the most rigid form of flat grid of struts. If this grid is placed onto suitable side faces of a polyhedral form of building the spatial stiffness of such structural system could be really very big. It would be advantageous if the polyhedron will have side faces in form of triangles. Figure 2a shows general form of a building composed of two elongated, vertically positioned and suitably transformed shape of the square anti-prisms. Particular part of this form has then form of elongated half of a cubooctahedron. The half of its side faces is perpendicular to the horizontal level. The density of the subdivisions of its skew faces is twice lower than the density of triangular grid of structural members placed onto the perpendicular faces. The functional reasons indicate that this form of structural system could be acceptable for design of the high-rise building. In this case the main perimeter support structure takes the form of triangular frames placed on each side face of building façade. This type of bar grid does not require the application of exactly rigid nodes. The height of a single storey is in this system only a part of the distance between two successive horizontal beams of the perimeter triangular grid. The single cubooctahedron part of that building is divided into nine basic units along the vertical direction. The height of each of them is the same. Almost all of these units have the height of six typical storeys except the first one, located close to the foundation. Because the first storey, at the ground level, is usually of considerably greater height than the height of others that is why the lowest basic unit has only five storeys. Therefore the building presented in Figure 2a is of the height of 107 storeys. The total height, given in meters, will depend on the height of a single storey. The same number of storeys has the building, general schemes of which are shown in Figure 2b, but it is of more complex form obtained on the basis of the shape of the previous one. In the both cases the inner core can participate in the force transmission and it will contain the means of the vertical transportation together with other technical equipment being the necessary for that type of building. This form was obtained by means of the applications and the additions of the tetrahedron modules, which are directed down and have the suitably face subdivisions and the arrangement of each corner of the basic form, compare Figure 2a. The density of the subdivision of these faces, being the common parts for the both types of solid units, should be of the less degree than the basic forms because of the useful reasons. The general schemes of the horizontal cross sections of the proposed form of the high-rise building are presented in Figure 2.c – Figure 2f.

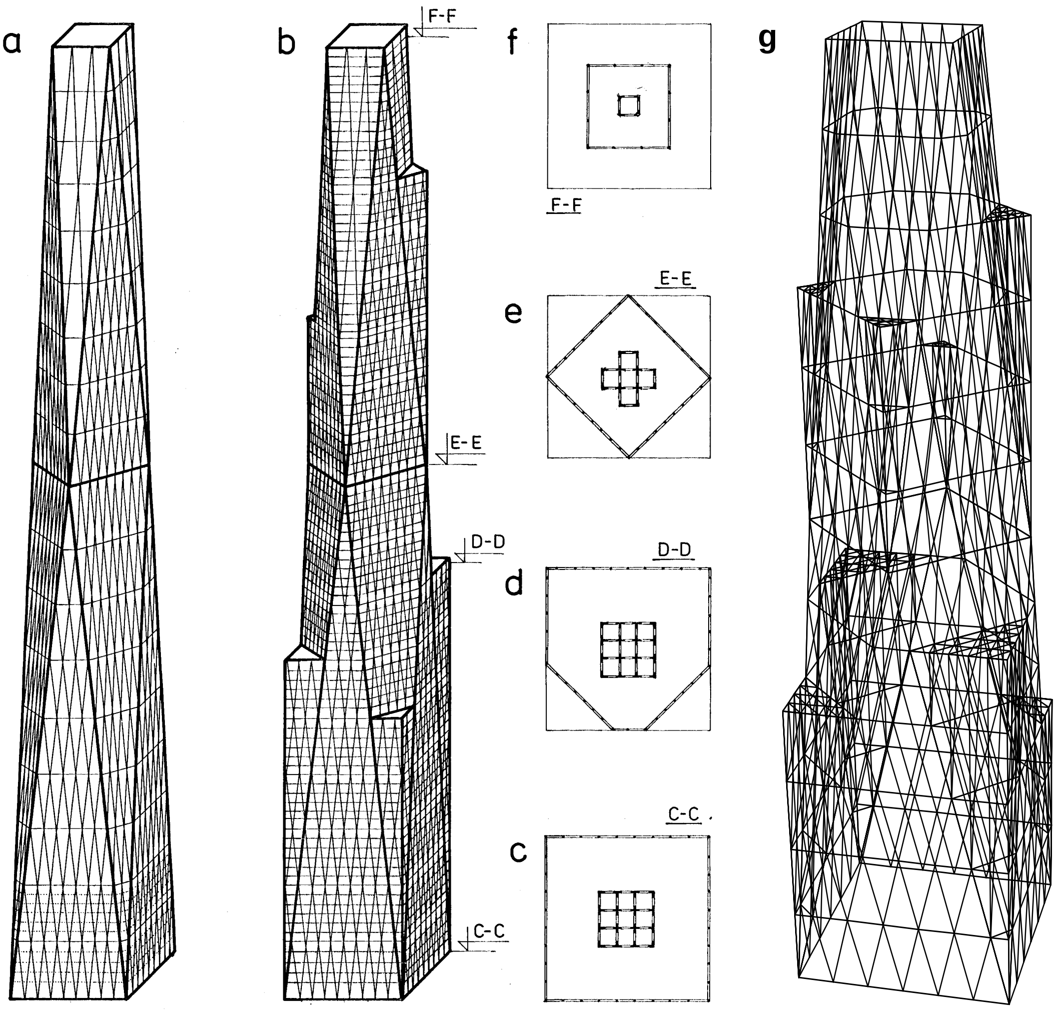

Figure 3. General schemes of exemplary forms of tall buildings designed by means of structural system called framed polyhedron

Numerical model of this complex type of structural system in the form of framed polyhedron was determined by means of Formian's program called Program62, which full version is presented below. The pattern obtained as a result of this program on a screen of computer is shown in Figure 3g.

Pogram62
01. m=6; (*)Density of triangular grid onto main triangular faces or walls(*)
02. w=4; (*)Density of triangular grid onto chosen triangular faces of the small corner segments(*)
03. w1d=4;w2d=5;w3d=3;w4d=5; (*)Density of triangular grids onto upper small triangular faces(*)
04. w1g=3;w2g=4;w3g=2;w4g=3; (*)Density of triangular grids onto lower small triangular faces(*)

05. EM13={[0,0,0;2,0,0],[0,0,0;1,0,1],[1,0,1;2,0,0]};
06. s3=3.48; (*)Geometric coefficient of vertical elongation(*)
07. SPP1=genis(m,m,2,1,1,-1)|EM13;
08. EM12={[0,0,0;0,1,0],[0,0,0;1,0,0],[0,1,0;1,0,0]};
09. SP=genid(m,m,1,1,0,-1)|EM12;
10. SW1=pos(3,[0,0,0;m,0,m;0,m,m],[0,0,0;m,0,0;0,m,0])|SP;
11. XMP=SW1#SPP1;
12. ModPod=rosad(0,0)|tranad(0,0,-m,-m)|XMP;
13. SX1={[0,0,0;0,1,0],[0,0,0;1,0,0],[0,1,0;1,0,0]};
14. SAP1d=genid(w1d,w1d,1,1,0,-1)|SX1;
15. SBP1d=pos(3,[0,0,0;0,m,0;0,0,-m],[0,0,0;0,m,0;m,0,0])|SAP1d;SCP1d=pos(3,[0,0,0;0,m,0;0,0,-m],[0,0,0;0,0,-m;m,0,0])|SAP1d;
16. EN11=SAP1d#SBP1d#SCP1d;
17. EN1d=tranad(0,0,-m,-m)|tran(3,w1d)|EN11;
18. SAP2d=genid(w2d,w2d,1,1,0,-1)|SX1;
19. SBP2d=pos(3,[0,0,0;0,m,0;0,0,-m],[0,0,0;0,m,0;m,0,0])|SAP2d;
20. SCP2d=pos(3,[0,0,0;0,m,0;0,0,-m],[0,0,0;0,0,-m;m,0,0])|SAP2d;
21. EN12=SAP2d#SBP2d#SCP2d;
22. EN2d=verad(0,0)|tranad(0,0,-m,-m)|tran(3,w2d)|EN12;
23. SAP3d=genid(w3d,w3d,1,1,0,-1)|SX1;
24. SBP3d=pos(3,[0,0,0;0,m,0;0,0,-m],[0,0,0;0,m,0;m,0,0])|SAP3d;
25. SCP3d=pos(3,[0,0,0;0,m,0;0,0,-m],[0,0,0;0,0,-m;m,0,0])|SAP3d;
26. EN13=SAP3d#SBP3d#SCP3d;
27. EN3d=verad(0,0,180)|tranad(0,0,-m,-m)|tran(3,w3d)|EN13;
28. SAP4d=genid(w4d,w4d,1,1,0,-1)|SX1;
29. SBP4d=pos(3,[0,0,0;0,m,0;0,0,-m],[0,0,0;0,m,0;m,0,0])|SAP4d;
30. SCP4d=pos(3,[0,0,0;0,m,0;0,0,-m],[0,0,0;0,0,-m;m,0,0])|SAP4d;
31. EN14=SAP4d#SBP4d#SCP4d;
32. EN4d=verad(0,0,270)|tranad(0,0,-m,-m)|tran(3,w4d)|EN14;
33. Dol1=ModPod#EN1d#EN2d#EN3d#EN4d;
34. Mdol1=bt(1,1,s3)|Dol1;
35. s2=0.5*sqrt|2; (*)Geometric coefficient (*)
36. s1=0.5*sqrt|2; (*)Geometric coefficient (*)
37. ModGrP=tranix(0,0,0)|verax(0,0,0,0,1,45)|bt(s1,s2,s3)|ModPod;
38. SAP1g=genid(w1g,w1g,1,1,0,-1)|SX1;
39. SBP1g=pos(3,[0,0,0;0,m,0;0,0,-m],[0,0,0;0,m,0;m,0,0])|SAP1g;
40. SCP1g=pos(3,[0,0,0;0,m,0;0,0,-m],[0,0,0;0,0,-m;m,0,0])|SAP1g;
41. EN21=SAP1g#SBP1g#SCP1g;
42. EN1g=tranad(0,0,-m,-m)|tran(3,w1g)|EN21;
43. SAP2g=genid(w2g,w2g,1,1,0,-1)|SX1;
44. SBP2g=pos(3,[0,0,0;0,m,0;0,0,-m],[0,0,0;0,m,0;m,0,0])|SAP2g;
45. SCP2g=pos(3,[0,0,0;0,m,0;0,0,-m],[0,0,0;0,0,-m;m,0,0])|SAP2g;
46. EN22=SAP2g#SBP2g#SCP2g;
47. EN2g=verad(0,0)|tranad(0,0,-m,-m)|tran(3,w2g)|EN22;
48. SAP3g=genid(w3g,w3g,1,1,0,-1)|SX1;
49. SBP3g=pos(3,[0,0,0;0,m,0;0,0,-m],[0,0,0;0,m,0;m,0,0])|SAP3g;
50. SCP3g=pos(3,[0,0,0;0,m,0;0,0,-m],[0,0,0;0,0,-m;m,0,0])|SAP3g;
51. EN23=SAP3g#SBP3g#SCP3g;
52. EN3g=verad(0,0,180)|tranad(0,0,-m,-m)|tran(3,w3g)|EN23;
53. SAP4g=genid(w4g,w4g,1,1,0,-1)|SX1;
54. SBP4g=pos(3,[0,0,0;0,m,0;0,0,-m],[0,0,0;0,m,0;m,0,0])|SAP4g;
55. SCP4g=pos(3,[0,0,0;0,m,0;0,0,-m],[0,0,0;0,0,-m;m,0,0])|SAP4g;
56. EN24=SAP4g#SBP4g#SCP4g;
57. EN4g=verad(0,0,270)|tranad(0,0,-m,-m)|tran(3,w4g)|EN24;
58. MOGP=ModPod#EN1g#EN2g#EN3g#En4g;

59. MGrP=tranix(0,0,0)|verax(0,0,0,0,0,1,45)|bt(s1,s2,s3)|MOGP;
60. GoraG=tranix(0,0,m*s3)|MGrP;
61. Budynek2= Mdol1#GoraG;
62. use &,vm(2),vt(2),c(1,1),lw(0.25),vh(24,-88,52,5,5,0,5,5,5);
63. draw Budynek2; (*) See Figure 2g(*)

In this place one should mention that to put numbering of rows in the real Formian's program is forbidden. In this particular case thee numbers serve to recognize important segments of this program. One should also remember that each program has to be started and finished by sign " <> " and it is advisable to put commend " clear " before commend " draw ".

EXAMPLE SHAPE OF PRISMATIC STRUCTURE SYSTEM

Specific group of proposed systems is presented here on example of so called star-shaped prismatic structure. General schemes of that form of the prismatic space frame as the main component part of the structural system proposed for the design of tall buildings are shown in Figure 4. This form is intended to focus main streams of forces along primary chosen direction. Because triangular bar grid has previously mentioned advantageous features therefore for the designed structure it was assumed generally a form of triangle and it would be inscribed most often in triangular patterns, see Figure 4a, appearing on walls of such a building. The basic shape of the prismatic structure is built my means of the space truss bands placed along the edges of a huge triangle. This triangle, as itself, can be the starting form for the creating a gigantic prismatic space frame of the height of many building storeys. Onto all the faces of the prismatic structure are put members, which in this case create also triangular bar grids, see Figure 4b. The inner space of this gigantic module will belong to the inner space of the whole building. In these spaces it is relatively easy to choose areas assigned for needs of the arrangement of the additional evacuation ways. These areas can interpenetrate the space of the main building in the eliminated parts, what may only in the limited degree restrict the useful area of each floor.

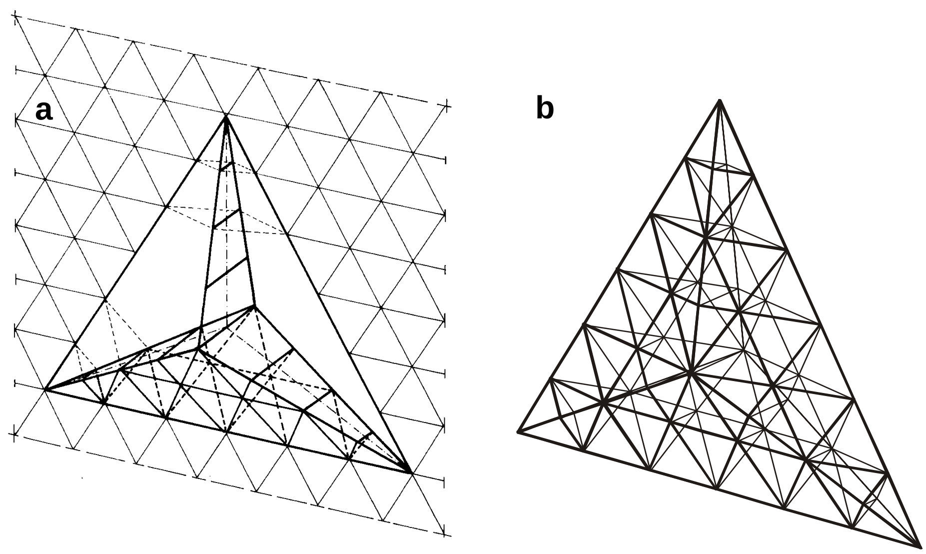

Figure 4. General views of example form of star-shaped prismatic structure

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 onto the tall building facades. The proposed shape of the prismatic space structure can be placed onto the every triangular side faces of the forms of the buildings shown in Figure 5 or it may be suitably arranged only on the every second of these triangular faces. The shape of the multi-storey building, shown in Figure 5a, consists of the vertically located regular anti-prisms of the square bases and the shape presented in Figure 5b is composed of the regular anti-prisms of the triangular bases. On the example of the this form of the prismatic space frame it is easy to notice that the resultants of the forces from its side faces will focus along the side edges of this huge spatial structures. The streams of forces will be directed along the designed lines, being edges of such a polyhedron, what will make possible the simple and relatively easy ways of the force transmissions in the entire structural system. The proposed form of the prismatic space frame is very rigid and it has enough inner space in order to contain the installations necessary to arrange the alternative ways of the evacuation in chosen parts of the perimeter spaces of the building. These e.g. staircases can be bounded by means of translucent glass walls, which may be fireproof and which may allow almost the unobstructed daylight of the inner floor. It can be expected that this form could in the very good way fulfill the requirements of the very safe and rigid structural system for the high-rise buildings. The structural system called framed polyhedron can be initially considered as an efficient technical solution application of which could moreover make possible to give to the designed high-rise building an interesting and an individual architectonic view.

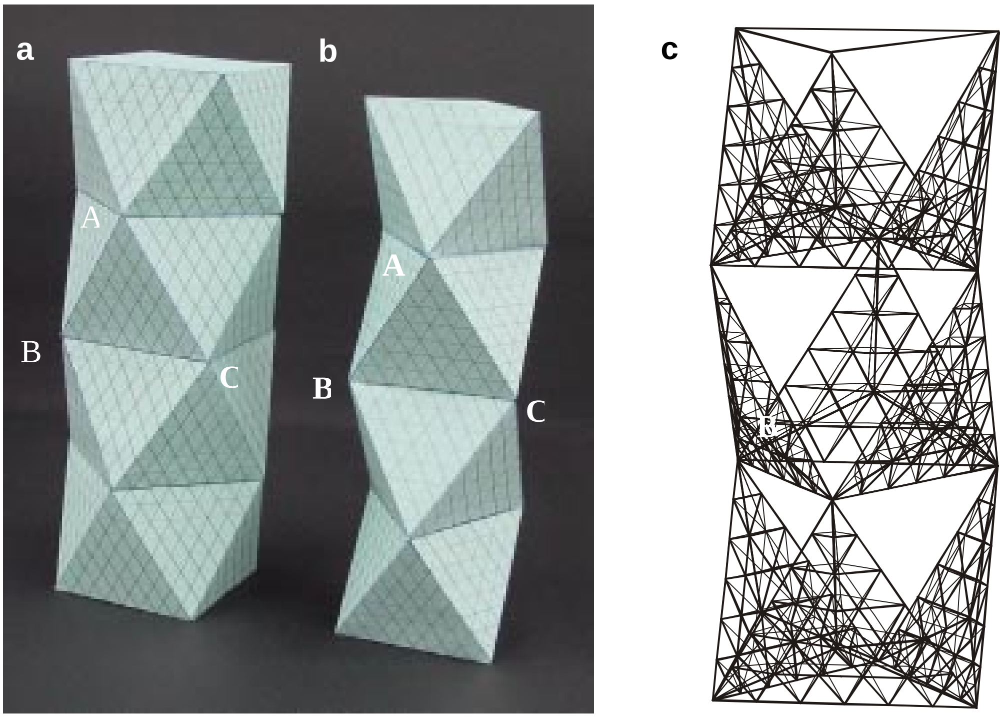

Figure 5. Examples of forms a tall building and application of a prismatic structure

Figure 5c presents a general view of an example of a proposed building system composed of the star-shaped prismatic structures suitably arranged on every second side face of the regular anti-prisms of the triangular bases The structural configuration, shown in this figure, is described by means of an appropriate Formian's program, which defines numerical model of the structure. In this program the prismatic structures are determined only in the half number of triangular side faces of such a form of a tall building. Because this particular Formian's program is somewhat complex and large that is why it is not presented here. The chosen forms of prismatic structures can be located on each triangular face of an assumed polyhedron or they can be arranged in suitable ways onto surfaces of the designed shapes of high-rise buildings [10, 11].

CLOSING REMARKS

Forms of structural systems proposed for tall buildings are obtained as suitable transformations of appropriate types of spatial structures. These systems may testify the great develop potential of structural formula of spatial structures and in this particular case of space frames. The high-rise buildings, due to the application of the proposed structural system, could be of the great space rigidity, their safety in emergency cases could be much greater than systems applied nowadays. Some forms of these structures can be subjected to further transformations undertaken in order to design spatial systems, which could successively take huge dynamic load caused by earthquakes. Buildings build by application of proposed structural systems can obtain the interesting and the individual architectonic views.

All the proposed types of the tall building structural systems should be subjected to many comprehensive analyses in order to estimate their practical suitability to the designed purposes. Numerical models of these structures, prepared in particular in programming language Formian, will be basis for these analyses and their application will enable the choice of the optimal technical solution for a given project of a high-rise building.

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