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STAGES AND ARCHITECTURAL STYLES IN DESIGN AND BUILDING OF SHELLS AND SHELL STRUCTURES

Abstract. *In a paper, architectural styles, constructive solutions, information on the history of appearance of structural building materials are briefly set forth and the stages of passion of thin-walled space large-span erections are analyzed. Particular attention is given to establishment of the exact dates in the chronology of appearance of styles, constructive solutions, and in the dates of erection of the first shells of corresponding styles and their authors. Elicit reasons of destructions of some well-known space structures are described and the influence of these destructions and damages for the subsequent designing and building of analogous type is analyzed. It is adduced, in general, positive views of noted architects on the role of shell structures in industrial, public, and civil building at present time. On the basis of the manuscripts published in specialized editions, varieties of points of view of architects to designing space structures are characterized. It was shown that interest of designers and architects in designing of shells in the form of analytically non-given surfaces, polyhedrons, and hipped plate structures is intensively extending. At present, bar metal architecture obtained subsequent development and came to be competitor for reinforcement concrete. In the XXI century, steel net and structural shells are the main means of forming vanguard buildings. Now, architects and structural engineers have wide potential in the selection of form, building material, methods of strength analysis, constructive solutions, styles, and examples of application of large-span thin-walled shell structures. All conclusions of the present work are corroborated by the results of researches containing in 54 references.*

Keywords: *large-span spatial erection, shell, grid system, architectural style, structural building materials, analytical surfaces in architecture, chronology of architectural styles.*

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ЭТАПЫ И АРХИТЕКТУРНЫЕ СТИЛИ В ПРОЕКТИРОВАНИИ И СТРОИТЕЛЬСТВЕ ОБОЛОЧЕК И ОБОЛОЧЕЧНЫХ КОНСТРУКЦИЙ

Аннотация. *В статье кратко изложены архитектурные стили, конструктивные решения, сведения об истории появления конструкционных строительных материалов и проанализированы этапы увлечения тонкостенными пространственными большепролетными сооружениями. Особое внимание уделено установлению точных дат в хронологии появления стилей, конструктивных решений и появлении первых сооружений соответствующих стилей и их авторов. Описаны выявленные причины разрушения некоторых знаковых пространственных сооружений и как эти аварии и разрушения повлияли на дальнейшее проектирование и строительство сооружений аналогичного типа. Приведены, в основном, положительные высказывания известных архитекторов о месте оболочечных сооружений в промышленном, гражданском и жилищном строительстве в настоящее время. На основании опубликованных в специализированных изданиях материалов охарактеризованы разновидности подходов архитекторов к проектированию пространственных сооружений. Показано усиление интереса дизайнеров и архитекторов к проектированию оболочек, очерченных по аналитически незадаваемым поверхностям и в форме многогранников и складок. Установлено, что в наше время архитектура из стержневого металла получила свое дальнейшее развитие и стала* *конкурентом железобетона. В XXI веке стальные сетчатые и структурные оболочки стали одним из главных средств формообразования авангардных зданий. Сейчас у архитектора и инженера-проектировщика имеется большой потенциал в выборе формы, материала, методов расчета, конструктивных решений, стилей и примеров применения большепролетных тонкостенных оболочечных конструкций.*

Ключевые слова: *большепролетные пространственные сооружения, оболочки, архитектурные стили, конструкционные строительные материалы, аналитические поверхности в архитектуре, хронология архитектурных стилей.*

1. Introduction

Large-span space structure is a structure coved big area without intermediate supports but overall dimensions of the structure in plan are equal or exceed the rise of the spatial structure. The Central Research Institute of Building Structures named after V.V. Kucherenko offers to isolate metal unique large-span erections in a separate group. Erections, having spans more than 60 m and new constructive solutions in the main that demand special methods of analysis, experimental researches, and so on, and objects with more than a 100 m span, having constructive solutions, successfully tested in practice of designing, building, and exploitation.

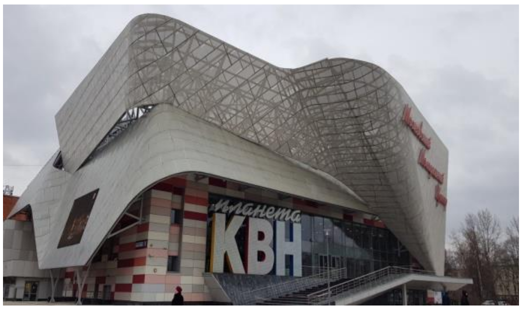

Figure 1 - The analytically non-given surface of the covering of the Moscow Youth Center

Figure 2 - The Ice Palace «Blue bird» (prismatoid), Otradnoe, Moscow

Figure 3 - Color appearance, Grozny, The Chechen Republic, RF

Figure 4 - «PITERLAND». One of the biggest wooden domes in the World with a 92 m diameter, SPb, RF, 2012

N.V. Kas'yanov [1] writes: «Large majority of engineer and architectural objects is utilitarian and unprepossessing orthogonal boxes and plates. Innovators of architecture and engineering art must move away off routine of traditional thinking. It raises the perspectives in innovative forming of public buildings and technical erections that can be more artistically sensible». One can agree with him or not but it is obviously that now structures and erections designed with using modern space forms are taken into consideration as symbolic objects for the district, town, or the country. Everyone puts his own meaning into such notion as "innovative forms". Ones consider that these are analytically non-given surfaces, created by architects according to their professional intuition and to technical demands (figure 1), rod regular and semiregular polyhedron structures attract attention of others (figure 2); the third group of architects pay the more attention not to form of the erection but to its colour appearance (figure 3); the fours take a great interest in increasing dimension of the erection (figure 4) and so on.

2. Architects and engineers about constructive materials for shell structures

Naturally enough, at first, builders used natural material such as stones, wood, brick clay, tufa, bricks. The necessity in erection of new buildings and, accordingly, in new structural building materials appears in certain historical period. After natural stones, timbers, and bricks, builders began to apply metal structures and later on thin-walled reinforced concrete structures, and at last the time of plastics and composites come [2]. At the beginning of the 20^{th} century, industrial manufacture of synthetic compounds, i.e. resins, was coming into being. From the beginning of the 30^{th} years, quantity of produced resins and plastics reached commercial scale and these materials began to be applied in industry and then in building. In the 50^{th} of the 20^{th} century, they began to use sheet plastic for building small-span domes (B. Fuller, 1950, USA). At present, a dome of mosque in Bahrein is the biggest composite dome in the World. Its diameter is 25 m. The dome was made of heat-proof plastic reinforced by glass fibers. The manufacturer gave a 30 years' guarantee for the material of the dome. New trend in development of architecture of plastic shells was supported by Zaha Hadid, M. Kurokawa (Japan), Matti Suuronen (Finland), Smiljan Radic (Chile) and others [3].

Every distinguished architect has his favorite architectural style and structural building material which they popularized for subsequent application. But sometimes well-known structural engineers made mistakes in their prognostications. For example, N.V. Nikitin was confirmed that steel delicate structures stayed in the past. But now some designers note that in the 21^{st} century, net shells became one of the main means of forming vanguard buildings.

Existing coated fabrics for tent coverings do not satisfy sometimes to all high demands of such structures. These are bioresistance, difficult for inflammation, capacity for work under low temperatures, long guaranty period of exploitation. At present time, industry begins to produce fabric for film coating combining all enumerated qualities. These coatings are made of composite materials on the basis of high-strength synthetic fibers with gas contained layer from resin or thermo-plastic film [outbel.ru]. Creation of hard-wearing fabrics and films not passing air stimulates appearance of pneumatic structures. There are examples of successful application of glued wood [4] and basalt fibre reinforced concrete for shell structures.

Additional information on constructive materials for thin shells and shell structures are given in a manuscript [5].

3. Brief classification of spatial large-span erections

Many classifications of thin-walled spatial forms and shells exist. They are offered by different authors and by building standards and rules. Usually, one main indication is taken as a basis of a classification and then they conduct an articulation into separate systems within this group.

From the classifications presented in a book [6], we shall use only classifications by structural type of covering (rigid and suspended shells, tensile membrane structures, suspended cable and cable-stayed structures, pneumatic and tent structures), by used material (reinforced concrete, steel, wood, composite, ferro-cement, and others), by method of erection (precast, monolith, precast-and-monolith), and by historically recognized form (dome, vault, cruciform shell, and so on).

4. The stages of passion for the shells

Based on the number and variety of shells built from the 1920s to the early 1960s, this period can be considered the golden age of concrete shell construction because in this period, important engineering solutions appeared that gave the possibility to increase the spans of coverings for industrial and public buildings. In that period, the shells from different building materials were built and the methods of their erection were derived. P.L. Nervi, Ed. Torroja [7], Heinz Isler, A. Tedesco [8], and F. Candela [9] were the most known designers and architects of shells at that time. Professor A.M. Haas, one-time president of International Association of Spatial Structures (1966) emphasized that "The men designing shells are the progressive-minded people; the aspiration for new forms, for new ways of solution combines them"[10].

The chronology of erection of thin *reinforced concrete shells* is described in detail in scientific and educational literature and that is why in this present work, only important and symbolic dates and events will be considered. Additional information can be taken from works [6, 10 – 13].

The era of thin reinforced concrete shells began when the manufacture of portland cement was put right. In 1905, French engineer E. Freyssinet (1879-1962) built the first reinforced concrete cylindrical parabolic shell. The helical stairs in the tower in the form of a right helicoid made of monolith reinforced concrete was built in Starie Lipy of Pskov region (Russia) in 1909. This structure can be called the first reinforced concrete shell in the form of a non-canonical surface. The first reinforced concrete continuous shells were built on the railway station Le Bercy in Paris in 1910. The 65 m diameter "the Jahrhunderthalle (Cenrennial Hall)" was designed by a German architect Max Berg and built in Breslau (now Wroclaw, Poland) in 1911-1914. It was the first dome type building from reinforced concrete with a radial-and-circular system of massive ribs. In the United States, reinforced concrete shells were extensively studied by the aircraft industry only in 1930s. In the 1950s and 1960s, architects payed attention to designing and building of public shell buildings in the form of analytical non-canonical surfaces with arbitrary form of the plan. The period of rapid development of architectural ideas, styles, methods of analytical analysis, and erection of large-span shell structures was in progress until 1965-1980. The whole Pleiad of distinguished architects and academics worked with shells. Then till 2010, shells have lost their popularity compared to their heyday in the 1950s and 1960s, when architects eagerly adopted them as a new means for artistic expression, and architectural reinforced concrete shells have almost disappeared. In the 1980s, in 1990s, and in 2000s, only a complex of umbrella buildings "Oceanographic Valencia Animal Welfare" (Spain, 2003), architect F. Candela, and "Ciudad de las Artes y las Ciencias" (2005, Spain), architects S. Calatrava and F. Candela, became the famous reinforced concrete structures. In 1984, Danilovskiy rinok (Danilovskiy market) with the precast covering was built in Russia.

At the beginning of the 21st century, reinforced concrete and fibercrete concrete thin-walled shells were used more in small-size building, i.e. for building of dwelling objects, café, small offices, sheds, and so on, for erection of shell roofs of industrial buildings or in the erections with specific technological process. Reinforced concrete shells with large spans had not practically been built. Trying to overcome certain crisis in designing large-span reinforced concrete shells, architects and designers created several new directions in architecture, widened the possibilities of reinforced concrete and fine-mesh wire-fabric reinforced concrete. Engineers have been created new technologies, materials, and numerical methods of strength analysis of large-span erections.

Steel rod (grid) structures have their firm position in architecture of public and industrial buildings. A space grid structure is a 3D system assembled of linear elements. When space grid structures have depth or thickness, they are referred to as *space frames*, *double-layer grids*, or *space trusses* [11]. The first shell metal structures i.e. domes, vaults, sheds, appeared in the middle centuries and they were spread over the World. A covering of the porch of Nev'yanskaya Bashnya (Nev'yanskaya tower) at the Urals (1725) is considered by the first cast iron structure in Russia. But rod spatial structures became to build at the end of the 19th century. It was bound up with complication of arrangement of assembly joints and, furthermore, need for the erection of these structures was absent. The first grid space mast structure was erected in Paris by Gustave Eiffel for International Exposition of 1889. This structure provoked heated arguments on its aesthetic, helpful, and expressive qualities. At the end of the 19th century, V.G. Shukhov built the first in the World grid hyperbolic tower (N. Novgorod, Russia, 1896) and later, a shell of double positive curvature (Vyksa, Russia, 1897). He is a forefather of steel grid structures in Russia (figure 5). Some researchers of net-and-rod shells give first place in building of steel net structures to Samuel Cutler, built steel net shells of gas-holders in East Greenwich (Blackwall Line) in 1886 – 1888, that is 8 years earlier than V.G. Shukhov. The first major commercial development of space frame structures began in the late 1930s [11].

Figure 5 - One of the last water tower of V.G. Shukhov in our days, Krasnodar, RF

Complex of China National Grand Theatre from titan and glass is the most striking metal shell erected in the 21 th century. It is the symbol of China. The complex was designed by French architect Paul Andreu. At present time, a project of a chalky clay store-house of the Babinovskiy cement plant in Novgorod region in the form of a 127 m diameter spherical dome was worked out. The height of the dome is 32 m. One planned to end the erection of the plant in 2014. Now in general, they became to build metal rod shell 3D structures. Shell thicknesses began to mount to several meters when very large spans. The three-layered shells had internal and external layers from sheet metal but the middle layer represents a rod structure. The work of architects, constructors, structural engineers, and builders of the biggest dome of sport-and-concert complex in Nagoya (Japan) excites respect.

The 188 m diameter dome was realized in the form of one-layer structure (lattice structure), 67 m high. This dome is a joint working out of Takenaka Corporation and Mitsubishi. The piping rods from steel tubes with a 65 cm diameter and 10 m long are bearing elements of the dome.

All-metal shells with elements of reinforcement are used usually as reservoirs for keeping of oil (drop-shaped shells [14]), water (water towers), and gases (gas-holders).

Steel net (mesh) shells (*lattice shell structures*) can be illustrated by a net spectacular glass roof of the Queen Elizabeth II Great court in British Museum in London. It was designed by N. Foster and was opened on 6 December 2000. *Geodesic domes* also can be called “net shells”. Geodesic domes were developed in the 1940s and 1950s by Fuller. Fuller’s motivation in pursuing these structures was to develop an economical shape that could be used in all parts of the world. Several large-scale damages happened in the world with reinforced concrete shells hastened extended production of steel net bearing shells in building practice. Steel net shells are operated in Russian climate without accidents. Shukhov’s steel net shells do non collapse without rust protection during 70-100 years. In the last years, net shell structures are used even more often than thin-walled reinforced shells.

In the *cable-stayed suspension systems*, guys (threads) or wire rope plane or space trusses support rigid bent elements (beams, plates, arches, frames) in the design position. Covering materials (roofing) are placed on these rigid elements working in bending. Stay suspension cables (guys) are called sometimes open cables, or open wire ropes, or tensioned straight cables and that is why cable-stayed structures are called also roof structures with pylons and open cables. The stay suspension cables are placed outside in the open air space, so they require the effective proof against possible corrosion. The first suspension roof structure with the transparent plastic roofing was built over a bus stop in Milan, Italy, in 1949 [15]. The very interesting information on the suspension structures realized in the projects or in real structures built in the XIX and XX centuries can be found in a book [16]. Today, cable-stayed suspension systems are considered as innovative constructive solutions [17].

The *wire rope suspension structures* (*cable-suspended structures*) differ from the cable-stayed suspension systems because the covering elements in them are placed directly on the wire ropes or on the wire rope net. The first suspended structures of cable type from narrow iron strips were erected by V.G. Shukhov at the Nizhegorodskaya fair in 1896. The closed ice-hockey playground designed by E. Saarinen in1958 became one of the first cable-suspended structures. Roof coverings from wire rope nets have wide opportunities of forming which are limited only by bearing capacity of wire ropes and support contour, and also by requirements of availability of negative curvature at every point of their surface [18]. Eremeev P.G. [19] considers that in the 21st century, the interest for design and building of large-span *cable-suspended* structures is growing. Practically all erected buildings of this type can be reckoned among unique and remarkable structures [20].

Metal suspended membrane roof structures are used considerably less than other types of suspended roofs. The metal suspended membrane roof structures or simply membrane coverings are a spatial structure consisting of thin metal sheet and rigid support contour. Some architects, especially from English speaking countries, attribute tent and air-supported pneumatic structures to membrane roof structures [21]. At present time, the investigations of application of glass-fiber-reinforced plastic membrane shells are in progress, but they are subjected to creep under action of sustained load. A membrane roofing of the grain elevator in the USA (Albany, 1932) appeared 35 years after the first membrane roofs made of steel strips and roofing steel designed by Russian scientist and structural engineer V.G. Shukhov (1896) for the four Pavilion for All-Russian art industrial exhibition in Nizhniy Novgorod. But Otto Frei in his book “Das Hängende Dach (Suspended roofs)”, Berlin, 1954, holds that the era of suspended roofs from sheet steel began after the Exhibition Pavilion in Zagreb (1937). In North America, the erection of tensile membranes began in the 1970s. In Russia, a considerable experience on analysis, design, and building of different types of membranes was accumulated, providing the opportunity to implement a number of unique large-span roofs for sport facilities of the Olympic Games-80. A known specialist in the field of designing and analysis of metal membrane roofs P.G. Eremeev [22] holds that economic effectiveness of suspended membrane roof structures is determined by “reduction of material consumption and labour content of consolidated assembly and erection of metal structures; by reduction of the cost of columns and foundations disposed below; by decrease of constructive height of the roof, by decrease of expenses for erection and exploitation of roofing at the expense of using membrane as water proofing”. But at present time, few design offices undertake to design and to escort the building of membrane suspended shells although all theoretical problems were solved.

Tensile pneumatic momentless shells are divided in air-supported shells and air-inflated flexible coverings. Air-supported membranes were first devised by Walter Bird in the late 1940s and were soon put to use as covers for swimming pools, circuses, aqua parks, temporary warehouses, and exhibition buildings. Air-inflated flexible structures are supported by pressurized air within inflated building elements that are shaped to carry loads in a traditional manner. Pneumatic structures are perhaps the most cost-effective type of building for very long spans.

Some of constructors suppose that F.W. Lanchester is a father of pneumatic structures. He received the first patent for pneumatic architecture. The first building pneumatic structure with the dimensions of 60×20 m in the plan and 6 m high for the design bureau appeared in Hemel Hempstead, England, in 1946. It is considered that Expo 70” in Osaka, Japan, gave strong impuls to development of building of pneumatic structures all over the world. Many countries presented air-supported shells (figure 6) and air-inflated flexible coverings pneumatic structures.

The development of pneumatic structures in Russia went off in three stages: the initial stage (1959 – 1970); a period of training of output of serial air-supported pneumatic erections (1970 – 1975), and a period of their serial output after the 1975th [23].

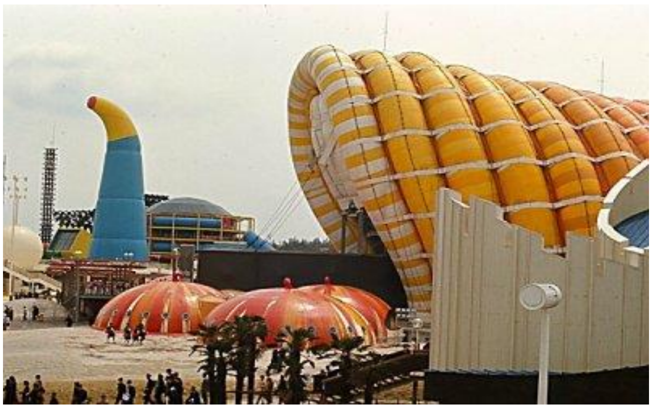

Figure 6 - Fuji Film Pavilion, photo Tom Krause, “Expo 70” (Osaka, Japan, 1970)

Having compared pneumatic structures of the 1970-1990s years with modern buildings, we hold that raising the quality of these erections and increase in their service life took place because of new synthetic coated fabrics. Forms of pneumatic shells practically did not have been changing. Pneumatic forms are all synclastic, and the prestress is internal pressure on the membrane. Domes and vaults are the most used forms. Architects and constructors working in this area consider that just their structures are the landmark erections of the 21st century. Supporters of the wide use of pneumatic structures claim that at present time air-supported structures by their properties approached to capital buildings. The advantages of pneumatic structures were called in question very soon in connection with problems of cleaning snow, potential opportunities of water accumulation, sagging coverings, and relatively high cost of exploitation. In 20 years period (1974-1993), fifteen cases of sagging of coverings have taken place at ten large objects built in the USA [24]. But now due to new material for pneumatic shells that are glass-fiber coated fabric from Teflon, increasing interest for application of these shells in stationary buildings is to be observed all over the world. Now near 100,000 pneumatic buildings and structures were assembled on all continents of the world. They are made in all technically developed countries.

In the 1920s, designing and building of *tent structures* in Russia were connected with names of architects V.A. Vesnin and A.A. Vesnin (*constructivist principles of forming*) and G.M. Ludwig (*symbolic-and-engineering functionalism*) [25]. In the 1930s and until the 1970s, the development of tent roof coverings in Russia was else the initial stage. Construction of tent structures was delayed because of the absent of durable and high-strength textiles. In the 1950s and 1960s, German architect F. Otto passed from experiments with models to full-dimension structures. Before the 1980th, tent structures were used only for exhibition pavilions but after the victory of Danish architect J. Otto Spreckelsen in the competition Arc of Esplanade de La Défense in Paris in 1983, tent coverings obtained the recognitions as architectural phenomenon. Myskova O.V. and Kazus I.A. [26] contend that “tent structures are the structures of the architecture of the future, forming the space free from cumbrous internal structures”. In the 21st century, tent architecture was recognized as the new tendency of modern architecture. The supporters of *productivism* consider that tent structures are *architecture of high technologies*. The ideas of productivism were formulated by K. Frampton who supposes that productivism today is largely represented by such architects as Norman Foster, Richard Rogers, and César Pelli. With a point of view of productivism, only elegant engineering, that is product of industrial design, may be a work of architecture. Architects of tent structures are sure that many outstanding structures of the world significance of the beginning of the new millennium were built with the application of tent structures. Experts of the company TENTMAX [25] suppose that “Russia has potential opportunities of application of tent structures because they are mobile, quick-erecting, easily transformed in accordance with changing functions, and they have high aesthetic merits.” In a paper [25], all tent structures categorized under 4 types.

There are signs, however, that shells are attracting interest among the new generation of architects, designers, and engineers who show interest in construction of large-span spatial coverings [11]. There are also new materials such as fibercrete concrete and fiber reinforced polymer composites that may be more often used in shells. At present, they may be too expensive for use in architectural shells, but with time this situation changes. Next to cost, the most frequently cited reason for the decrease in popularity of concrete shells was that they have fallen out of favor with architects [27]. The appearance of new forms in architecture of spatial structures that can be recommended for introduction into practice is the third motive of return of interest to shells.

5. Examples and reasons of collapses of the known space large-span erections

Destructions of buildings were according to plan of constructors or against their will. Very experienced architects and structural engineers were enlisted the services of design of spatial long-span erections but in spite of this, several resonance failures and collapses of already built long-span buildings have taken place. The planed destructions do not arouse particular alarm but sudden collapse demand sometimes revision of some building code or more accurate definition of methods of structural analysis of the structures.

Consider some examples and point out established reasons of the failure of the known space large-span erections. Additional information is presented in papers [28 - 30].

5.1. Collapses, arisen by breaches of the building code and standing rules of designing and exploitation of buildings

In 1956, the collapse of part of monolith reinforced concrete shed roof of melangeur plant with an area of 5,000 m^2, i.e. 18 shells, happened. Shell roofs of 5cm thick in the form of three-axial ellipsoid over cells with spans of 12×21 m were realized (figure 7). The commission of Gosstroy SSSR established that the collapse happened because of insufficient rigidity of and stability of all roof system in the direction of a 12 m span. Big load from ice crust generated in the valleys of the sheds is the second reason. Collapsed part of the shell roof was restored later.

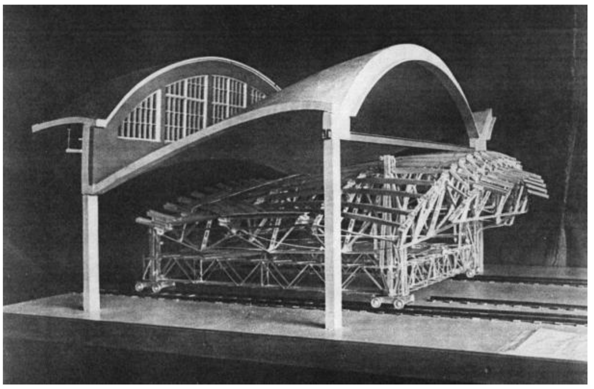

Figure 7 - A model of travelling shuttering for the reinforced concrete shell roof of the shop, developed by "Tekstilproekt", Russia

The Sport Palace in Milan, Italy, became the sights due to the collapse of its roof structure in 1985. This collapse was one of the greatest failures between suspended steel wire rope erections. The building built in 1975 was covered by round in plan suspended roof with a 126 m diameter in the form of the hypar. After snow storm, a 0.75 m in thick a snow layer occurred on the roof. This snow load together with hard wind, sharp change in the temperature gave rise deformation resulted in the collapse of the contour beam.

In Russia, the greatest failure of one-layered cable roof structure took place too. The suspended shell roof of Basmanniy Market, Moscow, was built in 1977; architect L. Gilburd, a constructor of the roof structure is N.V. Kanchelli. The gross violation of the rules of maintenance of the building was the reason of the collapse. This conclusion was presented by a Commission of Moscow government.

A reinforced concrete shell of variable thickness with inhomogeneous reinforcement and with a system of cross ribs collapsed in Moscow on 14 February 2004 (figure 8). A building of aqua park "Transvaal-park" was a unique structure and an application of standard methods for the evaluation of strength and bearing capacity gives the approximate result. Four versions of the collapse existed, that are breaches of design standards, mistaken in the process of building, incorrect exploitation, and ground motion. It was established that the main reason of collapse is neglect of non-linearity of concrete and reinforcement.

Figure 8 - The collapse of "Transvaal-park", Moscow [www. hexa.ru/presentations.php]

On the 1st November 1965, three of eight 114 m high cooling towers in Ferrybridge, England, collapsed simultaneously in the time of hard wind. Large failure took place in the process of building of a reinforced concrete cooling tower in Willow Island, USA, on the 27th April 1978. Here, a part of one of two hyperbolic cooling towers of the Pleasants Power Station collapsed. The project height of the cooling towers is 131 m. The collapsed cooling tower was built till the height of 109.1 m. Having studied the situation, the experts of the National bureau of standards of the USA confirmed that untimely transmission of building loads on the shell walls which had not enough strength was a reason of collapse.

On the 21st May 1980, collapse of unique the Berlin Congress Hall, an example of *post-war modernism*, built in West Berlin in 1957 took place. The suspended roof having the saddle form was designed by the American architect H. Stubbins.

At the end of the 2007th, a crash situation in the Ice Palace “Krylatskoe”, Moscow, came into existence because of sag of the roof. It was established that spoilage committed under making of metal structures of the suspended cable-stay roof with one bearing pillar was a reason of the crash situation [17].

A shell building of the main test stand of the All-Union Energy Institute in Istra, Moscow region, was designed in the form of an ellipsoid of revolution. The diameter of the base was 234 m, the height was 112 m. The building was erected from metal rod shell elements. In 1984, the grid shell collapsed after erection.

On September 1970, a roof of gymnasia Hennison, Virginia, collapsed completely. The roof consisted of four elements of a hyperbolic paraboloid. According to the experts’ conclusion, the collapse took place because of progressing deflection in the middle of the building. Deflection was 18 inches. The building measured 155 × 162 ft.

The analysis of collapses of the spatial erections presented in a paper [28] gave an opportunity to establish the main reasons of the failures. These are construction defects and poor quality of building-and-assembly works, violation of conditions of observance of rigidity and stability of the building in the process of design and its erection, application of materials and structures of low strength, the construction errors, overloading bearing structures because of neglect of real wind and snow loads, corrosion of steel elements, insufficient study of methods of strength, rigidity, stability, and dynamic analyses; absence of natural control for the work of shells during their use.

5.2. The planed destructions of spatial large-span erections

Sometimes, shell structures were destructed intentionally. On 26 March 2000, the closed baseball stadium “The King Dome” with a 201 m diameter parabolic dome built in 1976 was destructed to vacate the place for a closed football playing field.

The information occurred very often about blasting of existing reinforced concrete hyperbolic cooling towers and not in connection with deterioration but in connection with finishing of their using, for example, because of transition to other source of energy.

In 1999, a round cable-stayed roof structure with one bearing pylon was erected over a bus station in Minsk, Belorussian. This suspended roof structure was called a characteristic post-modern object of Belorussian architecture. On November 2014, this bas station was destructed for the vacation of the place for a sky-scraper [17].

Regrettable fate overtook the Sport Complex “Olympiyskiy” at the Mir Street in Moscow. This object associated with Olympiad-80. In 2009, its round cable roof cover and the whole erection itself were disassembled till the base due to the plan of reconstruction. In the process of disassembling of the roof, one wire rope broke and the roof came down. In 2003, new building will be the first closed many-functional sport complex.

6. Analytical surfaces in architecture of buildings and structures

Conical and cylindrical surfaces, surfaces of revolution of the second order curves and translational surfaces are called usually *canonical surfaces* and shells with middle surfaces in the form of the named surfaces are called the canonical shells [31]. Shells in the form of other analytical surfaces are called *shells of non-canonical form* [32]. The surfaces given by the numerical levels or by the frame from plane curves, for example, topographic surfaces, or fractal surfaces are called analytically non-given surfaces [33] and they are usually used in free form architecture.

E. Torroha says: "The best structure is the one whose reliability is ensured mainly due to its shape, and not due to the strength of its material. The latter is achieved simply, while the former, on the contrary, with great difficulty. This is the beauty of searches and the satisfaction of discoveries"[10]. The Swiss engineer Heinz Isler is regarded around the world as one the pioneers of new shapes for shell structures [34] but R.B. Fuller spoke of his architectural creations in the following way: "Let the architects flood about the aesthetics that forced the crowds of the riches to fall at their feet. I shell prefer the Dome, where stress and tensions go away". Some of well-known [35] and young [36] architects and structural engineers note in their quite numerous papers that well studied existing analytical surfaces do not give wide-spread opportunities for realization of their creative ideas. Architects and mechanical engineers require the creation and study of new shapes and surfaces described by analytical equations for their implementation in various branches of science and technics [37]. But academic I.A. Bondarenko [38] warns, "We must not slip to populism. It is necessary to keep sense of proportion. Unfortunately, all successes and failures of architects today are based on their personal practical and humane qualities. Individualism and hypertrophied creativeness countenanced too much. Professional achievement can be called insolvent decision but senseless design decision can be called architectural innovation". But only creation of new forms of shells cannot solve all architect problems. The famous Portuguese architect Eduardo Souto de Moura speaks: «I don't think that any global new forms will be appearing but new technologies and building materials will be created" [10].

7. Analytical surfaces in landscape architecture, on children's playgrounds, and in small architectural forms

Studying materials on this part, one can come to a conclusion that designers of these not big objects know analytical geometry of surfaces very well. Structures in the form of analytical surfaces can be seen practically on every child's playground, for example, in the form of cyclic surfaces or helical surfaces with congruent profiles (figure 9) and umbrella-type surfaces. It should be noted that analytical surfaces realized in real products can be seen very often only in the objects of landscape architecture (figure 10). Polyhedrons (figure 11) and geodesic dimes (figure 12) are widely used. Structures in the form of cones, quadrangular and hexagonal pyramids, and different prisms are on every child's playground [39].

Figure 9 - The helical surfaces with congruent profiles and two umbrella-type surfaces

Figure 10 - The sculpture "Non Object" from stainless steel, A. Kapoor, 2008 (pseudosphere)

Figure 11 - A dodecahedron in “Mathematical Garden”, Maikop, RF, 2018

Figure 12 - The geodesic dome on a child’s playground

8. Characteristic of varieties of approaches of architects to the design of shell structures

Described briefly architectural styles, their subspecies, and varieties, within the bounds of which, architects create landmark spatial large-span erections and curved structures of shell type. 26 architectural styles, used in shell architecture, are known [40] and the principal items of them are the following.

Art Deko Style

“Art Deko Style”, called also “Modernistic”, came into existence in the 1920s and became main style in West Europe and the USA in the 1930s. The aim is a creation of anti-traditional form of buildings. The distinctive traits of this style are simplicity, lucid but unusual forms, symmetry, geometrical ornament on the façade, using artificial materials jointly with natural.

Architectural style “Art Deko Style” was realized by William Van Alen in the external architecture of “Chrysler Building” and by a company Shreve, Lamb & Harmon in a building “Empire State Building”. These two buildings are the standard of the style. In the 1930s, this style was held in respect in South Beach in Miami. This region was even called “Historical area of the Art Deco architectural style”.

The Basilica in Belgium (figure 13) and Melnikov's dwelling house (figure 14) can be cited as examples of the use of this architectural style in the shell buildings that have been put into practice. The style went out of style during the Second World War. In the late 1960s, it was again in demand.

Figure 13 - A Roman Catholic Minor Basilica, Belgium, 1905-1965

Figure 14 - A dwelling house of K.S. Melnikov, Moscow, 1927-1929

Parametrical architecture

Parametric architecture is a new style in architecture based on analytical methods for defining surfaces, mathematical and computer modeling. This style was formed at the beginning of the 21 century. Zaha Hadid and Patrick Schumacher were the most famous architects who worked in this style. The most complete information about objects of parametric architecture is given in manuscripts [41, 42]. In a manuscript [41], the parametric architecture is illustrated by a large number of examples, and in a paper [42], the authors, with reference to authoritative architects, tried to give a theoretical substantiation of the importance of developing of this architectural style.

The study, conducted by I.A. Mamieva [41], shows that only 43 surfaces from the known in the world 600 analytical surfaces, are used in architecture and construction. A similar study carried out by her on the example of Moscow showed that only 18 analytical surfaces were used here. This data suggests that geometers have far outstripped the needs of architects and builders, or architects have not yet mastered the full range of analytical surfaces offered by geometers. Most of the analytical surfaces are considered by architects to be of little use for their creative concepts and they prefer analytically not defined surfaces; all the more with the advent of computer modeling methods, it is often enough to have only a set of reference points of a structure.

Currently, parametrical architecture methods are very widely used in projects of buildings and structures for the countries of the Persian Gulf and the Middle East, in some countries of East Asia.

Cubism

The architect and engineer F. Candela wrote that it would be tragic if the production of cubic structures on a rectangular plan, which would be perceived as a synonym for all architecture, won out in the minds of a young generation of architects. Cubism uses simple geometric three-dimensional forms (figure 15).

Figure 15 - A building in the style of "Cubism"

Cubism has been an influential factor in the development of modern architecture since 1912. The Cubist house of Raymond Duchamp-Villon and André Mare became a symbol of style. Architects Peter Behrens and Walter Gropius simplified building design using materials suitable for industrial production. They popularized extensive using of glass. The best known Czech Cubism came to naught in the second half of the 1920s with the emergence of new trends in architecture.

Free form architecture

Free form architecture or architecture of structures with analytically non-given middle surfaces appeared apparently because some of architects decided that innovative forming of large-span thin-walled shells with canonic middle surfaces and of buildings with simple rectangular forms exhausted itself and any new erection will be repeating analogue already built. They suppose that it is possible to show the creative conceptions only using an arsenal of new shells and grid structures in the form of analytically non-given surfaces [34]. One can receive clear idea about tendency in architecture of free forms from materials of a paper [43], where Pottmann H. with his colleagues note that in the 2005^{th} , rapid development of free form architecture promoted to appearance of architectural geometry for optimization of some problems arising in the process of this style design. Frank Gehry is a founder of free form architecture [44]. At present, a number of architects working in this direction is rising. It is possible to say also about a number of objects built in different countries (figure 16).

Figure 16 - “Glass rind” is the largest translucent structure in the world, Moscow Russia

Bionic architecture (architectural bionics)

Bionic architecture is closely related to free-form architecture [45]. Bionic architecture tries to integrate architectural objects into the natural environment as much as possible without entering into conflict with it (figure 17). The main direction in architectural bionics now is the creation of ecological houses with natural energy sources. Architectural bionics tries to avoid monotonous straight lines with gloomy smooth walls in the construction of houses and tries to turn them into a kind of landscape with the absence of corner sections and a varied lively color scheme. Large-scale building of ecological houses is already underway in Western countries and the USA. Russia is also keeping up with modern architectural trends [46].

Figure 17 - Architectural Bionics, arch. Jacque Fresco

There is a project of the vertical city "Bionic Tower" or "House-cypress" designed by architects Javier Pioz and Maria Rosa Cervera, Shanghai, China. The height of this skyscraper will be 1228 m, the number of floors is 300. The flower theme is very popular in bionic architecture. For example, the architectural bureau of Vincent Callebaut proposes a project of the floating city "Water lily". Several examples of structures made in the style of bionic architecture are given in a book [6] and in a paper [47].

Organic architecture

Organic architecture encompasses a wider range of structures than bionic. The American Louis Sullivan is considered the creator of a conception of organic architecture who is the founder of American modernism too. The concept of "organic architecture" was coined by Frank Lloyd Wright. A commitment to natural materials has become a distinctive feature of organic architecture. Stone, wood and glass are used instead of steel, concrete and plastic. Falling water house is the most striking representative of organic architecture. It was developed by F.L. Wright and was built in the reserve on the top of a nine-meter waterfall. American architect Robert Harvey Oshatz blended the house with natural surroundings to give the feeling of living in a tree house. A building in the shape of a giant lotus flower (Lotus Temple) in Delhi, India, architect Fariborz Sahba, is easily recognizable, it was built in 1986. Organic architecture treats a building and the external environment as a whole, which are inextricably linked.

Yu. Kurbatov, professor at Research Institute of Theory of Architecture and Town Planning, Moscow, believes that the term “organic” is used mainly in three meanings. In the first meaning, “organic” architecture means “following the nature of its purpose and materials”. The second meaning of the term “organic” means subjection to the conditions of the natural landscape that are the climatic conditions of the environment. The third meaning of the concept is following natural forms as models [48].

Polyhedron architecture

Over the past decade, architects, constructors and builders have greatly increased their interest in polyhedral. Even the term “architecture of polyhedrons” has appeared [49]. A large number of buildings were built in the form of polyhedrons and folds (figure 18).

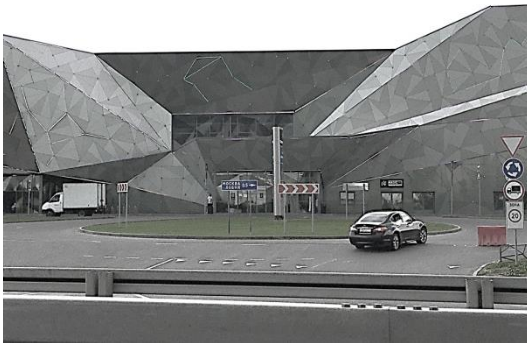

Figure 18 - Shopping and entertainment center, Dmitrovskoe highway, Moscow region

The research carried out in the paper [50], and confirmed by the illustrations contained in the book of Sonja Krasić [31], shows that only prisms, prismatoids, pyramids, hexahedrons (cubes) are taken as the basis for designing large architectural objects. There are several dozen objects in the form of antiprisms and rhomb cuboctahedrons. Inclined prism, tetrahedron, octahedron, icosahedron, truncated tetrahedron, truncated octahedron are used in isolated cases, and the rest of the regular and semi-regular polyhedrons are used mainly as small architectural forms or sculptural compositions (figure 11). Everything else exists only in the form of concept projects.

High – Tech

The hi-tech style appeared in the late 20 - early 21 centuries as a logical continuation of the architecture of postmodernism. It is customary to divide high-tech into two periods: early (1960s - early 1970s) and modern (from the middle of 1970s to the present day). A great contribution to the development of the style was made by O. Frey, who created kinetic structures, and by R. Fuller [51], who designed geodesic domes. In the 21st century, mesh shells have become one of the main means of shaping avant-garde high-tech buildings. High-tech architectural style is, first of all, the absolute functionality of buildings, emphasized by the clarity of spatial solutions and lightness of structures. The main materials are glass in all its types, metal and plastic. There are varieties of style: *geometric high-tech* (figure 19), *bionic* and *ecological high-tech*.

Figure 19 - A private house: geometric high-tech [I. Medvedeva, ReHouz]

Expressionism in architecture

Expressionism is the architecture of the First World War and the 1920s in Germany ("*brick expressionism*"), in the Netherlands (*the Amsterdam school*) and neighboring countries, which is characterized by the distortion of traditional architectural forms in order to achieve maximum emotional impact on the viewer. Preference is often given to architectural forms that recall natural landscapes (mountains, rocks, caves, stalactites, etc.). E. Mendelssohn, G. Scharoun, G. Höring are the most prominent representatives of this trend. The Sydney Opera House is one of the most famous buildings of the 20th century and Australia's most popular Expressionist architecture.

The Soviet Modernism as applied to shell structures

This architectural style is the continuation of the vanguard of the 1920s. It returned to Russia in the 1960s – 1980s. The style reserved the large objects and the objects of small form architecture. *Brutalism* that is a style of heavy architecture came up to take modernism place in 1970s [52]. But brutalism outgrew later on into *post-modernism*. The restaurant "Perl" in the form of an umbrella type in Baku (arch. V. Shulgin and R. Sharifov, 1962), a mushroom café “Vasara” in Palanga, Lithuania (arch. A. Eygidras, 1967, figure 20), and a Palace of Ceremonial Rites in Tbilisi (arch. V. Dzhorbenadze and R. Orbeladze, 1985) are the best specimens of the soviet modernism style. The idea of umbrella shell was offered by F. Candela.

Figure 20 - Cafe «Vasara», Palanga, Lithuania, 1967

Noospherical architecture

Noosphere architecture is a philosophical view on the relationship between human activity and nature [53]. Researches began in the first half of the 80s of the last century. Vitaly Grebnev created the concept and technologies for the construction of noospherical houses, houses where there are no right angles. The sphere is the best shape for a house under heavy wind and snow loads. The sphere has the largest volume with the smallest surface area (figure 21). V.I. Grebnev suggests creating a unified architectural and natural environment while preserving the environment as much as possible. It is necessary to design not only the spherical energy-efficient ecological structure from environmentally friendly building materials, but also the environment, that is, to create an eco-settlement.

Figure 21 - A dome house, Moscow region

9. Conclusion

The economic efficiency of thin-walled spatial structures has been proven in practice. Possessing enviable lightness, the thin-walled spatial shell system is an exceptionally strong structural form. One can say with certainty that shells are becoming one of the most characteristic design solutions in the world construction practice [54]. The ability to cover huge spans with thin-walled shell roofs without intermediate supports makes shells sometimes indispensable in the building of special structures.

Certain periods, during which interest in the building of spatial structures decreased, are associated with the transition from old constructive materials to new, with the emergence of new design solutions, the development of methods of strength calculation, or with the emergence of crises in the economies of countries. Some of architects turned from one architectural style to other in the time of their creative activity. It is difficult to attribute some of shell buildings to a definite architectural style.

So are there any prospects for the expanded application and development of the building of large-span structures? Of course, architects, designers, researchers and engineers who are involved in the analysis of large-span structures answer this question affirmatively. The Palace of

Callisthenic of I. Viner-Usmanova in Luzhniki, Moscow (RF) recently built confirms this supposition. The architecture of the Palace won already several International Prizes. Inauguration of the Palace was on 18 June 2019.

There is a decrease in the number of reinforced concrete thin-walled large-span shells being built in the world, but many rod and mesh metal shells, outlined on various surfaces, were built during the period under review. And more of them will appear every year. In our time, bar metal architecture has developed again and has become a competitor to reinforced concrete. In the 21st century, steel mesh and structural shells have become one of the main means of shaping avant-garde buildings. Structures with metal suspended membrane roofs are built more seldom than tents, grid metal structures, or shells from laminated wood.

The architect and civil engineer has great potential in the choice of shape, material, analysis methods, constructive solutions, styles and examples of application of large-span shell structures. More than 100 years of experience in the construction of these structures shows the continuing interest and human need for them. This manuscript will be a valuable addition to the library of all those architects, designers, builders, researchers, teachers and students who wish to expand their understanding of past accomplishments and future trends related to shell structures.

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