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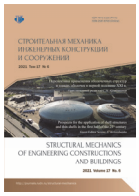

ОТ ПРИГЛАШЕННОГО РЕДАКТОРА ТЕМАТИЧЕСКОГО НОМЕРА ЖУРНАЛА
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Shell structures and shells at the beginning of the 21st century

Sergey N. Krivoshapko

Peoples' Friendship University of Russia (RUDN University), Moscow, Russian Federation
✉ sn_krivoshapko@mail.ru

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Abstract. Researchers know that "golden century of shells" falls on 1920–1960 when the finishing of building of a thin-walled shell became an important event in life of country where this shell was erected. Every built shell was analyzed in tens of scientific works with a point of view of used method of analysis, applied constructive materials, cost of erection. Later on, an interest to thin-walled shells fell down. On the base of the fulfilled research in a paper, it is shown that application of shell structures is increasing in the 21st century because it was closely connected with needs of different branches of human activity. It is proved, that practically in all countries of the world, design and building of shell structures and shells was carried out. Only priority in application constructive materials changed. In the main, reinforced concrete was used earlier but now bar curvilinear structures, composite shells, and bar structures with the glass filling are in priority. It is shown that young and prominent architects and engineers tale part in construction of considered structures and thin-walled shells. All conclusions are confirmed by references containing 38 used original sources.

Keywords: architectural styles, constructive building materials, thin-walled shell, shell architecture, shell analysis

Оболочечные структуры и оболочки в начале XXI в.

С.Н. Кривошапко

Российский университет дружбы народов, Москва, Российская Федерация
✉ sn_krivoshapko@mail.ru

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Аннотация. Общепризнано, что «золотой век оболочек приходится на 1920–1960-е гг., когда окончание строительства тонкостенной оболочки считалось важным событием в жизни страны, где оболочка возводилась. Каждая построенная оболочка анализировалась в десятках научных работ

Sergey N. Krivoshapko, DSc, Professor of the Department of Civil Engineering, Academy of Engineering, Peoples' Friendship University of Russia (RUDN University), 6 Miklukho-Maklaya St, Moscow, 117198, Russian Federation; ORCID: 0000-0002-9385-3699, eLIBRARY SPIN-code: 2021-6966, Scopus Author ID: 6507572305; sn_krivoshapko@mail.ru

Кривошапко Сергей Николаевич, доктор технических наук, профессор департамента строительства, Инженерная академия, Российский университет дружбы народов, Российская Федерация, 117198, Москва, ул. Миклухо-Маклая, д. 6; ORCID: 0000-0002-9385-3699, eLIBRARY SPIN-код: 2021-6966, Scopus Author ID: 6507572305; sn_krivoshapko@mail.ru

с точки зрения примененного метода ее расчета, использованного конструктивного материала, стоимости сооружения. Затем интерес к тонкостенным большепролетным оболочкам пошел на спад. В исследовании показывается, что применение оболочечных структур в XXI в. увеличивается в связи с запросами разных отраслей деятельности человека. Доказано, что практически во всех странах мира на разных континентах велось и ведется проектирование и строительство оболочечных структур и оболочек. Изменился только приоритет в применении конструктивных строительных материалов. Если раньше в основном применялся железобетон, то сейчас в приоритете стержневые криволинейные структуры, композитные оболочки и стержневые структуры с заполнением из стеклянных панелей. Продемонстрировано, что как начинающие, так и знаменитые архитекторы и инженеры принимают участие в проектировании рассматриваемых структур и тонкостенных оболочек.

Ключевые слова: архитектурные стили, конструкционные строительные материалы, тонкостенные оболочки, архитектура оболочек, расчет оболочек

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Introduction

The statements of the most outstanding architects and engineers on perspectives of using of large-span space structures and thin-walled shells at present time and in the near future are gathered in a paper [1]. The most of them back up the opinion that “golden century of shells” was in 1920–1960 years but later on, an interest to thin-walled shells fell down till 2000. Then the sphere of application of shell structures came to increase in connection with requirements for new forms of public and industrial buildings. The well-known and also young architects begin to display a keen interest in design of shell structures [2; 3]. An attempt to exposure the criteria of estimation of outstanding erections was made in a paper [4] where the authors gave their view on ten of the most outstanding shell structures of the beginning of 21st century.

The aim of this investigation is study of public requirements on design and building of large-span shell structures in the world at the beginning of the 21st century.

Architectural styles of shells and shell structures at the beginning of the 21st century

Twenty-five architectural styles, their varieties, and the directions as applied to shells and shell structures were described in detail in a paper [5].

Figure 1. Industrial building, style “Industrial architecture,” Borracha, Portugal, 2017
(Available from: https://www.pinterest.ru/pin/530298924878808497/ (accessed: 10.08.2021))

Figure 2. The building in the style “Architectural constructivism,” Moscow (photo by Sergey N. Krivoshapko)

In the 21st century, architects used 16 architectural styles that are:
– industrial architecture (Figure 1);
– architectural constructivism (Figure 2);
– deconstructivist architecture (Heydar Aliyev Center in Baku, Azerbaijan, 2012);
– bionic architecture (dwelling-house “Egg,” Moscow, 2002);
– organic architecture (villa “Shell,” Kuruizawa, Japan, 2008);
– expressionism (the Quadracci Pavilion of the Milwaukee Art Museum that received the 2004 Outstanding Structure Award from International Association for Bridge and Structural Engineering, Wisconsin, USA, 2001);
– American modernism (terminal 5 of John Kennedy International Airport, 2008);

– high-tech (geodesic grid shells; SONY Center dome, Berlin, 2000);
– geometrical high-tech (the biome domes of the Eden Project in Cornwall, UK, 2001);
– ecological high-tech (structures of ecovillage in Dietikon, Switzerland, 2009);
– polyhedron architecture (Figure 3) [6];
– brutalism [7];
– noospheric architecture (Figure 4);
– parametrical architecture [8];
– free-form architecture (digital architecture) (Figure 5);
– productivism (Figure 6).

The time of finishing of building of shells and shell structures is indicated in the text in parentheses.

Figure 3. Cultural-and-trade center "5 Planets," Dmitrovskoe Shosse, Moscow region, 2018 (photo by Sergey N. Krivoshapko)

Figure 4. A dome dwelling-house, Moscow region (photo by Sergey N. Krivoshapko)

Figure 5. A building "The planet KVN", Moscow, 2011 (photo by E.A. Grinko)

Figure 6. The arch pavilions, 8×8 m (Available from: https://prime-tent.ru/arched-design.html (accessed: 10.08.2021))

Naturally, every presented style was used not only in mentioned cases. For example, such architectural styles as free-form architecture, parametrical architecture, polyhedron architecture, and high-tech were used more often than other styles. It was occasioned by the rapid development of numerical methods of strength analysis, by appearance of computer modelling, new constructive building materials, and of standard computer programs of different purposes [9]. But some architects have another opinion. So, E.V. Ermolenko considers: "postmodernism, deconstructivism, parametrical architecture oversated space of life of man and style crisis came into existence" [10].

The researches on subject of this part showed that architects did not use nine architectural styles, their varieties, and the directions since the second half of the 20th century. That is why, application of all known diverse modern approaches to design of shell structures and shells practices in the 21st century also.

Constructive building materials for shells and large-span shell structures at the beginning of the 21st century

At all times, stone materials, bricks from burned clay, natural wood, glued wood, metals, reinforced concrete, plastics, composite materials, glass-reinforced plastics, glass, tent materials, and so on were used for building of shells. At different historical epochs, architects and builders gave preference to different constructive materials.

In the 21st century, architects and builders use glued wood [11] (Figure 7), rod steel [12], wire ropes, steel membrane (a covered skating-rink 200×120 m in Kolomna, 2009), aluminium (domes of a Wastewater Treat-

ment Plant, Haltom Region Ontario, Canada), titanium panels (National Grand Theater, Pekin, China, 2007), plastics, structural soda-lime glass (Figure 8), glass-reinforced plastic (a dome of Vladimirskiy Temple, posyolok Industriya, Moscow region, 2020), tent materials (the hip roof of SONY Center, Berlin, 2000), guys [13], reinforced concrete ("Shell residence" by Kotaro Ide, "Clever house" system, bionic architecture, Japan, 2008), and fine-mesh wire-fabric reinforced concrete (a cottage "Snail," bionic architecture, Mexico City, Mexico, 2006) for erection of shells and shell structures.

Figure 7. The biggest wooden dome in the world with a 43m height and a 90 m diameter, cultural-and-trade center "Piterland," St. Petersburg, 2012 (Available from: https://www.malls.ru/rus/malls/83604.shtml (accessed: 15.08.2022))

Figure 8. The greenhouse of the State Botanical Garden named after N.V. Tsitsin, Moscow, 2015 (photo by Sergey N. Krivoshapko)

It is obvious that all known constructive building materials found the application in building of considered structures and shells. But their application frequency changed. For example, reinforced concrete yielded to all of the rest of the constructive materials. Reinforced concrete shells are used now more in small-scale building, i.e. for building of dwelling objects, cafes, small offices, sheds, and so on, for erection of coverings of industrial buildings, or in erections where it is necessary for technological processes. Large-span reinforced concrete shells are not built practically. Thick-walled reinforced concrete shells, in general, of spherical and cylindrical shapes find the application in building of objects of civil defense.

Some countries where shell structures and shells were erected at the beginning of the 21st century

Consider some countries located on different continents.

Europe. *Russian Federation* (the biggest in Russia glazed dome in Nagatinskaya water-meadow over the central atrium, Moscow, 2020), *Spain* (Figure 9), *Federal Republic of Germany* (Philological library, Berlin, 2005 [14]), *Switzerland* (the CERN – Globe of Science and Innovation, timber, Geneva, 2007), *Czech Republic* (new building of National Library of the Czech Republic, digital architecture, Prague, 2011), *Portugal* (Figure 10), *Belarus* (the cable-stay two-belt system of a covering of MCSC "Minsk-Arena", 2010), *England* (Wembley Stadium with sliding roof structures and with the 134-metre-high Wembley Arch of 7 m in diameter, London, 2007), *Belgium* (Liege Guillemin's TGV Station, Liege, 2009), *Ireland* (the antenna from stainless steel of 121.2 m in height, Dublin, 2003, Figure 11), *Austria* (a roof of Martin Luther Church from bent steel plates of a 8 mm thickness and resting on the legs of the "table"-four steel columns, Hainburg, 2011), *France* (La Cité du Vin, Bordeaux, 2016), *Denmark* (National Aquarium "the Blue Planet" with a façade faced with aluminum plates, Copenhagen, 2013), *Hungary* (the glazed many-functional complex Central European Time (CET), built between two store-houses, Budapest, 2022), *Croatia* (the Mosque in Rijeka, Rijeka, 2013, arch. D. Vlahović, L. Vlahović, D. Đurkan-Horvat, and D. Mauser), *Turkey* (Sakirin Mosque with a 39.6 m diameter dome, Istanbul, 2009).

North and Central America. *USA* (World Trade Center Transportation Hub, New York, arch. S. Calatrava, 2016), *Puerto Rico* (an umbrella shell [15], Figure 12), *Canada* (Canadian Museum for Human Rights, Manitoba, 2014, arch. An. Predock), *Mexico* (a covering of the atrium from prestressed reinforced concrete, Institute of Advanced Technologies and Education, L.G. Land's arch. group, 2005 [16]), *Jamaica* (the ecovillage from poured-in-place domes, the Source Farm ecovillage, 2005).

South America. Extensive information on modern architecture of Latin America is given in a book of L. Finotti [17] containing 103 illustrations.

Brazil (the theater, Rio de Janeiro, arch. Oscar Niemeyer, 2007), *Chile* (the Baha' i Temple of South America in the form of nine veils, Santiago, design of Hariri Pontarini Architects (Canada), International Award of the Royal Architectural Institute of Canada, 2016), *Uruguay* (Montevideo Carrasco International Airport, the full length is 350 m, the width is 80 m, Montevideo, 2009).

Asia. *China* (a complex of the National Grand Theater from glass and titanium, 212×144×46 m, 2007), *Bahrain* (Bahrain Museum of Contemporary Art, Muharraq, arch. Z. Hadid, 2012), *United Arab Emirates* (82 snow-white domes of Sheikh Zayed Mosque, 2007); *India* (Global Pagoda, Mumbai, the biggest stone dome in the world built without support poles, the height of the dome is 29 m, 2009 [4]), *Georgia* (a covering over the "Mir" foot-bridge over the Kura river, Tbilisi, 2010), *Azerbaijan* (Heydar Aliyev Center in Baku, Azerbaijan, 2012), *Singapore* ("SportsHub" stadium contains the world's largest 312 m diameter dome structure with a sliding roof, Kallang, 2015), *Abu Dhabi* (a steel roof over the thematic park "Ferrari World," 2010), *Jordan* (Ayla Golf Academy and Clubhouse, waving shape of the covering in the form of sand dunes from air-placed concrete, Aqaba, 2018), *South Korea* (Dior shop in the form of vertical bud of flower, 2015), *Tajikistan* (Figure 13), *Israel* (Ashdod Performing Arts Center, Ashdod, 2012, arch. Naim Dotan), *the Lebanon* (Amir Shakib Arslan Mosque, Moukhtara, 2016), *Qatar* (Education City Mosque was declared the best religious erection at the World Architectural Festival in 2015, Doha, 2015), *Pakistan* (a cool tower of the sixth Nuclear Power Plant, Karachi, designed by China National Nuclear Corporation, 2021).

Figure 9. The Queen Sofia Palace of Arts
of complex "City of Arts and Science", Valencia, Spain, 2005
(photo by S.L. Shambina)

Figure 10. A cruise terminal in the port of Leixoes, Portugal,
arch. Luis Pedro Silva, 2015
(Availble from: https://www.pinterest.ru/pin/272608583674986563/
(accessed: 10.08.2019))

Figure 11. The base of the antenna, Dublin, Ireland,
arch. Jan Ritchie (photo by Sergey N. Krivoshapko)

Figure 12. A restaurant of "La Concha Hotel",
San Juan, Puerto Rico, arch. Jose R. Marchand, 2009
(Available from: http://www.architecturaldigest.com/homes/hotels/2009
(accessed: 10.08.2019))

Australia and Oceania. *Australia* (trade center, Melbourne, arch. A.R. McDougal, 2005).

Africa. *Algeria* (a dome of the Great Mosque of Algiers with a 50 m high, it is the third-largest mosque on the planet, Algiers, 2020), *Republic of South Africa* (the chapel "Bosjes" in the form of reinforced umbrella shell, Cape Town, 2016), *Rwanda* (three pavilions on Rwanda Cricket Stadium, it is the first cricket stadium in Africa, Kigali, 2017), *Nigeria* (traditional conic buildings, 2014 [18]), *Ethiopia* (a complex of the high-scraper and the dome of headquarters the African Unite, Addis Ababa, 2012), *the South Sudan* (International Airport in Juba, designed and erected by China Communications Construction Company, 2018), *Cameroon* (Musgum tolek or the co-called Musgum mud huts, Figure 14).

Every large-span structure or shell of unusual form becomes by innovative and unique erection. Many countries are proud of their famous large-span structures and shells built in the 21st century. Above, only some countries were enumerated and only one of several well-known structures in every country was presented. The aim of this part is to show an area of the spread of the structures and shells in question.

Figure 13. A tea-house in the form of melon, Gissar, Tajikistan, 2015 (Available from: comunicom.ru (accessed: 10.08.2021))

Figure 14. A clay dwelling dome, north of Cameron (Available from: fishki.net (accessed: 10.08.2021))

It is obvious that between 2000 and 2021, erection of shell structures and shells took place in many countries. Availability of analytical and numerical analysis methods for different building structures, the wide spread of progressive typical computer programs, acquaintance of architects and engineers with accumulated progressive methods of erection of rod shell structures and shells promoted their widened application for dwelling, industrial, and public buildings.

Numerical and analytical methods, used for strength and stability analysis of large-span structures

Research works on perfection of strength and stability analysis, on dynamical problems, on geometrical modelling of crooked structures for the search of optimal forms never dropped in spite of delay of pace of the application of shell structures and shells for real erections at the second half of the 20th century [19].

The shells of complex geometry are actively searched in Peoples' Friendship University of Russia since 1964. The first investigations in RUDN University were fulfilled under the leadership of the first head of the chair of strength of materials and structural mechanics of RUDN University V.G. Rekatch [20]. He set up a scientific school "Geometry and Strength of Shells of Complex Form" which continues to function now too.

All of the known methods of analysis of structures in question and shells are based on results of investigations carried out at the 20th century [21–23]. At that time, numerical (finite element method [24], finite difference energy method [25], finite difference method, method of global elements [26], boundary element method [27], and their varieties [28]), semi-analytical (asymptotic method of small parameters [29]), and analytical (momentless theory [22; 30], simple edge effect [22]) methods were devised for shell analysis.

At present time, one can solve any problem from the field of structural mechanics of shell with the help of a FEM. But V.V. Novozhilov, who took an active part in the development of analytical methods of thin-walled shell analysis, held that "shell theory that is a fundamental branch of science becomes one of the sections of applied mathematics. This tendency is side-line effect of intensive introduction of universal numerical methods [22]. Probably, analytical and numerical methods of shell analysis have the equal right for existence and must mutually add one another.

Now, analysis methods become more exactly [31; 32], additional factors are added [33], and computer modelling is introduced into practice [34]. Some useful information from the history of development of shell theory is given in a monography [22] and in papers [19; 35; 36]. By the way, all known at that moment methods of analysis of thin shells are presented in a manuscript of the noted American scientist J.G. Simmonds [36].

In the 20th century, engineers and academics studied, in general, physical-and-mechanical properties of new constructive materials [37], but in the 21st century, they began active introduction of new materials into practice. Hence, the demands for accurate methods of analysis of structures made of these new materials arose [38].

Famous architects, created designs of the most known spatial structures in the 21th century

E.V. Podgornov ("Piterland," Russia, 2012, Figure 7).

Helmut Jahn (SONY Center is one of the symbol of Berlin, 2000).

S. Calatrava (the Queen Sofia Palace of Arts and the planetarium of complex "City of Arts and Science," Valencia, Spain, 2005, Figure 9).

N. Foster (a center for music education, concerts, and conferences "Sage Gateshead", UK (Figure 15), made of glass and stainless steel, 2004 [4]).

Paul Andrea (China National Grand THeatre, China, 2007; Osaka Maritime Museum, Japan, 2000).

Zaha Hadid (Heydar Aliyev Center in Baku, Azerbaijan, 2012).

F.O. Gehry (Marques De Riscal Hotel, Elciego, 2006 [14]).

I.M. Pei (German Historical Museum, Berlin, 2001 [14]).

Hiroshi Nakamura (the futuristic wedding ribbon chapel in the form of a double spiral containing two separate stairways with a steel frame, Onomichi, Japan, 2013).

Oscar Niemeyer (Museu Nacional Honestino Guimarães By Oscar Niemeyer, 2006, Figure 16).

Figure 15. Sage Gateshead, UK, 2004
(Available from: hmong.ru (accessed: 10.08.2021))

Figure 16. The National Museum of Brazil, 2006
(Available from: tourweek.ru (accessed: 10.08.2021))

Sou Fujimoto (The House of Hungarian Music within Budapest' City Park with a floating roof with openings for trees, this is a model ecology with using of standards BREEAM, 2021).

Nader Khalili ("Eco-Dome" made of clay and straw, ecological dwelling for Africa).

V. Kramarenko (a glass dome over the Victory Hall, the museum of the Second World War, Minsk, Belarus, 2014).

Sh. Videchnik ("Borisov-Arena," stadium – "snake," 70 km from Minsk, Belarus, 2014).

Simon Vélez (bamboo architecture of shell structures, Columbia).

Conclusion

The conducted analysis of open sources gave an opportunity to draw only one conclusion that at the beginning of the 21st century, recession in interest to shell structures and thin-walled shells finished. It took place due to appearance of new constructive building materials, broadening of enumeration of analytical, point, spline, and frame surfaces suitable for the application as middle surfaces of shells, due to appearance of nice methods of analysis and new computer complexes, and due to raised needs for creation of structures in question. If one wants to make sure in it, he must analyze the pavilions of the World Exhibition "Connecting Minds, Creating the Future" EXPO 2020 in Dubai (United Arab Emirates). Shells and shell structures were chosen by many countries for forming external contours of their pavilions. For example, pavilions of Austria (a complex of cones of different height from clay and sand), Belarus (polyhedron architecture), Italy (digital architecture for the covering), Azerbaijan (a roof with air cushion for decrease of temperature, high-tech style), Iraq (geometrical high-tech style), Russia (a structure from out-of-order weave tubes, free-form architecture), United Arab Emirates (bionic architecture, arch. S. Calatrava), and many others, and also thematic pavilions "Mobility" (trefoil in high-tech style, arch. Foster + Partners), "Sustainability" (ecotech style, Grimshaw Architects), and interactive installation "Space forest" from stylized concrete "trees" of different height printed on 3D-printer (arch. firm MEAN, arch. style "Productivism") show stable interest of clients to design of shell structures at the beginning of the 21st century.

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