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CONCRETE
– TOPOLOGICAL MEDIUM

BETON
– MEDIUM TOPOLOGICZNE

A b s t r a c t

The invention of modern concrete adjoins at the timeline with the discoveries of modern geometry. Multidimensional, non-Euclidean spaces, and, above all, topology, drew the attention of artists and architects. New mathematics inspired artworks and aesthetics of the early twentieth century. Its influence is seen in post-war modernism, postmodernism and in the latest art movements.

The realization of topology-inspired buildings requires a highly plastic medium. Curvilinear surfaces resist manipulation with tools both on the drawing board and on the construction site. They require approximation, division into simpler elements, and a material that assumes a complex shape and will sustain it in a lasting way.

The article focuses on the importance of concrete for modern architecture inspired by the topology. It starts at the moment when architects of the modern movement, including LeCorbusier, F. L. Wright, used new inspirations. Marking the characteristic phenomena in the works of Eero Saarinen, JørnUtzon, Frei Otto, ArseniuszRomanowicz, Oscar Niemeyer, and Santiago Calatrava continues it. It ends with a reflection on the importance of digital techniques in the implementation of topologically inspired buildings made of concrete.

Keywords: Topology, freeforms, informationarchitecture, concrete, structuralism

S t r e s z c z e n i e

Wynalazek nowożytnego betonu sąsiaduje na osi czasu z odkryciami współczesnej geometrii. Przestrzenie wielowymiarowe, nieeuklidesowe, a przede wszystkim topologia, zainteresowały artystów i architektów. Inspirowały dzieła plastyczne i estetykę początku wieku dwudziestego. Jej wpływ widzimy w powojennym modernizmie, postmodernizmie i w najnowszych projektach światowych.

Realizacja budowli zainspirowanych topologią wymaga wysoce plastycznego medium. Krzywoliniowe powierzchnie niełatwo dają się ujarzmić narzędziom zarówno na desce kreślarskiej jak i na placu budowy. Wymagają przybliżeń, podziału na prostsze elementy oraz materiału, który przyjmie skomplikowany kształt i będzie go w sposób trwały zachowywał.

Artykuł koncentruje się na znaczeniu betonu dla architektury nowoczesnej inspirowanej przez topologię. Zaczyna się w chwili, gdy z nowych myśli skorzystali architekci międzywojnia, między innymi LeCorbusier, F. L. Wright. Kontynuowany jest przez oznaczenie

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charakterystycznych zjawisk w dorobku EeroSaarinena, JørnaUtzona, Frei Otto, Arseniusza Romanowicza, Oscara Niemeyera, Santiago Calatravy. Kończy się refleksją na temat znaczenia technik cyfrowych w realizacji złożonych topologicznie budynków wykonanych z betonu.

Słowa kluczowe: topologia, formy swobodne, architektura informacyjna, beton, strukturalizm

Oswald Spengler wrote that every culture has its own mathematics[1]. According to this point of view, there is no single, coherent mathematical structure with an image of the natural sciences. Mathematics, from a philosophical point of view, is just formal idealization, with basic assumptions, axioms, we a priori accept. Only on their basis, one can construct the theory. Different axioms lead to different theories. They are not contradictory, but expand the spectrum of possible formalizations.

Spengler believed that the range of mathematical interpretations is far wider than thefield of numbers, relationships, and figures. Mathematics affect all cultural products, including beautiful art pieces and architecture. What is more, mathematics is the mainstay of stylish homogeneity. What particular community considers right, from a mathematical point of view, influences the way it interprets nature, represents reality and, consequently, influences the aesthetic written in its creative activities.

Although nature builds irregular, curvilinear, complex creations, its cultural reflection has been operating for centuries in fairly simple forms. This was mainly due to the lack of mathematical means capable of capturing complex observations. We were able to reproduce, but suffered a defeat at homologous interpretations. In this article, I intend to trace the path that civilization has reached the point where fascinating curvilinear forms have become logically evolved signs of culture. I would also like to describe the role of concrete in fixing these signs as understandable structures and architectural symbols.

1. Nature, architecture, interpretation of complexity

The architecture of ancient Greece and Rome tended to reconcile afascination with nature on the ground of mathematics based on proportionate modularity. Vitruvius treated these two inspirations as completely coherent, presenting justifications resulting from the analysis of the proportion of the human body[2]. Indeed, the struggle with the taking of irregular forms of nature was a serious challenge for the ancients. The approximation of the spiral design or the "perfection" of the specific numbers is clear evidencefor that[3]. Vitruvian man, redrawn by Leonardo after making corrections rising from real anatomical measurements, ceased to fit in the concentric circle and square. This was because the Pythagorean mathematics was unable to quantify the disproportionate proportion. Scaling the results of observation to fractional formulation did not produce satisfactory results.

Apart from the modular approach of proportions, antiquity has left yet another instrument of representation. It was a feeling of theperfection of a circle and a straight line, two figures

[1] O. Spengler, *Zmierzch Zachodu*; Warszawa 2001, p. 70.
[2] Witruwiusz, *O architekturze ksiąg dziesięć*; Warszawa 1956, p. 44.
[3] *Ibidem*, p. 35, 44.

that did not lose their properties while moving along the original shapes. Plato expressed the philosophical meaning of this idea. At Vitruvius, we find an engineering consequence – the conviction that all projections can be made using a compass and line[4]. This assumption determinedto defineall shapes by means of descriptive techniques and constituted the basis for the representation of curvilinearity up to baroque.[5]

The seventeenth century is associated with the problem of the explanationof irregularities, inter alia, thanks to the legacy of the curve master, Francesco Borromini. The interiors of his churches are deprived of order that governed buildings in earlier epochs. The role of repetitive segments, based on an orthogonal scheme, was taken over by the curves and arcs.

The role of parallel shifting and mirror reflections weakens inthe design of the plan. The importance of complex symmetry increases, including center symmetry and projections. In spite of such complex workshop techniques, which allow for unprecedented expression, Borromini's geometry depends on the conservative logic of the compass and ruler. The real breakthrough of baroque geometric thought in architecture is connected with the work of another Italian. Guarino Guarini, used in his plans and sections geometry, which brought to mind the work of Newton, which at the end of the seventeenth century, resulted in publications on the differential calculus. Guarini constructed vaults of the Turin churcheson the base of innovative techniques. He described the course of variation rather than searched theprecise algorithmic definition of thecurve[6]. From this moment, a new mathematical concept, whichspells out the specifics of Western civilization, is becoming a profound influence on art and architecture. It is a reasoning based on relationships, dependencies, and finally – on coding the information.

2. Toward modernity, the invention of concrete, topology

At the end of the eighteenth century, James Parker, a gothic facade artist, came up with the idea of refining material that congeals while mixed with water. He named it in the patent documentation of Romanesque cement, referring to the ancient technique using naturally occurring minerals and volcanic materials[7]. Joseph Aspdin's formula for roman cement was further refined in 1824. This time the binder was called Portland cement by analogy to the natural stone found on the island of Portland. So the way of concrete expansion was opened – a novel, universal material for modern architecture. There was still no way to compensate the low tensile strength. The situation changed due tothe experience of Joseph-Louis Lambot, who in 1855, at the World Exhibition in Paris, presented a barge of concrete reinforced with iron rods. The history of the invention of the reinforced concrete ends with the patent of Joseph Monier (1877), although the new material was used before that to build the houses of François Coignet[8].

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4 *Ibidem*, p. 15.

5 Interpretations of master achievements in determination of geometrical divisions are described, [in:] W. Guzicki, *Geometria maswerków gotyckich*, Warszawa 2011.

6 J. Słyk, *Źródła architektury informacyjnej*; Warszawa 2012, p. 49.

7 R. Kozłowski, D. Hughes, J. Weber, *Roman cements – key materials of the built heritage of the nineteenth century* [w:] Boştenaru Dan M., Přikryl R., Török Á., Materials, Technologies and Practice in Historic Heritage Structures. 2010, Springer.

8 P. Collins, *Concrete: the vision of a new architecture*, McGill-Queen's Press, 2004.

The inventions of Parker and Aspdin reached out to the ancient material through which the Romans built the Pantheon. By analogy, the work of Saccheri, Schlafli and Poincare brought back theinterests of discipline, which, since the Euclid era, did not come to the fore of mathematical debate. Geometry had no such significancefor the development of natural sciences as algebra and analysis. In spite of this, it was precisely on the ground of geometry that several significant discoveries were made in the era of industrial revolution. They started on a theoretical basis. By denial of the fifth postulate, geometries alternative for Euclidean were formulated[9]. They opened the way to explain the phenomenon of micro and macrophysics of the world. Later, geometric objects were no longer interesting in the sense of their specific dimensions and angles, but rather by the ordering of the characteristics of origin and construction. Such general features of the figures are the topology domain.

The relationship between architecture and modern mathematics was not direct. Engineering methodology still used traditional instruments based on the Euclid concept. However, new inspirations appeared. Casting to the spherical and saddle surfaces, projections of four-dimensional figures to three-dimensional space, and finally – distinctive topological figures: ribbons and knots, strongly influenced the ideas and reasoning of architects. What is more, these ideas, thanks to materials such as concrete, became a viable prospect of creative expression.

3. Concrete minimal surfaces

The interest in concrete was related in the first period to the construction of structures based on straight angles. LeCorbusier's inter-war projects used monolithic construction to implement the principles of modern architecture. The column-load structural scheme provided the open plan. Reinforced lintels made it possible to obtain much longer window bands. Monolithic slabs have facilitated the transfer of loads from roof terraces. The dimensional freedom of woodcut formwork has facilitated the use of recursive modularity.

After checking the characteristics of a new material, it was time to try out completely new spatial effects. Already, at the end of the nineteenth century, the Belgian physicist Joseph A. F. Plateau was involved in searching for minimal surfaces occurring in nature. He studied the behavior of soaps that formed the membranes defined by the shape of the shoreline. These surfaces illustrated in a straight way the topological problems. The architectural consequence of Plateau's work was the projects of Frei Otto conducted at the *InstitutFürLeichtbau* in the sixties of the twentieth century[10]. Soaps were used there for the initial determination of the shape of suspended roofs. However, architects werealready intrigued by saddle surfaces. Ruled forms were the primary building blocks of Antonio Gaudi's structures and details. In

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[9] M. Kordos, *Wykłady z historii matematyki*, Warszawa 2010, p. 221.
[10] W. Nerdinger, *Frei Otto. Complete Works*, Basel 2005, p. 75.

Ill. 1. The roof of Unitéd'Habitation, designed by LeCorbusier
Ill. 2. Art. Museum, Niteroi, designed by O. Niemeyer
Ill. 3. Warszawa Powiśle train stop, designed by A. Romanowicz, P. Szymaniak

the modeling workshop, complex gypsum profiles were formed to further investigate the lines of their intersections difficult to determine with traditional sketch techniques.

Parabolic hyperboloids were one of the major fascination of the postwar architectural avant-garde. However, the construction of the new shape-based elements evoked problems. LeCorbusier and IanisXenakis learned about this at the Philips Pavilion at the Brussels World Exposition. The tent structure consisted of several sections of the saddle area. Authors intended to make it out of cast concrete, but it turned out to be technically too complicated. Concrete transmuted in the pavilion to the mold of prefabricated elements that hung on the structure of the steel cable net.

Also in Warsaw, in the middle of the fifties of last century, interest in the area of minimal surfaces flourished among architects. Arseniusz Romanowicz and Piotr Szymaniak started designing the railway stations at the time, which were realized in the next decade. The most imposing application of the conoidal cover is certainly Warsaw Wschodnia, which in 1969 won the honorable title of Warsaw's Master. The entrance hall facing Kijowska Street ends with a steel structure over fifty meters wide. Its outer edge, supporting the neon with the name of the station is a simple beam and the internal support is the bow. Between these supports, the roof steal elements were stackedalong the minimum surface. The size of the Warszawa Wschodnia Railway Station forced the use of steel girders. In the case of smaller roof spans, designers have used concrete proving that it is an excellent medium for roofing topologies. Along the railway route called Średnicowa, we find the entire catalog of new forms. The ticket hall of Warsaw Ochota (1962) is covered with a square parabolic hyperboloid. Two apexes are practically in contact with the ground. They drain rainwater and give a sense of support on the ground. Expressed raised corners of the second diagonal axis were used to lead the stairs to the platform and to lighten the hall. The western entrance of the Powiśle railway station (built in 1963) is covered by a conoid with a symmetry axis following the line of the Poniatowski viaduct. The lower eastern ticket hall was covered with an "inverted fungus" – a centrally symmetrical surface of a torus section. Geometric forms of the Średnicowa line identify an important infrastructure component in the landscape of Warsaw. They are also an expression of technological efficiency. Minimizing bending stress allowed the authors to reach for unprecedented surface slenderness. Concrete roofs were transmuted in Warsaw to the state of levitation of white sheets called by the inhabitants*the angel wing*, *twisted square*, and *the umbrella*.

In the world's architectural heritage, the minimal surfaces fixed by the concrete medium found many spectacular embodiments. These include the Felix Candela buildings such as the Cosmic Radiation Pavilion and the Valencia Marine Park. The example that I mention at the end, which speaks to me the most, is the Portuguese Pavilion at the Lisbon World Exhibition in 1998. AlavaroSizadesigned it contrasting the monumentalism and orderliness of the carrying pylons and the lightness of the suspended canopy. The concrete roof was spanned over a space of about 50 x 70 meters. The 20-centimeter thickness is not a mere demonstration of engineering efficiency. It creates a symbol of minimalism in every plane of interpretation. It is a minimal surface, minimal construction, minimal gesture for shading and rain protection.

Ill. 4. Warszawa Ochota train stop, designed by A. Romanowicz, P. Szymaniak
Ill. 5. TGV Terminal, Lyon, designed by S. Calatrava
Ill. 6. Mercedes&Benz Museum, Stuttgart, designed by UNStudio

4. Concrete organic expression

Apart from the trend of natural optimization, another strong movement has developed in the modern architecture, which uses the plasticity of the concrete medium. The freedom of shaping the formwork was used here to consolidate intentions and meanings. It was about creating structures that speak to the user by interacting with the senses and by writing recognizable symbols. The dimensions of the concrete elements of the *Notre Dame du Haut*LeCorbusier's chapel are not structurally justified. Walls are thick, but do not take load from the roof through the entire section. On the contrary, in the line of intersection of horizontal and vertical planes, the author designed the gap to bring light and hide the actual supports. The exterior of Ronchamps waves but it is not a regular wave. The hollows form the entrances. The eastern lenticular surface is the background of the outdoor altar. The south wall completely lost its structural dimension. Its variable thickness, rising to three meters in the main entrance zone, is the result of a search for unique interior lighting.

The Ronchamps Chapel exudes expression based on curved lines. A similar idea, realized by different means, can be found in a slightly later project of LeCorbusier and Xenakis. The Dominican Monastery in La Tourette operates on straight lines. It usesgeometricalforms to create liturgical symbols and elements that bring light into the interior[11]. Exceptional expression of the irregularities of the language of simple forms is the glazing of the La Tourette interior yard. Concrete ribs are placed there according to the XenakisMetastasis melody and rhythm.

Oskar Niemeyer quoted Einstein's curved universe for describing his love of organic forms. This statement must be treated as a metaphor. Brazilian architect is far from looking for amathematical explanation. He conceives creativity rather as an emanation of inner passion and sensitivity. This subjective attitude does not bother the coherence with the rules of the natural world. Lighted by the equatorial sun, the white Brazilian concretes allowed Niemeyer to freeze the symbolic scenes previously written in spontaneous sketches. In the case of the Cathedral, hyperbolic pylons represent a gaze to the sky. Deep below ground level, the temple looks upward like a flower growing out of theburnt ground. In the Parliament Building, the expression of concrete forms tends to ensure a sense of balance and harmony. The office tower and the lobby located in the horizontal base form the backdrop for two spherical canopies. The north onecovers the Senate's meeting room and the south- deputies' chambers. Niemeyer works, though unusual in form, enter into a close dialogue with the environment. Niterói Contemporary Art Museum creates a sign of the eastern tip at the entrance to Guanabara Bay. As the head of the port, rises on the high bank. From the mainland, available through a spiral inviting ramp, from the seaside dominating, providing orientation, matching the waving landscape. The buildings designed by Niemeyer are generallybuilt of concrete. In most cases, they also use the language of topological forms. Concave convexity, tangency, looping, wrapping are words that the author uses to extrude architectural relationships. It is worth noting that Niemeyer's topology is not scientifically studied. It is rather a language of personal expression. Natural language serving contextual matching.

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[11] Such as the symbol of cross arising after opening the gate leading to the monastery, which rotates about a vertical axis located at the point of golden division of its width.

5. Concrete topological structuralism

Thanks to the invention of reinforced concrete, the form of the structure and its exposition were significantly enriched. The freedom of forming formwork and the ability to reinforce the stretched zone, irrespective of its geometrical position, represented a new quality in nineteenth-century engineering. It was first used for the construction of industrial buildings and bridges. Swiss architect Robert Maillart has perfected the school of design in line with the natural flow of forces. His phenomenal bridges have become symbols of rational engineering and at the same time symbols of the beauty of civilization that faces the beauty of nature. The architectural analogy for Maillard's minimalistic design is a Milanese skyscraper designed in the fifties by GioPonti and Pier Luigi Nervi. During this period, high-rise buildings in the United States were based on standard, mostly steel construction systems. On the contrary, Casa Pirelli uses the reinforced concrete technology to achieve the optimum shape of the structure. The posts and shields were tapered upward. The cross-section of the building was like a skeleton of a living creature adapted to the needs by the forces of evolution. New York TWA terminal that belongs to the same periodis equally expressive but focused on outer shape. Eero Saarinen was striving for lightness. The terminal was covered with thin-layer concrete shells and was based on organic pylons smoothly passing through the roof edges. Nearly forty years later, another architect once again reached for the theme of a bird-shaped building. Santiago Calatrava designed the TGV train station, linked to the airport in Lyon. It strives to balance two components: the horizontal line formed by the rhythmic, shelled canopies of railway platforms and dominant volume – an axially symmetrical hall based on a spatial arch frame and wing-like aisles.

In all the examples discussed above, a form of loadbearing structure is exposed. Nowadays, the tendency also embraces the structure resulting from the ideological and spatial assumptions. Thanks to improvements on the ground of digital geometry and complex simulations, it became easier to play with a pure topology. In works of Danish architects grouped inUNStudio, this inclination started to be recognized in the nineties of last century. In this period, they designed a residence, the basic spatial component of which is the concrete band. Möbius's ribbon inspiration has led to the creation of a unique structural mold that supports the building while providing the right functional layout. An Even more distinctive example ofthe topological form was made at the Mercedes & Benz Museum, designed by the same company in Stuttgart. The multi-story spiral provides the ability to carry out two dependent exposures. The museum does not provide afeeling of the boundaries between traditionally shaped supports and slabs. The structure is continuous. It flows through the building consistent with the movement of people and with the logic of the display. Concrete mediumachieves in the Mercedes Museum an extremely sublime level. Reaching flowing lines and planes induced innovative solutions. They concerned the formwork system, which was largely digitally designed and produced. Also, the chemistry of concrete had to be magnificent here. Strength varies according to location. Surface finishing meets the highest standards of use.

6. Parametric concrete?

Speaking of the Mercedes Museum, we unnoticed the approached into a sphere in which the technology of reinforced concrete building coupled with the latest IT achievements. Modernist architecture used topological concrete forms as evidenced by buildings such as the TWA terminal and the New York Guggenheim Museum. However, limitations narrowed the implementation. The smooth curvature of the shells that allowed JørnUtzon to win the Sydney Opera Competition proved to be too difficult to achieve. The final shape came into being after simplification to the spherical sections. With many years of delay, the iconic roofs changed the landscape of Bennelong Point.

It is worth paying attention to two phenomena while looking into the concrete construction of tomorrow. First, digital building models have reached a level that allows for very accurate simulation. This increases chances of shaping individual forms, perfectly suited to the circumstances. Early experiences in this field, such as the Stuttgart Museum, require considerable effort and demand new tools. However, it can be expected that soon, thanks to the use of robots and numerically controlled machines, we will overcome the limitations. The phenomenon of *mass customization*displaces *mass production* even today. On the horizon, you can see completely automated technologies. Among them is the print of liquid concrete and robotic masonry with concrete elements.

The second trend affecting the freedom to operate a concrete medium is related to geometry. More and more commonly used volumetric definitions allow replacing traditional notions and instructions: lines, curves, planes, surfaces, and geometric transformations. Instead, a three-dimensional matrix of variable resolution is used. By writing information about individual cells in space, we define the presence of material and its physical characteristics. Volumetric definition is very flexible. It allows you to easily describe the topology. This is done in a process analogous to traditional carving – by subtracting and adding material.

The pursuit of architects for the use of topological forms was strong in history. The fluid characteristic of nature was inspiring. However, it was difficult to grasp both the definition and the suitable materials. Concrete, and especially its composites with steel and fiber, has created a new perspective for the development of the topological trend. This was in the first place optimization, later also the expression. Today, thanks to the use of digital techniques, we have taken another step towards unlocking the freedom to operate the concrete medium. By refining geometry and using automated production techniques, we can more easily manipulate the form. We can also control the effects of our actions on the building and consequently on the built and natural environment.

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