2020. 16(4). 271–278

СТРОИТЕЛЬНАЯ МЕХАНИКА ИНЖЕНЕРНЫХ КОНСТРУКЦИЙ И СООРУЖЕНИЙ

STRUCTURAL MECHANICS OF ENGINEERING CONSTRUCTIONS AND BUILDINGS

HTTP://JOURNALS.RUDN.RU/STRUCTURAL-MECHANICS

ГЕОМЕТРИЯ СРЕДИННЫХ ПОВЕРХНОСТЕЙ ОБОЛОЧЕК
GEOMETRY OF MIDDLE SURFACES OF SHELLS

DOI 10.22363/1815-5235-2020-16-4-271-278
UDC 514.8:539.3:72.01

RESEARCH PAPER

The opportunities of umbrella-type shells

Sergey N. Krivoshapko

Peoples' Friendship University of Russia (RUDN University), 6 Miklukho-Maklaya St, Moscow, 117198, Russian Federation
krivoshapko-sn@rudn.ru

Article history:
Received: March 19, 2020
Revised: May 23, 2020
Accepted: June 29, 2020

For citation
Krivoshapko S.N. The opportunities of umbrella-type shells. *Structural Mechanics of Engineering Constructions and Buildings.* 2020;16(4):271–278. http://dx.doi.org/10.22363/1815-5235-2020-16-4-271-278

Abstract

Relevance. The necessity of division of umbrella surfaces and surfaces of umbrella type into two separated classes is explained in introduction. Earlier, umbrella surfaces and surfaces of umbrella type were in the same class of surfaces because they consist of the identical fragments lying on the surfaces of revolution. Umbrella surfaces are compound surfaces on the base surface of revolution but umbrella-type surfaces are kinematic surfaces formed by continuous movement of a changing curve and that is why taking into account the methods of construction of these surfaces they were divided in two separate classes. ***The aim of the work*** is a collection of main publications on all areas of the investigation of umbrella-type shells. ***Methods.*** For the determination of principal results of investigation of umbrella-type shells, it is necessary to know differential geometry of surfaces, structural mechanics of thin shells, and approaches used in architecture of spatial structures. ***Results.*** In this article, the principal scientific papers on geometry, strength analysis, and offers of applications of thin-walled shells of umbrella type in building and of reflectors of umbrella type for space apparatuses. The accurate parametric equations of some determined surfaces are presented. The approximated computer models of middle surfaces of the real umbrella shells but in the form of umbrella-type surfaces are given. The examples of determination of stress-strain state of thin-walled shells of umbrella type without dividing of the whole shell in identical fragments are shown. New information and materials already known about shells of umbrella type give reasons to suppose that the shells of this type will be claimed by engineers and architects.

Keywords: umbrella shell, shell of umbrella type, waving dome, reflector of umbrella type for space apparatus, shell of radar installation, finite difference energy method

Introduction

At present, the movement in the direction of increasing of the interest for design of large-span structures begins to show. Interesting facts from the history of building and design of thin-walled spatial structures and perspectives of their application in future are presented in a review paper [1] where the authors insist that "there are signs, however, that shells are attracting interest among the new generation of architects and engineers". The modern architects' views at the place of shell structures in modern architecture of arbitrary forms and in building are set forth in papers [2; 3].

Consider the investigations on geometry, analysis, and application of umbrella-type shells and show up their advantages in comparison with umbrella shells.

Sergey N. Krivoshapko, Professor of the Department of Civil Engineering of Academy of Engineering, DSc, Professor, eLIBRARY SPIN-code: 2021-6966, ORCID iD: https://orcid.org/0000-0002-9385-3699

The definitions of umbrella surfaces and umbrella-type surfaces are given in a monograph [4] or in an encyclopedia [5]. Adduce them almost word for word.

"A cyclic symmetrical spatial structure formed from several identical elements is called *an umbrella dome* (Figure 1). Curves obtained as a result of the intersection of their middle surfaces are the generatrix curves of any dome-shaped surface of revolution. A dome-shaped surface of revolution, on which the contour curves of the elements of a dome are placed, is called *a contour surface*. The contour curves of the element are the curves bounding the contour of the middle surface of the element of the dome."

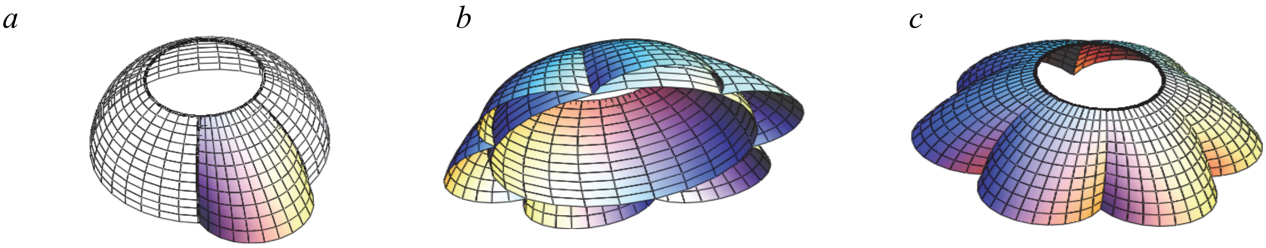


Figure 1. The formation of an umbrella dome with the opening at the top [6; 7]

In scientific and technical literature, the shells put together from identical fragments of the hypar are also called umbrella domes. F. Candela [4; 8] designed and built the first umbrella shell in the form of four intersecting hypars that formed a covering of a restaurant in Xochomilco, Mexico, in 1957.

"The cyclic symmetrical surfaces consisting from several identical elements are called *surfaces of umbrella type*. But unlike an umbrella surface, the whole surface of umbrella type and all surfaces of the identical elements forming the whole surface are determined by one and the same explicit, implicit or parametrical equations. In popular scientific literature, the umbrella-type shells are often called also waving or wave-shaped domes."

Much useful information is presented in a manuscript [9] where 240 individual solutions of different domes are given and various classifications are presented. Some types of domes presented in this manuscript can be reckoned among umbrella shells, for example, *wave-and-folded domes* with folds of arched form and *segment domes*.

The results of investigation

A review of researches on geometry of umbrella-type surfaces

Firstly, umbrella-type surfaces were introduced into practice in papers [10; 11] where fourteen surfaces were proposed, their analytical formulas were given, and Gaussian quantities of the first and second orders in the theory of surfaces were obtained. Later, a part of these surfaces was investigated with the help of the MathCAD computer program in a work [12] where changes of the surface form were examined depending on constant parameters containing in analytical equations of surfaces of umbrella type.

Two surfaces from fourteen surfaces presented in works [10; 11] were offered by other authors. These are the Skidan's ruled surface [13] and the crossed trough [14. P. 286]. V.N. Ivanov [15] offered a method of forming of the umbrella-type surface in the shape of Joachimsthal canal surface with a director circular sinusoid. This surface is formed by the rotation of the circle of variable radius with the common chord [16] (Figure 2). The generatrix circles of canal surfaces are lines of principal curvature. Cutting out from the common surface the fragment with radii r_1 and R, one can obtain an umbrella-type shell with the opening at the vertex.

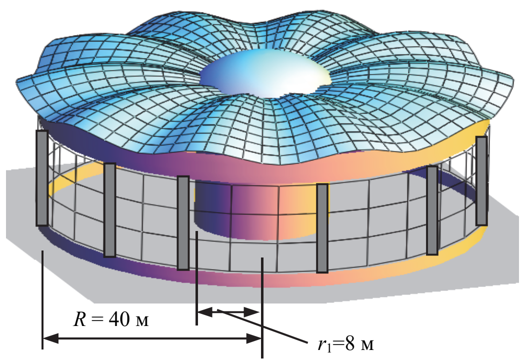


Figure 2. A surface of umbrella type on the base of the canal surface of Joachimsthal [15]

Following after V.N. Ivanov's method [16], his postgraduate student Nasr Younis A. Abboushi [17] made several models of Joachimsthal canal surfaces defining three methods of their formation:

1) a surface is formed by the rotation of the circle of variable radius $R(u)$ so that a distance from the axis of rotation till the point of contact with the generatrix circle $c = (r^2 - R^2)^{1/2}$ remains constant;

2) a surface is formed by the rotation of the circle of variable radius $R(u)$ around the common chord;

3) a surface is formed by the rotation of the circle of variable radius $R(u)$ around the common tangent, i.e. $c = 0$, $r = R$. Here, $r(u)$ is a distance from the axis of rotation till the center of the generatrix circle.

The methods 2 ($r < R$) and 3 ($r = R$) give the opportunity to obtain umbrella-type surfaces.

A computer program in the AutoCAD system for tracing of umbrella-type surfaces with parabolic generatrixes and with a circular opening at the vertex is presented in a paper [18]. It gives the possibility to consider a process of forming umbrella-type surfaces in dynamic conditions by means of making mini-film. Analogous program for another surface of umbrella type is given in a paper [19] (Figure 3).

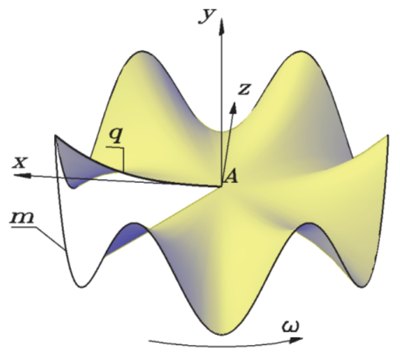


Figure 3. A forming surface with radial sinusoidal waves damping in the central point and formed by the cubic parabolas

Umbrella-type surfaces with elliptic contour surfaces and with the circular sinusoidal equator were taken as a base of research of waving domes in a paper [20]. A vector equation of the waving ellipsoidal surface may taken in the form

$$\boldsymbol{r}(u,v) = a\{[1 + \mu\cos(pu)]\cos v \cdot \boldsymbol{h}(u) + \gamma\sin v\boldsymbol{k}\},$$
$$\boldsymbol{h}(u) = \boldsymbol{i}\cos u + \boldsymbol{j}\sin u,\ \gamma = b/a, \qquad (1)$$

where a, b are the semi-axes of the ellipsoid of revolution; u, v are the parameters at the interval $[0, \pi]$; $\boldsymbol{i}, \boldsymbol{j}, \boldsymbol{k}$ are the unit vectors; μ is a ratio of the amplitude of the sinusoid to the radius a of the circle; p is a number of waves of the sinusoid. The waving ellipsoidal surfaces were modeled under different parameters γ, μ, p.

Umbrella shells and umbrella-type shells in architecture and technics in the 20th and 21st centuries

It should be noted, that umbrella shells are presented in architecture of the 20th century very widely [4; 21]. Real erections in the form of umbrella-type surfaces were not found. But outward examination of some shells showed that their middle surfaces can be quite given by analytical formulae, i.e. these shells can be number among umbrella-type shells. For example, a covering of a restaurant attached to a hotel “La Concha Hotel”, San Juan, Puerto Rico [22], arch. Jose R. Marchand, 2009 [Available from: http://www.architecturaldigest.com/homes/hotels/2009], can be approximated by a paraboloid of revolution with four radial waves [5. P. 388] or by a surface with astroidal level lines that is generated by biquadratic parabolas [5. P. 392].

A wave-shaped surface of the Marché Royan, France, consisting of 13 reinforced sinusoidal parabolic fragments is well simulated by a paraboloid of revolution with radial waves [5. P. 388], that has a parametrical form of definition:

$$x = x(u,v) = cu\cos v,$$
$$y = y(u,v) = cu\sin v,$$
$$z = z(u,v) = [a\sin(nv) + b]u^2, \qquad (2)$$

where v is the angle read from the axis Ox in the direction to the axis Oy; $a = \text{const}$ is an amplitude of a wave; n is a number of the vertexes of the waves; b is a constant parameter of the datum paraboloid of revolution, $c = \text{const}$. W

When $a = 0$, a paraboloid of revolution with radial waves degenerates into a paraboloid of revolution. The real shell has a 100 mm thickness and a 50 m span. It supports at 13 points along the outward perimeter (Figure 4). A market was built in 1956 and now it is architectural and historical possessions of the town.

Figure 4. Marché Royan, France, and its possible computer model

The three-tiered many-waved umbrella church in the suburb of St. Louis (USA) designed by G. Obata with participation of P.L. Nervi apparently was arranged from fragments of cylindrical parabolic shells [22; 23]. Middle surfaces of these three tiers can be easily approximated by a paraboloid of revolution with radial waves (Figure 5), i.e. by a surface of umbrella type (2) $a = b$.

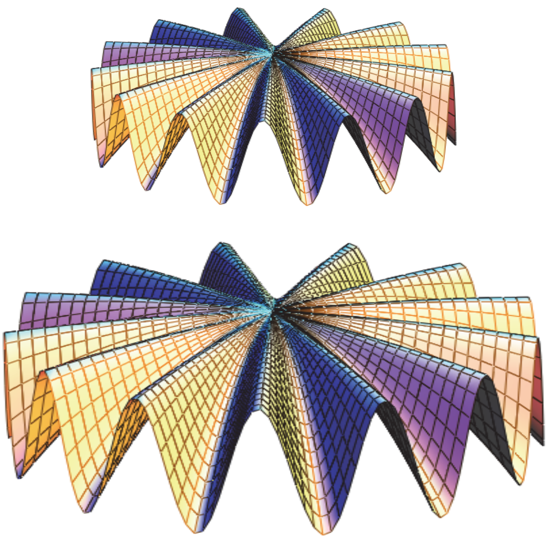


Figure 5. Approximated two lower tiers
in the suburb of St. Louis, USA, 1966

Umbrella glass-fibre plastic dome of radar installation consist of fragments of the same type united between themselves by bolted joints (Figure 6, *a*) [24]. The joints are sealed by glass fabric on elastic special mastic. Airports Domodedovo, Vnukovo, Sheremetyevo, and other airports of Russia exploit the shells of this type. The form of these domes is rather like surface of a sphere with external cycloidal crimps (Figure 6, *b*) which may be given by parametrical equations:

$$x = x(u,\varphi) = \left[(R+r)\cos\varphi - r\cos(n+1)\varphi\right]\cos u,$$
$$y = y(u,\varphi) = \left[(R+r)\sin\varphi - r\sin(n+1)\varphi\right]\cos u,$$
$$z = z(u) = R\sin u,$$

where u is the angle read from the plane xOy in the direction of the axis Oz; $0 \le z \le R$; $0 \le \varphi \le 2\pi$; $0 \le u \le \pi/2$. In the cross section of the surface in question by the planes z = const, i.e., when $u = u_0$ = const, we have the epicycloids:

$$x = x(\varphi) = \left[(R+r)\cos\varphi - r\cos(n+1)\varphi\right]\cos u_0,$$
$$y = y(\varphi) = \left[(R+r)\sin\varphi - r\sin(n+1)\varphi\right]\cos u_0$$

with n = const, n is a number of the vertexes of the epicycloid on the circular plane; $n = R/r$, $2r$ is the maximum amplitude of the crimps at the base of the surface; R is a radius of the equator of the sphere; φ is the angle read from the axis Ox in the direction of the axis Oy.

In case of need, domes of radar installation can be designed in the form of corrugated paraboloid of revolution with external crimps (Figure 6, *c*) with a circular waving curve at the foot with the vertexes directed out of the center of the circular base:

$$x = (R + a|\cos n\varphi|)\cos\varphi,$$
$$y = (R + a|\cos n\varphi|)\sin\varphi, \quad z = 0,$$

where n is a number of the vertexes of the sinusoid on a circular plan; a is an amplitude of the crimps at the foot of the surface; R is a radius of the base circle of the corrugated paraboloid in the foot relative to which, the circular sinusoid is constructed.

Parametrical of the definition of the corrugated paraboloid of revolution with the external crimps:

$$x = x(r,\varphi) = r\left(1 + \frac{ar|\cos n\varphi|}{R^2}\right)\cos\varphi,$$

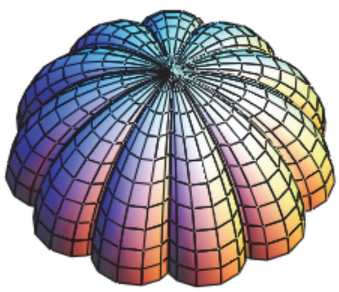
$$y = y(r,\varphi) = r\left(1 + \frac{ar|\cos n\varphi|}{R^2}\right)\sin\varphi,$$

$$z = z(r) = h\left(1 - \frac{r^2}{R^2}\right),$$

where h is the height of a corrugated paraboloid of revolution, $0 \le z \le h$; $0 \le \varphi \le 2\pi$; $0 \le r \le R$.

a

b



c

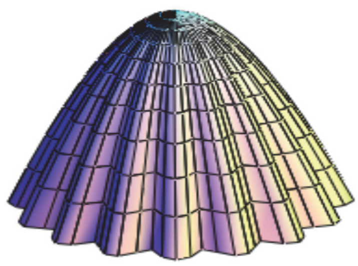


Figure 6. An umbrella dome (*a*) and computer models of the umbrella-type shells (*b, c*):
a – the composite shell of radar installation (OAO “Avangard”); *b* – a sphere with external cycloidal crimps (n = 12);
c – a corrugated paraboloid of revolution with external crimps

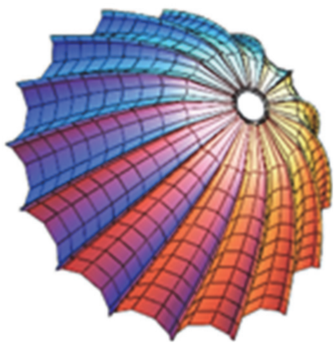


Figure 7. A form of a parabolic reflector of umbrella type

a *b*

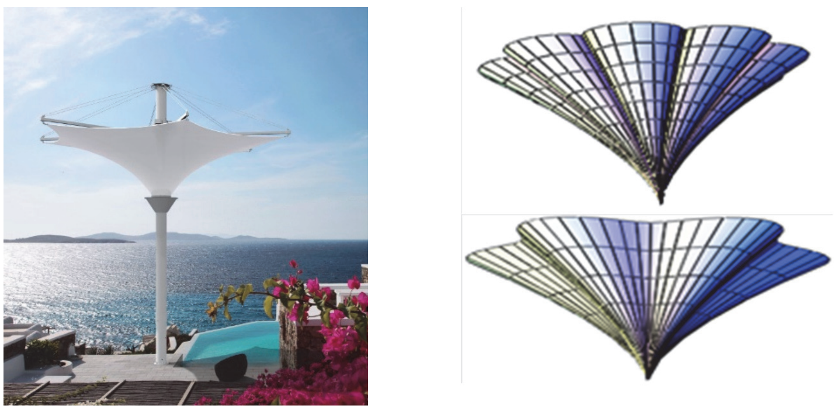


Figure 8. The tent umbrella structure and its proposed computer models

One can find several works devoted to design of parabolic reflectors of antennas of space apparatus of umbrella type. In a paper [25], a review of results of modeling of parabolic reflectors the structure of which consist of parabolic spokes and a form of the reflecting surface is created by metal mesh cloth. The initial form of the spokes coincides with contour curves on a theoretical paraboloid. Having assumed an edge of a reflector in the form of a hypocycloid one may create a surface of umbrella type with the parabolic generatrixes and the round opening at the vertex [5. P. 389] (Figure 7). In any cross section of the surface by a plane passing through the central axis, the parabola would be placed. Suitableness of the proposed surface for the reflectors with taking into account distortion of the reflecting surface one can corroborate only by experimental measurements.

Designers offer enormous choice of tent umbrella structures for sheltering from the sun and rain. For these purposes, it is possible to use existing surfaces of umbrella type. For example, architectural street umbrellas "Edelveis" designed by specialists of the firm "TeniRadi" are unique durable umbrella structures for using at the grounds with large wind loads (Figure 8, *a*). They have built-in drainage system. In Figure 8, *b*, two possible forms for approximation of a surface of an umbrella shown in Figure 8, *a* are presented. The upper surface is a surface of umbrella type on the cycloidal plan formed by semi-cubic parabolas, the lower surface is a waving surface formed by semi-cubic parabolas with the waving foot line [10; 11].

The works on strength analysis of umbrella-type shells

At the middle of the 20th century, some principles of forming surfaces of umbrella and umbrella-type domes and methods of their strength analysis were absent and that is why architectural and technical conceptions were bound [26]. But attempts of building of umbrella domes were undertaken by different architects and builders. Simplified methods of strength analysis were offered. For example, every fragment of the covering of the market in Royan (Figure 4) was considered as a beam on two hinges: at the foot and at the vertex of the dome. Taking into account that the covering works already 60 years, an analysis circuit was chosen successfully and can be recommended for preliminary calculation of umbrella-type shells at present time.

As it was noted before, middle surfaces of umbrella-type shells are defined by one analytical equation and it gives the opportunity to use the standard computer programs and to derive author's programs for static and dynamic analysis of considered shells on diverse types of loading.

For example, a thin shell shown in Figure 2 was examined on action of dead load with the help of finite difference energy method [15]. This method was used also for strength analysis of two types of umbrella-type shells with middle surfaces in the form of Joachimsthal canal surfaces. They were subjected to action of their own weight [27].

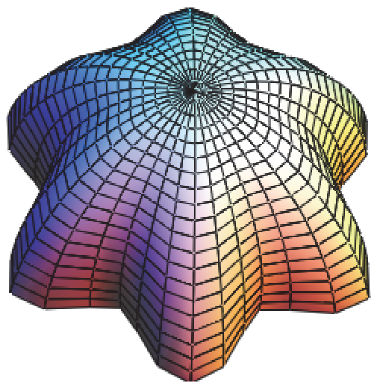


Figure 9. A corrugated sphere

A finite element analysis of stress-strain state of a reinforced concrete shell of umbrella type with an elliptic contour surface (1) was realized in a work [20]. The analysis was fulfilled on action of the own weight when $\gamma = 1$ and the shell has the hinged supports. A program complex LIRA SAPR 2013 was applied. It was established on the example of a shell with the sphere contour surface (Figure 9) that a waving shell has more rigidity but in the comparison with the smooth shell, torque internal moments appear. Considerable reduction of strength characteristics when a spherical contour middle surface of the shell is substituted for the elliptic surface is not observed. We can increase rigidity of the shell if we shall increase the vertical semi-axis of the ellipse.

Conclusion

Builders began to erect umbrella stone domes several hundred years ago but thin-walled umbrella shells appeared only in the middle of the 20th century. At that time, geometrical science could not give a strict definition of umbrella surface. A shell divided into identical segments and analysis fulfilled for one fragment but the results applied to all shell.

At the beginning of 21st century, analytical umbrella-type surfaces were singled out of a class of umbrella surfaces into the separate class. More than two tens of new surfaces were introduced into practice. Scientific papers devoted to the determination of stress-strain state of umbrella-type shells and suggestions on their application began to appear. At present, only numerical methods of analysis are applied.

Real umbrella-type shells were not used else. But the author agrees with V.A. Lebedev [26] that "revival of highly artistic umbrella form in modern dome building is possible only in the shape of thin-walled structures. <…> These forms undoubtedly must find the wide application in building".

References

1. Bradshaw R., Campbell D., Gargari M., Mirmiran A., Tripeny P. Special structures. Past, present, and future. *Journal of Structural Engineering*. 2002:691–701.

2. Krivoshapko S.N. On opportunity of shell structures in modern architecture and building. *Structural Mechanics of Engineering Constructions and Buildings*. 2013;(1):51–56. (In Russ.)

3. Krivoshapko S.N. Shells and rod structures in the form of analytically non-given surfaces in modern architecture. *Building and Reconstruction*. 2020;(3):20–30. (In Russ.)

4. Krivoshapko S.N., Mamieva I.A. *Analiticheskie poverhnosti v arhitekture zdaniy, konstruktziy i izdeliy* [*Analytical Surfaces in Architecture of Buildings, Structures, and Products*]: monography. Moscow: LIBROCOM Publ.; 2012. (In Russ.)

5. Krivoshapko S.N., Ivanov V.N. *Entsiklopediya analiticheskikh poverkhnostei* [*Encyclopedia of analytical surfaces*]. Moscow: LIBROKOM Publ.; 2010. (In Russ.)

6. Ivanov V.N., Krivoshapko S.N. Design of umbrella shells from the fragments of cyclic translation shells. *Structural Mechanics of Engineering Constructions and Buildings*. 2011;(1): 3–7. (In Russ.)

7. Bock Hyeng Ch.A., Krivoshapko S.N. Umbrella-Type Surfaces in Architecture of Spatial Structures. *IOSR Journal of Engineering* (*IOSRJEN*). 2013;3(3):43–53.

8. Draper P., Garlock M.E.M., Billington D.P. Structural optimization of Félix Candela's hypar umbrella shells. *Journal of the International Association for Shells and Spatial Structures*. 2012;51(1):59–66.

9. Tsvingman G.A. Types principaux des domes, leur construction et l'architecture. In: Alexandrov A.J. (redacteur) *Problèmes D'Architecture: Recueil des Matèriaux* (vol. 1, livre 2). Academie D'Architecture De L'Union des R.S.S; 1936. p. 25–385. (In Russ.)

10. Krivoshapko S.N. Geometrical investigations of surfaces of umbrella type. *Structural Mechanics of Engineering Constructions and Buildings*. 2005;(1):11–17. (In Russ.)

11. Krivoshapko S.N. New examples of surfaces of umbrella type and their coefficients of fundamental forms of surfaces. *Structural Mechanics of Engineering Constructions and Buildings*. 2005;(2):6–14. (In Russ.)

12. Ariarskyi O., Shagalova I., Kravchenko T., Kulakova E. Umbrella surfaces morphology and their application in the architecture and design. *Pratzi TDATU*. 2011; 4(49):178–190. (In Russ.)

13. Skidan I. General analytical theory of applied formation. *The 10th International Conference on Geometry and Graphics (July 28 – August 2, 2002, Kyiv, Ukraine)*. 2002; 1:104–107.

14. Von Seggern D.H. *CRC Standard Curves and Surfaces*. Boca Raton, FL: CRC Press; 1993.

15. Ivanov V.N. Analyses of stress-strain state of roofing of trade center in the form of umbrella shell by difference variation method. *Structural Mechanics of Engineering Constructions and Buildings*. 2008;(4):86–89. (In Russ.)

16. Ivanov V.N. Kanalovye poverkhnosti Ioakhimstalya s ploskoi liniei tsentrov [Canal Joachimsthal surfaces with plane line of the centers]. *Issledovaniya prostranstvennykh system* [*Research of spatial systems*]: materials of the seminar of the Department of Resistance of Materials of RUDN University]. Moscow: RUDN University Publ.; 1996. p. 32–36. (In Russ.)

17. Abboushi N.Y.A. Volnoobraznye kupola [Wave-shaped domes]. *Stroitelnaya mekhanika inzhenernykh konstruktsii i sooruzhenii* [*Structural Mechanics of Engineering Constructions and Buildings*]: interuniversity collection of scientific papers. 2002;(11):49–58. (In Russ.)

18. Romanova V.A. Features of the image of process of formation of surfaces in AutoCad system. *Structural Mechanics of Engineering Constructions and Buildings*. 2014;(3):19–22. (In Russ.)

19. Romanova V.A. Visualization of forming of umbrella-type and umbrella surfaces with radial damping waves in the central point. *Structural Mechanics of Engineering Constructions and Buildings*. 2015;(3):4–8. (In Russ.)

20. Chepurnenko A.S., Kochura V.G., Saybel A.V. Finite elemental analysis of the stress deformed condition of waveform shells. *Construction and Industrial Safety*. 2018;11(63):27–31. (In Russ.)

21. Krivoshapko S.N., Alborova L.A. *Unikalnye sooruzheniya v forme lineichatykh, zontichnykh poverkhnostei, poverkhnostei vrashcheniya i perenosa* [*Unique Erections in the Form of Ruled, Umbrella Surfaces, Surfaces of Revolution and Translation*]. Moscow: VNIINTPI Publ.; 2008. (In Russ.)

22. Krivoshapko S.N., Mamieva I.A. Umbrella surfaces and surfaces of umbrella type in the architecture. *Prom. i grazhdansk. stroitelstvo*. 2011;7(1):27–31. (In Russ.)

23. Maan H. Jawad. *Design of Plate & Shell Structures*. ASME PRESS, NY; 2004.

24. Krivoshapko S.N. The perspectives of application of thin-walled plastic and composite polymer shells in civil and industrial architecture. *Journal of Reinforced Plastics and Composites*. 2018;37(4):217–229. doi: 10.1177/07316 84417740770.

25. Ponomarev S.V. Transformed reflectors of antennas of space apparatus. *Vestnik Tomskogo Gos. Universiteta*. 2011;4(16):110–119. (In Russ.)

26. Lebedev V.A. *Tonkostennye zontichnye obolochki* [*Thin-Walled Umbrella Shells*]. Leningrad: Gosstroyizdat Publ.; 1958. (In Russ.)

27. Abboushi N.Y.A. Chislennyi analiz kanalovykh poverkhnostei Ioakhimstalya na sobstvennyi ves variatsionno-raznostnym metodom [Numerical analysis of Joachimsthal's canal surfaces on a gravity load by variation-difference method]. *Arkhitektura obolochek i prochnostnoi raschet tonkostennykh stroitelnykh i mashinostroitelnykh konstruktsii slozhnoi formy* [*Shells in Architecture and Strength Analysis of Thin-Walled Civil-Engineering and Machine-Building Constructions of Complex Forms*]: Proc. of Int. Scientific Conference (Moscow, June 4–8, 2001). Moscow: RUDN University Publ.; 2001. p. 297–306. (In Russ.)

DOI 10.22363/1815-5235-2020-16-4-271-278

НАУЧНАЯ СТАТЬЯ

Возможности оболочек зонтичного типа

С.Н. Кривошапко

Российский университет дружбы народов, Российская Федерация, Москва, 117198, ул. Миклухо-Маклая, 6
krivoshapko-sn@rudn.ru

История статьи:
Поступила в редакцию: 19 марта 2020 г.
Доработана: 23 мая 2020 г.
Принята к публикации: 29 июня 2020 г.

Аннотация

В статье объясняется ***актуальность*** разделения зонтичных поверхностей и поверхностей зонтичного типа на два разных класса. Раньше зонтичные поверхности и поверхности зонтичного типа входили в один класс поверхностей, так как состоят из тождественных фрагментов, лежащих на поверхности вращения. Учитывая способ построения этих поверхностей, а именно то, что зонтичные поверхности – составные поверхности на базовой поверхности вращения, а поверхности зонтичного типа – кинематические поверхности, образованные непрерывным движением изменяющейся кривой, они были разделены на два отдельных класса. ***Цель статьи*** – собрать воедино основные публикации по всем разделам исследований оболочек зонтичного типа. ***Методы.*** Для получения основных результатов исследований оболочек зонтичного типа были изучены сведения о дифференциальной геометрии поверхностей, строительной механике оболочек и подходах, используемых в архитектуре пространственных структур. ***Результаты.*** Представлены основные научные работы по геометрии, расчету и предложениям по применению тонкостенных оболочек зонтичного типа в строительстве и для рефлекторов зонтичного типа космических аппаратов. Приведены уточненные параметрические уравнения некоторых рассматриваемых поверхностей. Продемонстрированы аппроксимационные компьютерные модели срединных поверхностей существующих зонтичных оболочек, но в форме поверхностей зонтичного типа. Показаны примеры определения напряженно-деформируемого состояния тонкостенных оболочек зонтичного типа без разбиения целой оболочки на тождественные фрагменты. Полученные новые и уже известные сведения об оболочках зонтичного типа дают основания предполагать, что оболочки этого типа будут востребованы инженерами и архитекторами.

Ключевые слова: зонтичная оболочка, оболочка зонтичного типа, волнистый купол, рефлекторы зонтичного типа космических аппаратов, оболочка радиолокационной станции, вариационно-разностный метод расчета

Для цитирования
Krivoshapko S.N. The opportunities of umbrella-type shells // Строительная механика инженерных конструкций и сооружений. 2020. Т. 16. № 4. С. 271–278. http://dx.doi.org/10.22363/1815-5235-2020-16-4-271-278

Кривошапко Сергей Николаевич, профессор департамента строительства Инженерной академии, доктор технических наук, eLIBRARY SPIN-код: 2021-6966, ORCID iD: https://orcid.org/0000-0002-9385-3699

Список литературы

1. *Bradshaw R., Campbell D., Gargari M., Mirmiran A., Tripeny P.* Special structures. Past, present, and future // Journal of Structural Engineering. 2002, June. Pp. 691–701.

2. *Кривошапко С.Н.* О возможностях оболочечных сооружений в современной архитектуре и строительстве // Строительная механика инженерных конструкций и сооружений. 2013. № 1. С. 51–56.

3. *Кривошапко С.Н.* Оболочки и стержневые структуры в форме аналитически незадаваемых поверхностей в современной архитектуре // Строительство и реконструкция. 2020. № 3. С. 20–30.

4. *Кривошапко С.Н., Мамиева И.А.* Аналитические поверхности в архитектуре зданий, конструкций и изделий: монография. М.: ЛИБРОКОМ, 2012. 328 с.

5. *Кривошапко С.Н., Иванов В.Н.* Энциклопедия аналитических поверхностей. М.: ЛИБРОКОМ, 2010. 560 с.

6. *Иванов В.Н.*, *Кривошапко С.Н.* Конструирование зонтичных оболочек из отсеков циклических оболочек переноса // Строительная механика инженерных конструкций и сооружений. 2011. № 1. С. 3–7.

7. *Bock Hyeng Ch.A., Krivoshapko S.N.* Umbrella-Type Surfaces in Architecture of Spatial Structures // IOSR Journal of Engineering (IOSRJEN). 2013. Vol. 3. Issue 3. Pp. 43–53.

8. *Draper P., Garlock M.E.M., Billington D.P.* Structural optimization of Félix Candela's hypar umbrella shells // Journal of the International Association for Shells and Spatial Structures. 2012. Vol. 51. No. 1. Pp. 59–66.

9. *Цвингман Г.А.* Основные типы куполов, их конструкция и архитектура // Проблемы архитектуры: сб. материалов: в 2 т. Т. 1. Кн. 2 / под ред. А.Я. Александрова. М.: Изд-во Всесоюзной Академии архитектуры, 1936. С. 25–385.

10. *Кривошапко С.Н.* Геометрические исследования поверхностей зонтичного типа // Строительная механика инженерных конструкций и сооружений. 2005. № 1. С. 11–17.

11. *Кривошапко С.Н.* Новые примеры поверхностей зонтичного типа и их коэффициенты основных квадратичных форм // Строительная механика инженерных конструкций и сооружений. 2005. № 2. С. 6–14.

12. *Ариарский О.Е., Шагалова И.В., Кравченко Т.В., Кулакова Е.А.* Формообразование зонтичных оболочек и их применение в архитектуре и дизайне // Праці ТДАТУ. 2011. Т. 49. Вип. 4. С. 178–190.

13. *Skidan I.* General analytical theory of applied formation // The 10th International Conference on Geometry and Graphics (July 28 –August 2, 2002, Kyiv, Ukraine): in 2 vols. Vol. 1. Kyiv, 2002. Pp. 104–107.

14. *Von Seggern D.H.* CRC Standard Curves and Surfaces. Boca Raton, FL: CRC Press, 1993. 388 p.

15. *Иванов В.Н.* Расчет напряженно-деформированного состояния покрытия торгового центра в форме оболочки зонтичного типа вариационно-разностным методом // Строительная механика инженерных конструкций и сооружений. 2008. № 4. С. 86–89.

16. *Иванов В.Н.* Каналовые поверхности Иоахимсталя с плоской линией центров // Исследования пространственных систем: материалы семинара кафедры сопротивления материалов РУДН. М.: Изд-во РУДН, 1996. С. 32–36.

17. *Аббуши Н.Ю.А.* Волнообразные купола // Строительная механика инженерных конструкций и сооружений: межвуз. сб. науч. трудов. Вып. 11. М.: Изд-во АСВ, 2002. С. 49–58.

18. *Романова В.А.* Визуализация образования поверхностей зонтичного типа // Строительная механика инженерных конструкций и сооружений. 2014. № 3. С. 19–22.

19. *Романова В.А.* Визуализация образования зонтичных поверхностей и поверхностей зонтичного типа с радиальными волнами, затухающими в центральной точке // Строительная механика инженерных конструкций и сооружений. 2015. № 3. С. 4–8.

20. *Чепурненко А.С., Кочура В.Г., Сайбель А.В.* Конечно-элементный анализ напряженно-деформированного состояния волнистых оболочек // Строительство и техногенная безопасность. 2018. № 11 (63). С. 27–31.

21. *Кривошапко С.Н., Алборова Л.А.* Уникальные сооружения в форме линейчатых, зонтичных поверхностей, поверхностей вращения и переноса. М.: ВНИИНТПИ, 2008. 42 с. (Строительство и архитектура. Вып. 2. Строительные конструкции и материалы).

22. *Кривошапко С.Н., Мамиева И.А.* Зонтичные поверхности и поверхности зонтичного типа в архитектуре // Промышленное и гражданское строительство. 2011. № 7 (1). С. 27–31.

23. *Maan H. Jawad*. Design of Plate & Shell Structures. ASME PRESS, NY, 2004. 476 p.

24. *Krivoshapko S.N.* The perspectives of application of thin-walled plastic and composite polymer shells in civil and industrial architecture // Journal of Reinforced Plastics and Composites. 2018. Vol. 37. Issue 4. Pp. 217–229. doi: 10.1177/0731684417740770.

25. *Пономарев С.В.* Трансформируемые рефлекторы антенн космических аппаратов // Вестник Томского государственного университета. 2011. № 4 (16). С. 110–119.

26. *Лебедев В.А.* Тонкостенные зонтичные оболочки. Л.: Госстройиздат, 1958. 172 с.

27. *Аббуши Н.Ю.А.* Численный анализ каналовых поверхностей Иоахимсталя на собственный вес вариационно-разностным методом // Архитектура оболочек и прочностной расчет тонкостенных строительных и машиностроительных конструкций сложной формы: труды Международной научной конференции (Москва, 4–8 июня 2001 г.). М.: Изд-во РУДН, 2001. С. 297–306.