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FOLDED SURFACES IN ARCHITECTURE

Abstract. *There is now a growing interest in the design and construction of shells whose median surfaces cannot be defined by analytic formulas, i.e. it is difficult to apply geometric modeling, and shell structures of the folded type formed by the intersection of flat or curvilinear elements. These structures are executed in the style of digital architecture or experimental methods. Based on the research of descriptive and analytical geometry, architects in the 20th and early 21st century created many memorable folded structures of various purposes. This is illustrated in the article on the example of many flat-sided structures. The illustrations found on the Internet and the author's personal photos were used. Based on the carried-out research it is concluded that flat-sided folds were used very widely in various fields of architecture and construction. The availability of numerical methods of calculation makes it possible to design structures of various degrees of complexity. This is confirmed by references to numerous sources used. However, some architects disagree with this conclusion, believing that despite many attempts on folding, it remains one of the least studied forms in architecture.*

Keywords: *folded squamous structures, polyhedra, folding dome, folding vault, experimental approach in architecture, architectural trend "Origanic architecture".*

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СКЛАДЧАТЫЕ ПОВЕРХНОСТИ В АРХИТЕКТУРЕ

Аннотация. *В настоящее время поднялся интерес к проектированию и строительству оболочек, срединные поверхности которых нельзя задать аналитическими формулами, то есть трудно применить геометрическое моделирование, и оболочечных структур складчатого типа, сформированными пересечением плоских или криволинейных элементов. Эти сооружения выполняются в стиле дигитальной архитектуры или применяются экспериментальные методы. Опираясь на исследования начертательной и аналитической геометрий, архитекторы в XX-ом и начале XXI-го веков создали много запоминающихся складчатых сооружений различного назначения. Это проиллюстрировано в статье на примере многих плоскогранных сооружений. Использовались иллюстрации, обнаруженные в сети интернета, и личные фотографии автора. На основании проведенных исследований сделан вывод, что плоскогранные складки применялись и применяются очень широко в различных областях архитектуры и строительства. Наличие численных методов расчета позволяет проектировать структуры различной степени сложности. Это подтверждено ссылками на многочисленные использованные источники. Но с этим выводом не согласны некоторые архитекторы, считающие, что, несмотря на множественные попытки осмысления складки, она по-прежнему остаётся одной из наименее изученных форм в архитектуре.*

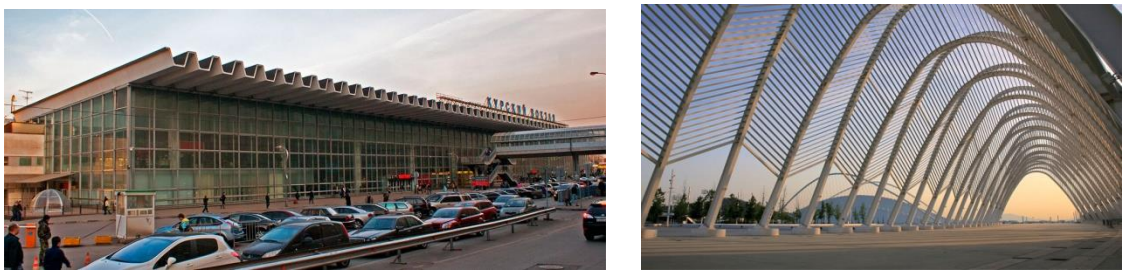
Ключевые слова: *складчатые плоскогранные структуры, многогранники, складчатый купол, складчатый свод, экспериментальный подход в архитектуре, архитектурное течение «Origanic architecture».*

Introduction

Currently, architects working with thin-walled shells have a large selection of architectural styles [1], construction materials [2], examples of realized projects [3, 4] and geometric forms [5]

for the implementation of their creative ideas and production requirements. A special place is occupied by folded structures and analytically undetermined forms of objects [6], which cannot be set by analytical formulas, and therefore it is difficult to apply methods of parametric architecture [7] and geometric modeling. However, if analytically undefined forms of shells are already widely introduced in the architecture of buildings of different purposes, then folds are still in the experimental stage.

a) b)



c) d)

Figure 1 - Static Folding Diagrams
a) Kursk railway station (bar scheme), b) Olympic Sports Complex in Athens (arched scheme),
c) Ice Palace "Blue Bird", Otradnoye, Moscow (spatial frame scheme), d) Hasan-Uddin Khan. Kuala Lumpur State

Folded structures and folds are thin-walled construction structures consisting of flat elements (face plates) connected to each other at some dihedral angles. There are four types of static schemes of folded structures: beam (figure 1,a), arched (figure 1,b), frame (figure 1,c) and folding shells (figure 1,d). Hermann Ruhle in his book Spatial Coatings (1973) defines folds as follows: "The fold-ed structure is a system of spatially connected thin (usually flat) face plates."

Now a number of new types of folded shells, which consist of fragments that do not have the structure of the plane, are becoming actual: composite shells from sections of hyperbolic paraboloid (figure 3) and composite shells from sections of cone and cylinder [8]. These types of compound shells have different compositional differences from known planar folds and will not be considered in the article (figure 2, 3).

Figure 2 - Philips Pavilion, Expo 58, Brussels

Figure 3 - Danilovsky Market, Moscow

Planar folded structures can also be divided by their appearance: the bodies of Plato, the bodies of Archimedes, folded plates, folded domes, folded vaults; a combination of pyramids, prisms or a joint combination of prisms and pyramids, folds and approximating torso surfaces; folds formed by arbitrarily intersecting planes, such as the Origanics architecture.

Prisms, prismatoids, bodies of Plato (5 species) and bodies of Archimedes (13 species) are often called regular convex polyhedra and semiregular polyhedra, obtained from the regular cutting of their vertices [9]. Some geometers classify them as folds because they fall under the definition of folding structures. Classification of folding structures is also offered in work [10], where the structural materials for their manufacture (reinforced concrete, metal, wood, glass and plastics) are considered.

Folded domes are built on a round plan (figure 1,d; 3). They are usually classified as umbrella shells. An umbrella dome is a cyclically symmetric space structure formed from several identical elements that intersect the median surfaces of which produce curves that form some domed surface of rotation.

Figure 4 - Triangular pleats

A striking example of the folded structure of the covering in the form of a solid-walled plate-fold is the covering of the Kursk railway station (figure 1,a). On the cross section the folds are triangular (figure 4), rectangular and trapezoidal (figure 1,a). For example, trapezoidal folds are used for covering a sports school on Vasilievsky Island in St. Petersburg, triangular - for blocking the elling of the yacht club "Trud" on Petrovsky Island in St. Petersburg or at the bus stop on Kurortny Avenue in Sochi. Prismatic folding coatings were built in large numbers in the monolithic way in the 1920s for production enterprises. Prefabricated "span" folds are widely used in Italy.

Figure 5 - Folding vault, Maiori, Latvia, 2008

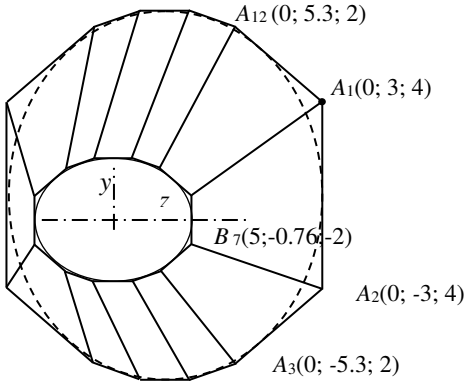


Figure 6 - Torso approximation with circle and ellipse on opposite ends of prism

The folded vault can be illustrated by covering the sports complex of the primary school in Ma-iori, Latvia (figure 5). It is particularly easy to approximate the curved torso surface of the zero Gaussian curvature with the folded surface. It is known that the face is formed by a one-parameter family of planes touching the torso along a straight line. By selecting some planes beyond the edge of the folded surface, you can obtain all the necessary geometric parameters for plotting the sketch of the resulting folded structure. Figure 6 shows a torso with an ellipse and a circle at the ends and a folded surface based on it. The technique of construction of folds on the torso, the opening of the torso of the fold is described in articles [11, 12].

A large number of folding structures are built as a combination of pyramids (figure 1,d; 7), a prism (figure 8) or a joint combination of prism and pyramids (figure 9).

It can sometimes be difficult to assign a folded structure to one type or another, or to dissect a combination of simple shapes in a construction. At present, there are 75 uniform polyhedral shapes, a large number of them are star formed and 9 quasipolyhedral [13].

Only very wellknown architects are involved in the design of folds formed by arbitrarily intersecting planes (figure 10).

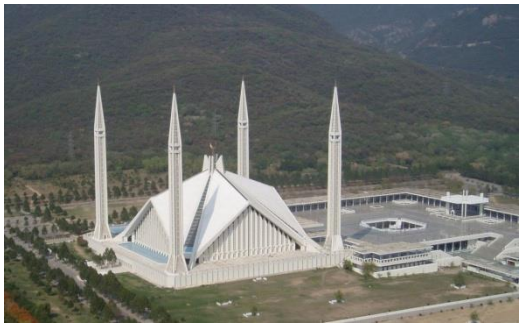


Figure 7 - Shah Faisal Mosque, Islamabad, Pakistan, 1986, arch. V. Dalokaj

Figure 8 - Philosophical Institute of FU, Berlin, 2012, arch. N. Janberg

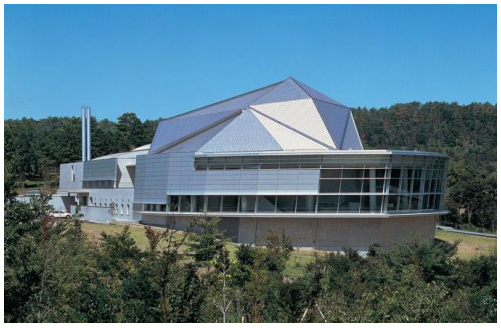


Figure 9 - Kirishima Cocert Hall, Kagosima, Japan, arch. Fumihico Maki, 1994

Figure 10 – Shopping Mall in Dolgoprudny, Moscow region

History of folded structures

In the work [14] it is noted that various folded forms were present in the Byzantium, Japanese, Tibetan, Aztec and Russian architecture. Folded structures were first developed and applied in 1898 by Professor F.S. Yasinsky for the overlap of the Alexander workshops of the Nikolaev railway. The first light foldable metal structures were arched and vaulted buildings. Abroad, folded structures in the first half of the twentieth century were made of reinforced concrete and only later switched to the use of other construction materials [10].

The first patent for foldable coating was issued in 1937. In our country the first author's certificate for foldable structures was issued in 1945 for foldable arch of sheet metal.

The classic folded structures with inclined planes and sharp angles were designed by a Russian architect: K. Melnikov within the architectural style "Soviet Avant-Garde". His designs had a significant impact on subsequent generations of architects: D. Libeskind, P. Eisenman, Z. Hadid [15].

The Origanic architecture, models of which can be made from a single sheet of paper by bending (Japanese paper folding) and cutting it (Japanese paper cutting), was founded by the Japanese architect Masahiro Chatani (1934 - 2008). He began creating creative folded forms out of paper in the mid 1980s and continued to work in this direction until 2008. He is considered the world-famous architect of folded structures made of paper. The technique of forming structures from one sheet of paper is based on Japanese traditions.

Examples of folded structures erected in the 20th century

Several types of folded structures are already discussed in the introduction. Let's explore this topic by introducing the most famous folds created in the 20th century and the less well-known but interesting structures in terms of geometry.

When considering folded structures, they are often illustrated by their architectural expressiveness in the example of the U.S. Air Force Cadet Church, consisting of inclined triangular prisms (figure 11), Colorado Springs, 1959-1962. This building became a classic example of modernist architecture, architect W. Netsch, engineer-constructor R.E. McKee.

The visitors were greatly impressed by the Soviet pavilion at EXPO-70 (figure 12) in Osaka, Japan, the covering and walls of which are folds. The pavilion was built by a Japanese company according to the project of M.V. Posokhin and V.A. Svirsky. The maximum height of the pavilion is 104 m.

Figure 11 - United States Air Force Academy Cadet Chapel

Figure 12 – Soviet pavilion at EXPO-70

Well-known folded structures include the church of Christ Dieter Oesterlen (Dieter Oesterlen's Christ Church) in Bochum (Bohum), West Germany, 1957-1959; Kirishima International Concert Hall (Miyama Conseru), Airagun, Japan. Fumihiko Maki, 1994 (figure 9); lightweight folding covering of monolithic reinforced cement folds of variable cross-section with a span of 28 m with double-sided cantilevers over the customs hall in the village of Torfyanovka on the Russian-Finnish border, hand. group of architects S. Speransky, 1966, etc.

Wood was used for the construction of folded domes. In work [16] examples of wooden domes are given. Their merits are illustrated by the example of a wooden folding dome above the pavilion "Hartwald Clinic Pavilion, Bad Zwesten Germany", arch. A. Frank (figure 13). Wooden folded structures (cross-laminated timber) in external and internal spatial forms of buildings is considered in the article [17]. It has been shown that buildings of this type become the most rational for some climatic conditions.

Figure 13 - Wooden folding dome, Germany, 1977

In the article [18] the authors assert that the best material for folded large-sized structures is reinforced concrete. To prove this statement they give many examples of erected structures of reinforced concrete and metal.

Examples of folded structures erected at the beginning of the 21st century

In recent decades, the folded set of planes has become widespread. Considering the fact that they can be assigned to non-convex polyhedra, such famous landmark structures are have reached quite a number to be mentioned. These include the Centre for Sustainable Energy Technology in Ningbo, China. M. Cucinella Archtects, 2008; Nestle Chocolate Museum (Toluca), 2007. M. Rojking, A. Pereyra, etc.; undulating walls and plating, outlined on linear surfaces, railway station in Reg-gio Emilia, 2013, S. Calatrava, etc.

The above discussed folded structures are, mainly, coatings of structures. But there are examples of folded structures that make up the walls of structures. For example, the oval sports and concert complex "Baku Crystal Hall" has walls in the form of rhythmically repeating identical polyhedra (figure 14). The complex was opened in 2012 in Baku, Arh. Alpine Bau Deutschland AG.

An interesting architectural solution of the building of the Centre de la Francophonie a Cotonou, Cotonou, Benin (figure 15).

Figure 14 - Baku Crystal Hall, Baku, Azerbaijan 2012

Figure 15 - Centre de la Francophonie, Cotonou, Benin

Let's illustrate the use of architectural techniques "Origanics" on concrete examples. The most famous building in this style is the Health Department in Bilbao (Bilbao Health Department), Spain, 2004. (figure 16) with a broken (folded) facade (arch). Coll-Barreu Architectos). Tel Aviv Museum of Fine Arts was founded in 1932. In 2011, a new grey concrete wing of the museum was opened (figure 17), designed in the style of "Origanics".

Figure 16 - The facade of the Health Department in Bilbao, Spain, 2004

Figure 17 - Tel Aviv Museum of Fine Arts, 2011

In addition, the following folded structures are made in the style of "Origanics": reinforced concrete chapel in Valleaceron (arch. Sol Madridejos, Juan Carlos Sancho, 2001), Spain; Church of

Santa Monica of plasterboard and corten steel (Vicent + Ramos Architectos, 2006), Spain; "Chap-el for the Deaconness, St. "Switzerland, 2008".

Currently, interest in the design of folding structures in Russia and abroad does not subside, as evidenced by the project of a new international terminal of the Muravyov-Amursky airport in Blagoveshchensk or the project of an open gallery (figure 18).

Figure 18 - Gallery of Open-Sided Shelter (arh. Ron Shenkin Studio-1)

Numerical methods for calculating folded structures

In the first half of the XX century, analytical methods of calculation of building structures [19, 20] were mainly used, which caused great difficulties in the design of folded structures, except for solid slabs-folds on the "span". Since the second half of the last century, numerical methods of calculation have been introduced. This greatly simplified the process of designing folded structures. Numerical calculation methods seem to have influenced the wider adoption of folded shells. Currently, architects and design engineers have a wide range of numerical methods for calculating folds on stability [21], on strength [22, 23], on dynamic effects [24].

Conclusion

Studies of available materials suggest that folded structures were in most cases used in construction in the 1980s. But in the 21st century they are used on a large scale. A large number of scientific and technical articles have been published on the subject of the article, some of which are listed in the list of used literature. In these sources and on various Internet sites, very many real flat-sided folded structures and structure projects are described for implementation. To give illustrations of all these folded structures of different purposes in one article or book is unrealistic. Only a very small part of realized folded structures is given in this article. On the basis of the above, it can be concluded that the folds were used and used very widely in various areas of architecture and construction. The availability of numerical methods of calculation allows to design structures of various degrees of complexity.

But some architects believe that despite many attempts to understand the fold, it still remains one of the least studied forms in architecture [14], that is, the artistic and aesthetic potential of folded forms is not fully disclosed and deserves more attention of experts in this direction.

A.V. Korotich [25] believes that the planar folds are well studied and proposes to expand the range of folding systems by means of tent tensioning shells, convertible quickerectable structures and shells of fractal structure. He believes that research into shells that do not have a planar structure is particularly relevant today and that of all possible ways to model folding systems, the most productive is the experimental approach.

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