The problem of space in architecture raises the need to address the questions: what is space? what is architecture? (...) [1]. Architecture is a part of space, and space is a part of architecture. In some simplification it can be assumed that an architectural object extracts a “quantity” of a larger space, of an infinite whole [1]. Nineteenth-century art historians formulated the definition of architecture, innovative at that time, as being “the art of shaping space” [2]. Architecture constructing an architectural object can limit and close space, and at the same time, through the closure, create a new kind of space.

1. ARCHITECTURAL SPACE

Democritus defined space as a combination of two elements – void and atoms. According to Plato, space consists of ideal forms, because these prevail in the universe. Aristotle saw it as a place where objects (bodies) were located [3]. Materiality in antiquities was defined by the concept of divisibility. Point objects, which do not have any extent, and simple objects that do not have an internal structure, could not be qualified as material beings [4]. In this context disputes about the divisibility of matter are also rejected atomism, the opinion that there is an end to the divisibility of matter, and the thesis about the existence of a vacuum. Modern mathematical concepts of space electrons are modifying the concept of Euclidean geometry. In the nineteenth century, a new approach to geometry was the work of Carl Friedrich Gauss, so-called non-Euclidean geometry can provide suggestions for solving geometric problems of any degree of complexity [5]. Logical precision is, one of the means to detect interconnected relationships between geometry. In mathematics, the concept of space is defined as a set of arbitrary objects that are called points by analogy with geometry, but most often they are functions. As part of this scheme, the features of these objects are referred to as relations occurring...
between such “points”, these relations define the “geometry” of a given space. This approach allows you to study the individuality of hypothetical objects using specialized terminology. This type of method generates a number of different types of “spaces”, the most important categories of which are: a) topological space; b) metric space; c) affine space. Different versions of these spaces are used by modern architecture. The space is more complex, and at the same time better adapted to the needs of users and applications in research practice. Existential space, formulated by Christian Norberg-Schulz on the ground of psychology, is the area of satisfying the basic existential needs of man, which is closely related to social space or rather social spaces [6]. In each of these areas there is a boundary between the sacrum and the profane. The most direct, human social space, designated by birth and death, family life and relationships with friendship, work and rest, includes private territory (house, flat, own room) and numerous common areas: places of worship (church and cemetery), places of work (school, university, factory), places of social services of all kinds (shop, laundry, hospital, but also town hall), and finally fun places (cafes, bars, restaurants) [7]. They form both existential space and social space closely related to architecture.

2. ARCHITECTURE

What is architecture? According to the basic dictionary definition, architecture is a discipline that organizes and shapes space in real forms necessary to satisfy the material and spiritual needs of people [8]. Tadeusz Broniewski stated in 1948: “There are three factors in the work of architecture: function, design, and form.” All must work together. According to the author’s assumptions, function means adapting to the purpose which the building serves and to the role it should fulfill. Construction refers to all material parts, closely related to the function and shape of the building. Form is the type of material and the technology that can be applied to the material [9].

The twentieth-century discourse of architectural theorists assumed as an axiom that architecture is a spatial/spacetime type of abstract art:

- “architecture is a game of solids in space” [Eugène Baudouin],
- “architecture is the masterly, correct, and magnificent play of masses brought together in light” [Le Corbusier],
- “architecture provides us with space of three dimensions” [Geoffrey Scott].

This, along with the modernist statement that “form follows function” [Louis Sullivan], has significantly shaped the modern way of thinking about architecture, as well as ways of defining it. Dariusz Kozłowski says: “There are still architects who believe that architecture is the art of shaping space. (...) The claim that form follows function was never a certainty; today, at the time of the overarching need for architectural originality, it seems to have completely outdated” [2]. Therefore, in relation to the twenty-first century architecture, it is reasonable to assume that “a modern architectural object is a complex interdisciplinary mechanism, whose structure consists of technical engineering solutions in various fields, sociological reflections, philosophical trends” [1].

Swarabowicz, in the dissertation “External space as a material of architecture”, refers to the definition for-
mulated by the Mexican architectural theorist Enrique Yáñez, who distinguishes the following within the architecture/architectural space: internal space, external space, and construction space. Enrique Yáñez says that “architecture is located at the junction of the internal space and external space” citing Bruno Zevi’s postulate that “space is the main character of the architecture” [10]. The ideogram illustrating the concept of architecture by Enrique Yáñez in the first part shows the spatial divisions within the architectural object, distinguishing between the following:

- external space,
- internal space,
- construction space.

The internal space is the opposite of the external, is an artificial space, separated from the external space, understood as the natural space. The illustration of the expansion of Yáñez’s spatial divisions – the internal space may be an extension of the external space, architecture may open up to the natural space [Fig. 1a, b].

### 3. STRUCTURE

Following the ideas of Enrique Yáñez, architecture can be defined as a system for dividing space into external and internal. This division does not include temporary situations, when they are divided and penetrate each other. The postulate of transformability and variability of architectural space characteristic of Second Modernity [11] enforces the extension of understanding of architectural structure. It is understood as a complex interdisciplinary mechanism characterized by variability. For an architectural object, it may be related to the fluidity and plasticity of shaping the internal or external space. The classification extended to the internal space with partitions, and the internal space of different volumes extracted in the void between the structural elements. [Fig. 1, c, d]. Moving parts of an object such as sliding inner walls give the possibility of modifying the internal space. Movable roofs and exterior walls opening the architectural structure make it penetrate with external space.

### 4. ARCHITECTONICS OF STRUCTURE

The concept of “tensegrity” (tensional integrity) was patented by Richard Buckminster Fuller in 1962. Initially, structural studies were performed on physical models. Tensegrity structures are spatial structures composed of simple rods and strings, in which mutual stabilization of the stretched and compressed elements occurs. They are characterized by durability comparable to lattice systems. The concept of the cytoskeleton described by Donald Ingber is significant also in the context of Architecture [12]. The cytoskeleton is a network of protein fibers and tubules that form the cell scaffold. Observations made on live cells showed that the cells attached to the hard substrate are flattened, while on the flexible substrate their shape is approaching a spherical form – the cell model whose construction is based on the spatial structure formed of rods and strands also allows deformations of the model, similar to those found in nature [Fig. 2]. The structure of human body can also be described by the spatial rod-tension structure in which the skeleton plays the role of the rods, while the function of the tensions is fulfilled by the muscles, sinews, and ligaments [13].

In 1921, Karl Loganson presented “self-stretching constructions”, which are considered as prototypes of tensegrity structures. In 1948, Kenneth Snelson, an American sculptor, presented, independently of
Loganson’s work, a self-supporting rod-tension structure [Fig. 3]. The first realizations of spatial structures – tensegrity – are sculptural installations and design projects. Richard Buckminster Fuller’s patent application is dated November 13, 1962, that is why he was honored as the first researcher of tensegrity structures, however, it should be remembered that almost simultaneously with Fuller, the issues of tensegrity were also dealt with by David Georges Emmerich and Kenneth D. Snelson. The patent application for David Emmerich’s tensegrity structure (Simplex) dates back to September 28, 1964, and Kenneth D. Snelson’s to February 16, 1965 [14].

With the development of computer technology supporting design, it became possible to simulate the structure’s work as a structural element object, and with the advent of this possibility, spatial structures of this type began to be used in the realization of architectural objects. It is difficult to divide tensegrity structures into clear-cut categories, but they can be described by the following parameters:

- number of nodes (N),
- number of compression components (S),
- number of tendons (C),
- system type: regular (R), irregular (I), depending on the length of the components,
- spheric (SS) homeomorphic to the surface of the sphere.

For example, one of the simplest elements of tensegrity, the equilateral triangle prism, can be described as N6, S3, C9, I.

Examples of tensegrity structures correspond to the types of architectural spaces [Fig. 4].

Existing objects with a tensegrity structure can be subdivided into the following types:

**Roof covering – roofing:**
- The roof of the SuperSam commercial pavilion, architects: Jerzy Hryniewiecki, Maciej Krasinski, Ewa Krasinska, constructors: Wawrzyniec Zalewski, Stanislaw Kuś, Andrzej Żórawski, realization 1962, Warsaw, Poland,
- The roof of the Spodek sports and entertainment hall in Katowice, architects: Maciej Gintowt, Maciej Krasinski, constructor: Andrzej Żórawski, realization 1971, Katowice, Poland,
- The roof of the Olympic Gymnastics Arena, architect: Kim Swoo-geun, constructor: Dawid Geiger, realization 1984, Seoul, South Korea (bicycle wheel construction – outer ring, inner ring, tension cables connecting both wheels),
- The roof of Ciudad de La Plata Stadium, architect: Roberto Ferreira, constructor: realization 1993–2009, La Plata, Argentina (construction of a spatial bicycle wheel – outer ring and two inner
rings, each of them at a different height, tension cables connecting the wheels),
- The roof of Suncoast Dome St. Petersburg, architect: Criswell, Blizzard & Blouin Architects, realization 1990, St. Petersburg, Florida, USA (construction of a spatial bicycle wheel – outer ring and three inner rings, each of them at a different height, tension cables connecting the wheels),
- The roof of Georgia Dome, architect: Heery International, Rosser FABRAP International, realization 1992, Atlanta, Georgia, USA (the elliptical ring construction – the outer ring and the two inner rings, each of them at a different height, the tension cables connecting the rings), [Fig. 5a]
- The roof of the World Cycling Centre in Aigle, Velodrome, architects: Pierre and Pascal Grand, realization 2002, Aigle, Switzerland (the elliptical ring construction – the outer ring and the three inner rings, each of them at a different height, the tension cables connecting the rings).

Buildings:
- “The Cloud” EXPO 2002, architects: Pierre and Pascal Grand, realization 2002, Yverdon-les-Bains, Switzerland, [Fig. 5b]
- Para-tension pavilion architects: Guangyuan Li, Merate Barakat, Sebastian Nau, Sevinj Keyaniyan, realization 2010, London, England,
- MOOM pavilion, architects: C + A Coelacanth, realization 2012, Noda, Japan,
- Santiago Antenna Tower, architects: Smiljan Radic, Gabriela Medrano, and Ricardo Serpell, realization 2014, Santiago, Chile,

Bridges:
- Kurilpa Bridge, architects: Cox Rayner Architects, realization 2009, Brisbane, Australia
- Forthside Pedestrian Bridge, architect: Keith Brownl, realization 2009, Stirling, Scotland, [Fig. 5c]
- The concept for the footbridge over the S7 road in Magdalenka near Warsaw, designers: Bogusław Markocki, Radosław Oleszek, 2011, Magdalenka, Poland.
- The concept for the footbridge over the Oder River in the vicinity of the Wrocław University of Science and Technology campus, designer: Józef Szybiński, 2012, Wrocław, Poland.

Artistic installations:
- Skylon Tower, architects: Hidalgo Moya, Philip Powell, Feliz Samuely, realization 1951 London,
Based on such assumptions, the existing objects were studied for the character of the space they represent. Four samples from each of the above types were selected for the study [Tab. 1].

Currently, the most common type of roofing is a spatial layout similar to that of a bicycle wheel. [Fig. 6]. It is most commonly used as a cover for sports facilities, employed both for the ease of design and construction [21].

England

- Needle Tower, architect: Kenneth Snelson, realization 1968, Washington, D.C., USA,
- Rainbow Arch, architect: Kenneth Snelson, realization 2001,
- Maxim’s Arch, architect: Maxim Schrogin, realization 2002, Berkeley, California, USA,
- “The Thing”, architect: Jasper Latté and Jaap Hos realization 2010, Enschede, Netherlands [Fig. 5d].
The sculptural spatial structure was used in the construction of a footbridge over the Brisbane River in Australia [Fig. 7]. The small number of implementations is caused by the difficulties arising at the design stage. Complex calculations and displacement simulations for structural nodes are required then. Current design tools do not facilitate the rapid application of structure at the concept stage.

The programs for parametric and generative design which are more and more often used simplify the approximation of structures to architects. Applications such as Grasshopper enable simulations of simple elements, while preventing the formation of complex structures, which has been shown in previous studies by the author [Fig. 8].

Currently, algorithms are created to simulate the behavior of structures, based on the mapping of natural forms found in nature. [20] A similar tendency exists in architectural design. In the case of rod-tension spatial structures, we are dealing with some sort of research synergy – a model of spatial layout derived from technical sciences, empirically tested, and then implemented in biology to analyze the structure of living organisms. The analysis of the behavior of living structures provides the chance to introduce modifications of parameters of spatial structures used in technology. The development of rod-tension spatial structures in the last decade (2007–2017) has been mainly related to the possibility of tension regulation of tendons, to make the tendons behave in a spatial structure just like muscles and tendons in human body [21]. Similarly, it is possible to modify the entire spatial structure. In the case of architecture, this gives the opportunity of free shaping of the internal and external space of the object. Horizontal and vertical partitions, undergoing a change of position in space and their own dimensions' deformation allow the shaping of the internal space object.

5. CONCLUSIONS

The use of the spatial rod-tension structure in the construction of an object will allow:
- free shaping of the internal space and opening of the object to the outside,
- changing the shape of an architectural object, during operation,
- regulation of sun exposure and ventilation of the building, during usage.

The types of existing objects correspond to the nature of space:
- Stadium roofs – closed
- Bridges – open
- Buildings – dependent
- Artistic installations – dispersed

Due to the difficulties arising at the design stage, the possibilities of separating space by means of tenserotic structures have not been studied yet. Systematizing and determining the suitability of types is a further field of study.

REFERENCES


Photos:

[Fig. 5a]
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[Fig. 5b]
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[Fig. 5c]
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[Fig. 5d]
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[Fig. 6]
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[Fig. 7]
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