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Carbon fiber reinforced polymer and tensegrity structures in search of model architectural and engineering solutions

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Abstract

The current era of nanomaterials brings advancements in science and technology. This creates new solutions and possibili-ties in the creation of novel spatial structures. This study leads through the presentation of iconic architectural objects creat-ed with the use of high strength composite materials and tensegrity structure. Then presents the design process, numerical simulations of the three-way tensegrity grid prototype module. Static stress simulations were done within the simulation engine of the Fusion 360 software. Moreover, 1:1 scale prototype was developed. It could be used as a modular construction slab of a novel architectural design. One of the key characteristic features of high strength composite materials, high strength-to-weight ratio, combined with tensegrity structures allows to develop lightweight and hence very durable spatial structures. This gives tensegrity structures a very low dead load value as compared to traditional reinforced concrete struc-tures. Thanks to the application of high strength and hence lightweight materials, the dead load of the prototype is only 0,18 kN/m^2.

Keywords: architecture, carbon fiber reinforced plastics (CFRP), composite materials, lightweight structures, tensegrity, static stress simulation

1. Introduction

The process of creation of architecture consists of numerous coexisting elements. In the oldest and yet still valid treaty on architecture and the art of building, *The Ten Books on Architecture*, Vitruvius formulates three principles that should be fulfilled by a building, a complex of buildings, and finally by a city. The Vitruvian Triad, *firmitatis*, *utilitatis*, *venustatis* – stability, utility, beauty – was also referred to as structure (construction), function, form (Morgan and Warren, 1960). Over subsequent millennia, the mutual harmony of these elements determined, as it still does, the foundations for the quality of a completed work of architecture.

The immemorial matter used in the process of creating architecture – an artificial 'ecological niche' of man, or the built environment we inhabit – are elements given to man by Nature and anthropogenic elements. This two-fold matter that an architect has at their disposal, its comprehension and a skillful use of the potential embedded in it, determine the development of architecture, (Franta, 2019). The first material, the one provided by nature, is the 'primary material', which could be referred to as 'the elements', in doing so highlighting their not only utilitarian, but also associative and metaphorical meaning, as well as – which is particularly crucial today – ecological meaning, (McDonough and Braungart, 2003). The element of earth is understood as both a material and a context – natural resources and their technical potential along with the significance of individual materials for the local tradition and identity, as well as natural (including tectonic) features of a particular place. The element of air is regarded as a carrier (of smells, sounds, warmth) and a specific filling of the space, decisive for biological comfort. The element of fire stands for light and energy, whereas the element of water signifies biological safety and dynamics. And finally, there is an element added as the fifth one: the element of life – the gift and continuity of existence. It finds its reflection in the spirit of the place, and it emphasizes that what is crucial is regarding each designing activity as a part of a broad context in a specific time and place. The sense and symbolism of these elements has always been present in human activity.

The second group is constituted by elements associated with human activity. It stands for form, or shaping objects with human thought. Function, the use of things, and therefore desirable and possible activity thanks to its qualities. Motion understood as the dynamics of an object itself and the dynamics of its perception. Time, or the duration of things, but also the changeability of their images associated with the time flow. And, finally, technology – technical capacity to materialize thought into an object. All these constitute anthropogenic elements, generated by human intelligence so as to make use of the priceless material provided by nature.

The last of the elements listed above, technology is of key importance in the deliberations contained in this paper. As it has been said, technology stands for the technical capacity of civilization allowing to materialize a thought into an object. It ensures the realization of the urban and architectural space so that man could start to utilize it in a usually long utilization process, frequently associated with functional as well as structural modifications. Thus, technology is understood as constructional and material means of implementation, as well as means which serve the materialization of some special aspects of influence (light, motion, sound, etc.) and utilization (including smart utilization) of the object of architecture in the utilization process. The inherent technical capacity and the way it is used must go hand in hand with the respect for Nature and for the anthropogenic environment. Therefore, the greater technological capacity, the greater the respect itself as well as the sense of responsibility associated with it should be.

In the past a sensible and responsible solution was directly associated with natural limitations (climate, locally available material), possibilities offered by the level of civilization, and the requirements (canon) dictated by the culture of a specific community. These were the three external determinants. The contemporary global technological coverage and the rapid pace of the solution pattern exchange shifted the determinants of choice from the external to the sphere of consciousness and subconsciousness of the creator; to the sphere of their professionalism, talent, sensitivity to the multifaceted context of the place and the essence of the task itself implemented in a specific place and not anywhere else. The conditions of the present day refer to the culture of the creator in operating possibilities offered by civilization when implementing a task: adding a contribution to the existing identity. Thus, the actions of an architect also consist in ‘composing’ technology – materials and structures – in order to make optimum use of the possibilities embedded in it or to discover its potential for creating architecture.

Construction material is indispensable to build any object of architecture. Technologies of obtaining and processing construction materials have been changing over centuries; however, they were mainly natural materials subjected to processing. And so it was that wood, stone, all sorts of mixtures of natural aggregates, as well as materials obtained in thermal processing, such as ceramics, and subsequently complementary materials, such as metals and glass, became – and still are – the main material for architecture. Contemporary achievements in the field of material engineering offer possibilities of developing construction materials demonstrating completely new properties and parameters (Ashby, Ferreira and Schodek, 2009). The application of such materials as carbon fiber reinforced polymers (CFRP), Kevlar, Zylon, Dyneema, or even carbon nanotubes (CNT) opens up possibilities of creating light and at the same time durable structures. The process of manufacturing most of these materials has been known for only several decades (Bakis and Bank, 2002).

Structural systems connected with the material – resulting from its properties – offered the possibility of creating diversified architectural forms, sometimes acting as a breakthrough impulse in this respect. The corbel arch introduced by ancient Romans, where the material (stone, brick) works exclusively by compression (squeezing), i.e. optimally to its inherent properties, provided subsequent centuries with a completely new pace in creating architectural structures which were more advanced in terms of structural efficiency, the scale of buildings, and their formal uniqueness. The occurrence of iron and steel as a construction material, thanks to its value – high tensile strength – opened up new technological and formal/spatial possibilities for large-size reinforced concrete and steel structures. Le Corbusier put it this way: “reinforced concrete and steel allow for such feats” (Corbusier, 2012).

The search for structures and structural systems equally resistant to different types of forces have led to the creation of a system where there is a reciprocal stabilization of tensioned and compressed elements. Spatial systems known as Tensegrity consist of rigid elements (most often bars or struts, but also 3D elements), interconnected by means of flaccid elements (tense tendons, cables, etc.), (Fest, et al., 2003). Architectural realizations and spatial experiments applying CFRP as the main construction material and implemented Tensegrity structures signal a potential for the creation of innovative architectural forms that is inherent to this material as well as in the structure itself. Detailed descriptions of such realizations shall be the subject matter of this paper. The article will be completed with a description of conducted research on models aiming to integrate both elements – to build prototypes of Tensegrity structures made of high strength composite materials.

2. CFRP – new possibilities of forming architecture – illustration of the potential inherent to the material

2.1. Carbon fiber and its properties

Modified CFRP which demonstrate unique properties, unattainable for metals, ceramics, or organic polymers, today are a valuable and often irreplaceable material in many industries. Intensified research on carbon fibers began in the early 1960s, (Bacon, 1960; Millington and Nordberg, 1966), although for the first-time carbon fiber was used by Sir Joseph Wilson Swan in an early incandescent light bulb.

A carbon fiber consists of nearly exclusively stretched carbon structures, chemically similar to graphite. They are characterized by low density, high tensile strength, high Young's modulus, high fatigue strength, and creep strength. At the same time, they are good at suppressing vibrations and are highly abrasion resistant, have high dimensional stability, low thermal conductivity in low temperatures, are resistant to sudden temperature fluctuations and to numerous chemical factors, as well as demonstrate good conductivity, (ASCE Committee, 2003). High tensile strength of the carbon fiber, as well as its high Young's modulus, are associated with the degree of orientation of the fiber structure in relation to its axis, as well as with the density of cross links.

Due to quite high production costs, nowadays the use of CFRP is not widespread. Instead, they are applied in highly specialized areas most of all in space structures, aircraft structures, and in the automotive industry (Huu, et al., 2018), (Lin and Gigliotti, 2018). Their properties referred to above in combination with their high ability to suppress vibrations and considerable fatigue strength and abrasion resistance make carbon composites a perfect material for building innovative architectural structures. They offer possibilities of creating light and at the same time very durable structures. (Ashby, Ferreira and Schodek, 2009).

The currently undertaken research work titled "Consortium for the Production of Affordable Carbon Fibers in the United States," conducted by Western Research Institute (WRI, Laramie, Wyo., U.S.), aims at the development of new methods of production of carbon fibers from such materials as coal, petroleum, and biomass, which would lead to cost reduction with no loss as to the technical properties of this material. Each type of fiber has different properties, depending on what it is made from and how it is manufactured, hence it is suitable for specific applications. The emerging new carbon fiber production technologies are to reduce their production costs considerably, simultaneously broadening the possibilities and economic effectiveness of the implementation of such materials in architecture and civil engineering.

2.2. Opening of new formal and functional opportunities thanks to the use of CFRP

In the last decade architects searching for new material solutions offering opportunities to create more and more technologically and formally advanced structures have begun to apply CFRP in their projects. One of representative examples is the Steve Jobs Apple's Theatre, erected in Cupertino, California, USA. Designed by a renowned design studio Foster + Partners in cooperation with Eckersley O'Callaghan and Arup, the edifice sets new trends in the application of CFRP in building innovative architectural forms. The building, situated on top of a small hill, is a part of a 71ha urban complex, Apple Park, which serves as the headquarters of Apple. One of the principal assumptions made by the company – a pioneer in digital technologies – was a ground-breaking approach to the building itself, its structure, materials and form.

The only visible element of the entire edifice of the Steve Jobs Apple's Theater is the entrance pavilion, which leads to an auditorium seating 1,000 patrons, located entirely underground. The pavilion comprises a number of material and structural solutions never applied before in such a scale. The lens-like roof delicately rests upon a transparent glass cylinder of the height of 6.6 m and the diameter of 41.1 m, see Fig. 1. The roof, with the diameter of 60 m, is mainly made of CFRP. Its structure consists of 44 radial panels, assembled on the site. Next the 80.7 tons roof structure was placed on the supporting glass cylinder and only one crane was used for its installation. The composite structure of the roof was created by the FRENER & REIFER.

Fig. 1. View of a lens-like CFRP roof structure of The Steve Jobs Theater hallway. Source: Nigel Young/Foster + Partners

The glass cylinder is made of four layers of construction glass, 12 mm thick each. All service ducts for electric wires and sprinkler pipes are invisibly integrated in 30mm-thick silicone connections of the curved glass panels. Since Cupertino is situated in a high seismic risk zone, the structural requirements that the glass cylinder had to satisfy were particularly. demanding. The properties of glass – its inherent fragility – required a detailed analysis so as to guarantee the necessary safety requirements. The designers applied a number of strategies protecting the building against seismic activity. The curved glass panels are fixed at their bottom by means of structural silicone to a steel channel, which transfers the shock energy. The channel is designed in a way that enables it to deform before the glass breaks, securing the integrity and durability of the entire bearing structure of the roof.

The building was put into use in 2017. It is the largest CFRP structure supported exclusively on construction glass, as well as a largest structure of the type as such. A year later, the building was awarded by the Institute of Structural Engineers – IStructE Award for Structural Artistry 2018. This project is an excellent example how thanks to innovative parameters of the materials used, carbon fiber and construction glass, new possibilities of creating form, function, and structure emerge.

2.3. CFRP and protection of existing structures providing buildings with a new form in perception

Pursuits of new ways of using CFRP in architecture often assume a form of cooperation between the architect and the manufacturers of materials. An excellent example of such cooperation is the design of the Komatsu Seiten office building in Japan, see Fig 2a. The building is located in Ishikawa, in a high seismic activity zone. The task of re-designing of the building was entrusted to a world-famous Japanese architect, Kengo Kuma. The main objective was to protect the building against the effects of earthquakes. The architect along with engineers from KOMATSU MATERE strengthened the entire structure with CFRP rods.

The technology of CABKOMA strand rods was developed specially for the purposes of this project, opening up new possibilities of strengthening existing structures in order to provide an additional, effective anti-seismic protection of buildings. By means of this material it is possible to obtain anti-seismic reinforcement outside as well as inside buildings. In the said example, the application of CFRP strand rods provided reinforcement by combining the roof level with the foundation level outside, additionally giving the building a new formal expression. But also, additional reinforcements were introduced inside the building in the form of a mesh made of CABKOMA strand rods. The rod is made of carbon fiber embedded in thermoplastic resin, which means that it is easily bendable and thermally processed. It immensely improves its workability on construction sites. According to the producer, the CABKOMA strand rod is the lightest anti-seismic reinforcement system in the world. It has many desirable properties. It is characterized by high tensile strength, a delicate and yet strong structure, brilliant aesthetics. Its specific weight is one fifth of a typical steel rebar, and at the same time it is five times as durable as a steel rod of the same cross-section – a roll of 160 m of the rod weighs only 12 kg.

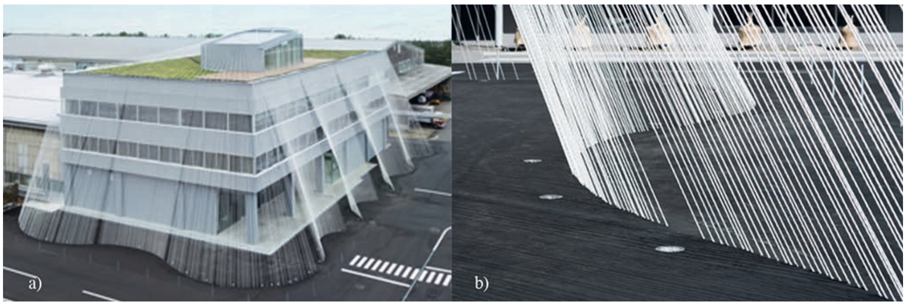

Fig. 2. a) View of the Komatsu Seiten Fabric Laboratory strengthened with CABKOMA strand rods, b) Connection view of the CABKOM strand rods with the foundation level. Source: (KomatsumateRe)

In 2018 the CABKOMA strand rod received international recognition of JEC Group in the category of innovative materials – JEC Group was established in 1963; it is the world’s largest non-profit organization involved in composites, and its goal is to promote the development and application of composite materials on the international arena. The strand rods had been nominated on the basis of several key properties, such as: high efficiency at relatively low costs, high durability and strength, rust resistance, small weight, foldability, and easy application in the realization process. This easy installation satisfied ‘a huge potential need in the construction industry’ (JEC Group, 2018), as the product is easy to install, easy to maintain, and exceptionally durable. When considering its application as anti-seismic reinforcement, the main advantage of the strand rod is the fact that it can be applied on existing structures made of wood, concrete, ceramics, steel, as well as in new structures, combining them with other materials. The CABKOMA strand rod also has additional potential – it enriches the structural value with an aesthetic one. Other anti-seismic reinforcement systems are usually designed in a way that allows them to be hidden within the building structure.

The headquarters of Komatsu Seiten are a representative example of how an anti-seismic reinforcement system may fulfil the function of a curious architectural detail, see Fig. 2b. Its properties, method of application, but also its illumination provide the building with a form which is dynamic in perception, both during the day and at night. The building is effectively protected against the effects of seismic shocks, achieving at the same time a ‘delicate but strong structural body’, as the author of the design stated himself (Overstreet, 2016).

2.4. CFRP vs. protection of existing historic structures without compromising the building and its perception

Composite materials – carbon, glass, aramid fibers – are used for the reinforcement of all sorts of existing historic structures, (Lawrence and Bank, 2006). Thanks to the aesthetics of the CABKOMA strand rods, they are particularly interesting in the context of protecting monuments and historic sites. Opinions on the visual effect of reinforcement on historic structures are subjective and can differ significantly. However, the application of these strand rods is one of rare examples when it is possible to use a contemporary element of structural modernization in a building with high historic values without compromising the integrity and expression of historic architecture. This advantage allows to use the CABKOMA strand rods in projects whose aim is to protect and maintain historic structures of the utmost importance. It can be 'used for the protection of monuments, which initially could not be sufficiently reinforced' (JEC Group, 2018). Carbon fiber strand rods are rust resistant and satisfy all the requirements defined by FEMA in terms of anti-seismic modernization of existing structures, including historic ones. Furthermore, their use is consistent with guidelines on revitalization of protected structures.

Fig. 3. a) Outside view of the Temple of KYOZO Sutra Repository of Zenkoji, b) View of the anti-seismic CFRP reinforcement of the interior of temple structure. Source: (KomatsumateRe)

In 2017 this material was used in the reinforcement. Of a building important for the national heritage of Japan, the temple of KYOZO Sutra Repository of Zenkoji, located in Nagano, see Fig. 3a. The application of CABKOMA strand rods provided protection for this monument against potential earthquakes, and at the same time, thanks to their delicate structure, the reinforcement is not eye-catching – it is like a nearly invisible spider's web, which does not hinder full formal expression of all architectural elements of the building interiors, see Fig. 3b. It is planned to use the strand rods in the reinforcement of world heritage monuments, Tomioka Silk Mill West Cocoon Warehouse, and Fujiyama Hotel in Miyanoshita, Hakone, which only proves the success of the first project, (Ikebata and Uzawa, 2018).

2.5. Methodology of further research on the use of CFRP – searching through implementation experiments

The search of new techniques and forms of implementation of composite materials has become an ambition of numerous research and development teams worldwide (Cheung and Gershenfeld, 2013; Cramer et al., 2019; Dong and Wadley, 2015; Kayser et al., 2018; Knippers et al., 2018). One of the leading units involved in the subject of applying composite structures in the architectural scale is the Institute for Computational Design and Construction. (ICD) and the Institute of Building Structures and Structural Design (ITKE) based in Stuttgart. Their main goal is the development of the design process based on the latest achievements of digital as well as material technologies. Pavilions created by scientists every year constitute examples of innovations in search of formal architectural realizations in which CFRP are used. Since 2012 they have been subsequently creating pavilions which demonstrate the results of their research and set trends of their further pursuits. The structures are mainly made of carbon and glass fibers. The starting point for designing each pavilion is always inspiration with nature – a selected biological structure. Through the observation of principles operating in biology and an analysis thereof, scientists transfer them into the field of architecture.

Processes observed in architecture create biological structures which are highly effective in terms of materials and functions, and on top of that they are quite unique and exceptional in their forms. The pavilions constitute the result of years of studies on the integration of architecture, engineering, and principles of biometrics, which have tried to find the answer how systems of biological fibers can be transferred onto architectural systems. Biometric research conducted in ICD and IDKE demonstrates how interdisciplinary studies of biological foundations combined with the most advanced computing technologies can lead to the creation of an innovative and fully digital system of building of composite fibers, including CFRP, see Figs. 4–6. Only several years ago such pavilions would be impossible to design, not to mention to build.

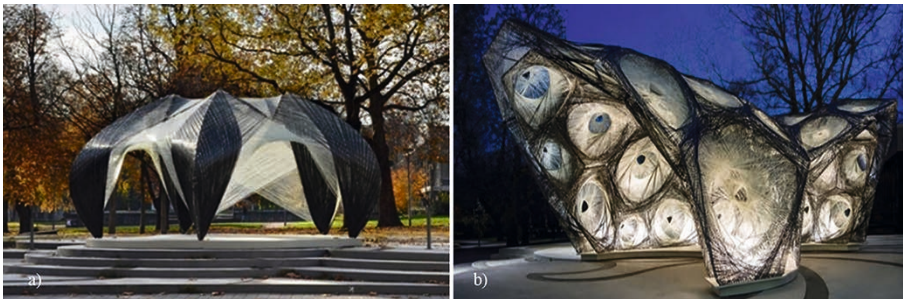

Fig. 4. a) ICD/ITKE Research Pavilion 2012. Inspiration – a lobster skeleton (Homarus americanus) – a model of a durable biological structure of an exoskeleton used in the structure of the pavilion (Knippers et al., 2015), b) ICD/ITKE Research Pavilion 2013-14. Inspiration: Elytron – a protective cover of a beetle forewing and abdomen, of a naturally effective structure – a model for the highly effective structure of the pavilion in terms of material (Doerstelmann et al., 2015). Source: ©ICD/ITKE University of Stuttgart

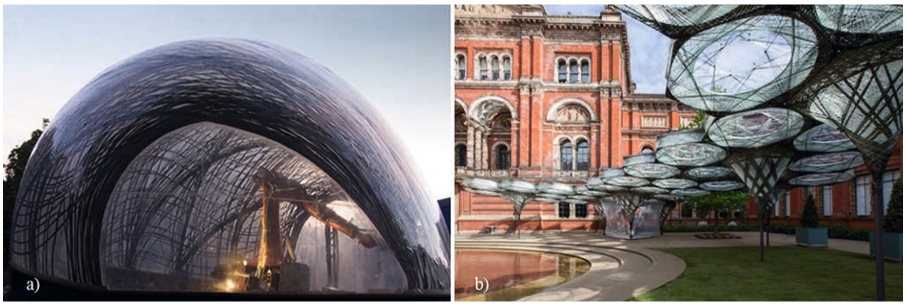

Fig. 5. a) ICD/ITKE Research Pavilion 2014-15. Inspiration: Process of building of a web by the diving bell spider (Agyroneda Aquatica) and its basic behavioural patterns – the principles were identified and transferred to the technological process of construction (Doerstelmann et al., 2015), b) Elytra Filament Pavilion 2016. Inspiration: The structure of forewings of beetles – optimisation of the materials use distribution in a point-supported self-supporting structure (Prado et al., 2017). Source: ©ICD/ITKE University of Stuttgart

Fig. 6. BUGA Fibre Pavilion 2019 – comprehensive application of ICD/ITKE research work. Source: ©ICD/ITKE University of Stuttgart

As advanced computer software and algorithms started to be in operation, new possibilities of creating complex geometries of designed structures emerged. The design process is completed with a number of complex strength analyses, which results in the most effective selection of form for the building and the course of its implementation. The software referred to above also controls a robotic arm, which often cooperates with drones. These devices weave a digitally defined structure of the pavilion from carbon and glass fibers (Knippers et al., 2015; Doerstelmann et al., 2015; Felbrich et al., 2017; Prado et al., 2017). The research conducted by scientist from the University of Stuttgart prove – by the pavilions built as part of it – the immense potential of composite fibers in the process of building of an iconic form, as well as an extremely rational one in terms of the logic of structure and material use.

The latest spectacular example of the application of carbon fibers in architectural projects are three gates for Expo 2020 in Dubai. For decades now structures of World Expos have been presenting the latest achievements in the field of new structural and material solutions and formal pursuits, setting designing tendencies in subsequent decades. The form of the three entrance gates to Expo 2020 in Dubai, designed by an English architect, Asfi Khan, is extremely lightweight. The 30-metre-long and 21-metre-tall gates are located in three points leading to the area of the world exhibition. Visitors will enter through each of the gates, passing between two open walls made of CFRP. The entire structure is crowned with an openwork lattice made of the same material, which closes the interior of the portal. Each of the entrances is equipped with two 10.5-metre-wide and 21-metre tall doors. Depending on the pedestrian traffic intensity, the doors can be opened in different positions, from partly to fully open.

The form of the gates makes a reference to a mashrabiya, an architectural element characteristic for the traditional Islamic art, which often assumes a shape of window and balcony shutters with a rich, geometrically intricate openwork form. The main function of mashrabiyas is to protect building interiors against overheating caused by sunshine. Therefore, the gates are also a specific respite zone before or after visiting the exhibition, offering some dispersed shade, which improves thermal comfort to a certain extent. When asked about the concept of the project, Khan said, “I wanted to create a mashrabiya like no other, for it to be impossibly thin and impossibly light, like a drawing in the sky, and at such a scale that it could become an architecture in itself … There was only one material that is capable of producing this effect, and that is carbon fibre”. This statement seems to be the best summary of the potential for the creation of innovative forms that is inherent to this material.

3. Tensegrity – the potential residing in the structure

3.1. From an artistic concept to a structure

The search for structures and structural systems equally resistant to different types of forces have led to the creation of a system where there is a reciprocal stabilization of tensioned and compressed elements. Spatial systems known as tensegrity consist of rigid elements (most often bars or struts, but also 3D elements), interconnected by means of flaccid elements (tense tendons, thin cables, etc.), (Emmerich 1988). Rigid elements usually must not be in contact with each other. The term ‘tensegrity’ was coined in 1960s by one of the leading promoters of such structures, a famous architect, constructor, philosopher, and inventor, Richard Buckminster Fuller (Mark and Fuller, 1973). However, the pioneer in the work on tensegrity systems was a Latvian artist – constructivist, Karl Ioganson (Gough, 1998). His sculptures – spatial structures from the 1920s, which were works of art, at the same time provided the foundations for further deliberations on tensegrity structures (Melaragno, 1994), The trend of artistic pursuits was continued by an American sculptor, Kenneth Snelson, who was a student of Richard Buckminster Fuller. The first tensegrity structures in the sculptural scale created by him in the 1950s and 1960s evoked greater interest in this subject, whereas his works from the 1970s were already in a scale close to the architectural one (Snelson, 1973). Therefore, it can be concluded that initially after the presentation of sculptures by Ioganson and Snelson, tensegrity systems found their application as sculptures – artistic objects – in different scales. Currently, it is constructors and architects who are interested in applying the principles of tensegrity in their designs and realisations, both architectural and infrastructural ones. The definition of a tensegrity system associated with its application in construction and most often referred to in literature devoted to the theory of structural systems was proposed by Anthony Pugh: “A tensegrity system is established when a set of discontinuous compressive components interacts with a set of continuous tensile components to define a stable volume in space” (Anthony Pugh, 1976).

3.2. Implemented examples of the application of tensegrity systems in architecture

It is worth mentioning that ones of the first applications of a tensegrity structure in architecture in the world were designs for the sports and entertainment hall ‘Spodek’ in Katowice, Poland. The design of the hall was selected in a competition organized by the Katowice branch of the Association of Polish Architects in 1959. A team of Warsaw-based architects: Maciej Gintowt and Maciej Krasiński along with a constructor Wacław Zalewski, proposed a structure with a very distinct form.

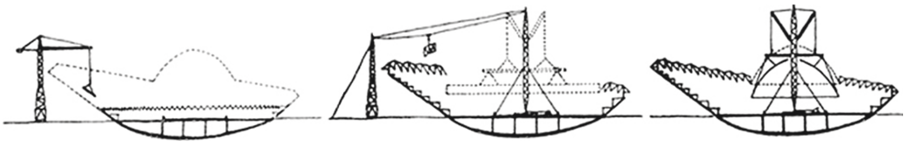

Fig. 7. Design-phase sketch drawing by Wacław Zalewski illustrating idea of tensegrity roof assembly. Source: David M. Foxe WZ Structure An Archive of Structural Designs by Waclaw Zalewski (1917–2016)

The original roof structure proposed by Wacław Zalewki was a tensegrity structural system. It consisted of radially arranged lower and upper cables with vertical rods supporting the sloping surface of the hall roof. The material proposed for this structure then was steel rods and steel wires. The structure proposed by Zalewski guaranteed that the distinct asymmetry characteristic for the original concept of Spodek, highlighting the dynamics of the building, as if frozen in gyring, see Figs. 7–8.

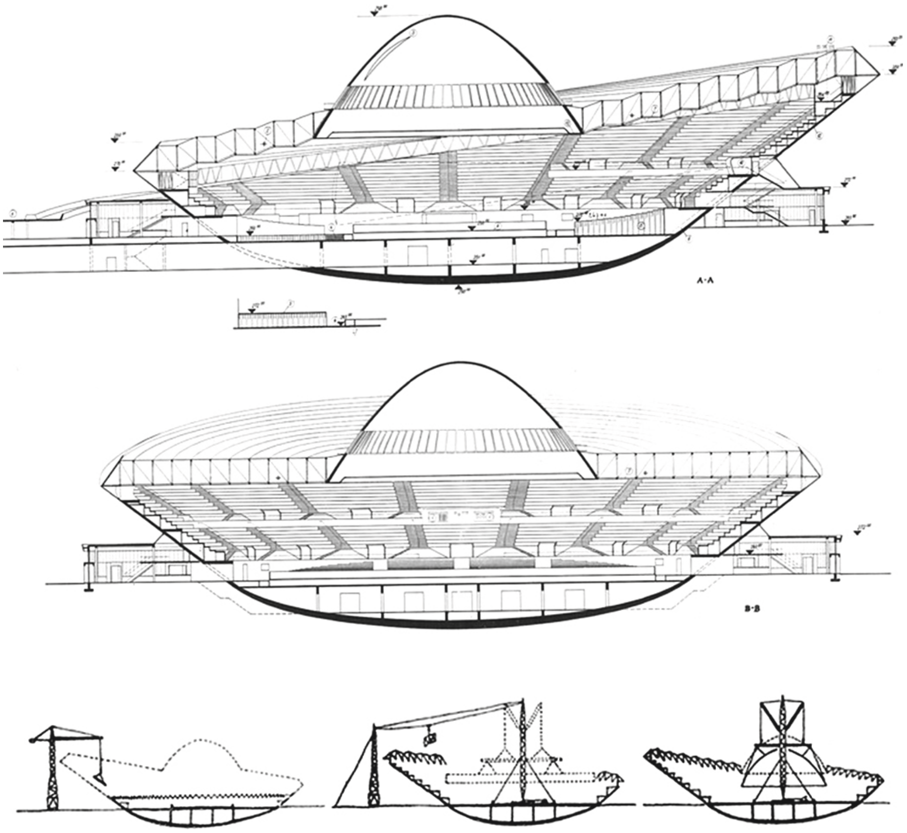

Fig. 8. Design-phase section drawings showing a tensegrity roof structure designed by Wacław Zalewski. Source: David M. Foxe WZ Structure An Archive of Structural Designs by Waclaw Zalewski (1917–2016)

Eventually municipality resigned from the tensegrity structure design in favor of traditional steel truss structure. The total span of the roof is 126 m, and its structure consists of an outer steel ring of the diameter of 100 m combined with an inner steel ring of the diameter of 32 m. Both elements are linked with each other by means of 120 radially arranged strut-cable girders. The interiors of the hall are illuminated by a dome resting on the inner ring of the roof. This building, put into use in 1968, thanks to it avant-garde, characteristic form became a landmark and symbol of Katowice (Pelczarski, 2013).

Similarly, to world expo exhibitions, structures implemented for Olympic games provoke the creation of innovative. structures, hence the application of a tensegrity structure in the Olympic Hall in Seoul, as well as in Georgia Dome in Atlanta. The roof of the Olympic Hall in Seoul built in 1986 is an example of a strut-cable tensegrity structure. The roof, spanning. 120 m, was designed by David Geiger – and American engineer who also invented the air-supported fabric roof system (Rastorfer, 1988). The type of structure implemented in the Olympic Hall in Seoul bears the name of Geiger's dome, after the name of its creator, see Fig. 9a. The structural system consists of radially arranged upper steel cables, supported by steel tubular struts resting on slanting and circumferential cables. The roof is characterized by unique lightness of form, and this impression is enhanced by the access of daylight along the circumference of the structure (Fu, 2006), see Fig. 9b.

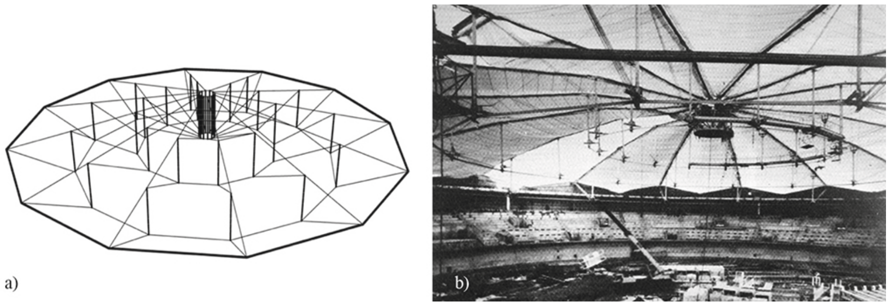

Fig. 9. a) Construction diagram of Geiger's dome, b) Inside view of the Olympic Hall in Seoul with the visible tensegrity structure of the roof. Source: (Columbia)

Georgia Dome in Atlanta designed by a constructor Mathhys Levy, was another implemented example of applying strut-cable tensegrity systems. The stadium, put into use in 1992, a predominantly sports facility, which hosted the Olympic games of 1996, was furnished with the world's largest cable dome. The structural system of the roof was designed on an elliptical plan with the dimensions 233.5 m × 186 m. Its structure was based on steel struts as well as steel cables. The struts were arranged vertically, and the cables were attached to their lower and upper surfaces. After three stages of prestressing of the main cables, together with the struts they formed an evenly tense dome. The surface of the dome features an outline of a triangular structural network of strut and cable connections, see Fig. 9a. The material solutions applied and the structure with its rich and sophisticated shape made an observer feel that the roof levitated in the air with no support Castro and Levy (1992), see Fig. 9b. Regrettably, in 2017 the Olympic stadium was demolished due to the. construction of a new facility located in its close vicinity.

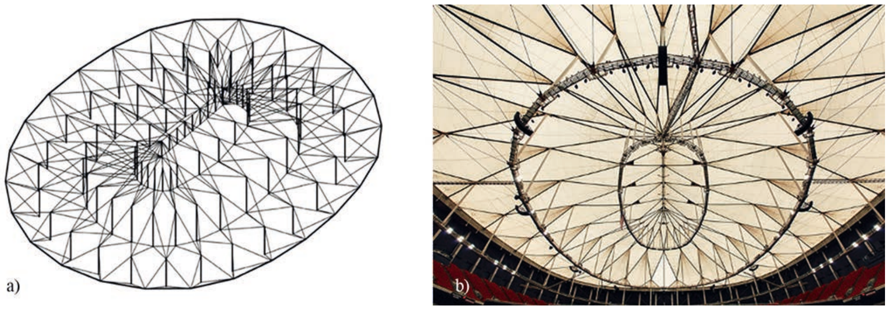

Fig. 10. a) Construction diagram of Levy's dome upon the example of Georgia Dome, b) Interior view on the Georgia Dome structure. Source: (Solomon Fortune, 2016)

The tensegrity system has been also used in bridge structures. The design of a foot and bike bridge Kurilpa in Brisbane, Australia, connecting the Central Business District with the Cultural District and the Gallery of Modern Art situated there, was selected in a competition concluded in 2006. The winning concept was implemented and put into use in 2009. The project was entrusted to a consortium of two design studios, Cox Rayner (architecture) and Arup (construction). According to the competition guidelines, the footbridge was to be an iconic structure – characteristic for this part of the city. For this very reason a very original design with tensegrity features was selected. The resultant structure has a sculptural character, defined by the arrangement of cables and tubular struts made of steel. Three spans of the bridge rest on two reinforced concrete pillars. The total length of the bridge including the ramps is 430 m, and the clear width of the bridge is 6.5 m (Kasprzak, 2014). This project proves the potential of tensegrity systems for the construction of linear engineering structures. In line with the initial objectives of the competition, the structure became an icon of Brisbane, see Fig. 11.

Fig. 11. View of the Kurilpa Bridge seen from William Jolly Bridge. Source: (Wikimedia, 2018)

4. CFRP based tensegrity structure prototype

4.1. Experimental studies on tensegrity structures

Tensegrity structures fascinate many researchers worldwide. One of the directions of their pursuits is the application of tensegrity structures in two-way spatial grids. Due to their geometry, which forms a flat surface, they can be used in plate structures. Extensive research on such structures has been conducted in the Laboratory of Mechanics and Civil Engineering at the Montpellier University II (Laboratoire de Mécanique et Génie Civil (LMGC), France, within the scheme of the project “Tensarch”. The research works, conducted under the supervision of René Motro, resulted in numerous solutions of the tensegrity grids (a detailed description of the research can be found in the PhD dissertation of Vinicius Raducanu, written under the supervision of René

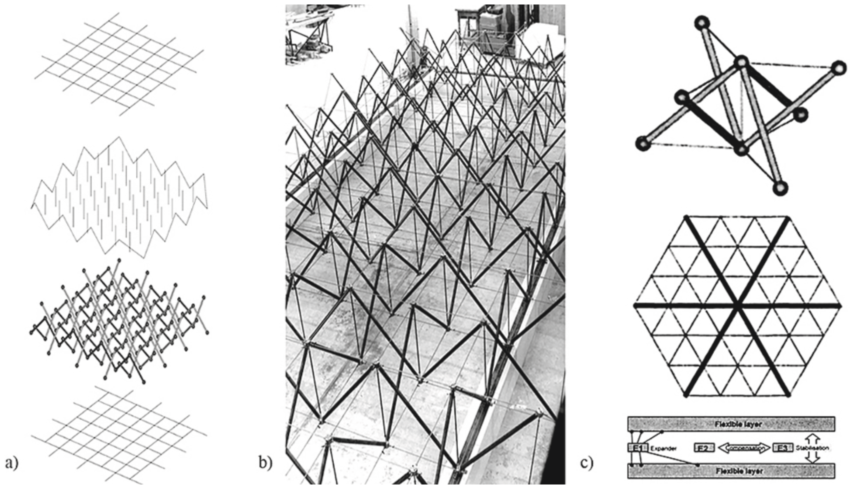

Fig. 12. a) Exploded view of the 2-way tensegrity grid, b) realized prototype of the 2-way tensegrity (Motro, 2012), c) structural diagram of the 3– way tensegrity grid (Motro, 2003)

Motro). The geometrical foundation (the network of cables and struts) of the base of the designed structures allows to build plate structures in a relatively easy way thanks to their modular composition. Within the scheme of the project, a prototype of one of the solutions was developed: a 2-way tensegrity grid with the surface area of 82 m^2, consisting of 64 nodes and 177 elements – 52 struts and 125 cables, of the total weight of 900 kg (Motro, 2012) see Fig. 12a,b.

This research project provided theoretical foundations for further scientific studies, inspiring others to multifaceted pursuits. The ones presented below focus on combining features of tensegrity structures with the advantages of a composite materials.

4.2. Studies on models of tensegrity structures with the application of CFRP

The studies conducted – a review of the latest realizations using CFRP and tensegrity structures – became a foundation for a further search of potential applications of CFRP in the process of building tensegrity structures. The research focusing on the development in the aforementioned methodology was launched during the Fullbright Student Programme at the Faculty of Architecture at UC Berkeley, Zając (2019).

Described by Motro 3-way double layer tensegrity grid was selected as a base model for the research work, see Fig 12c. Structure is described on a modular grid consisting of equilateral triangles. Designed distance between nodes situated on intersections of the construction mesh is 114 mm. The nodes are connected by means of cables. This grid defines the arrangement of struts which constitute the compressed part of the system. The length of the strut is 180 mm. Total height of the model is 126 mm. This height defines the thickness of the structure and the location of the nodes. The total number of nodes in the developed prototype is 78, 39 on the lower and 39 on the upper surface, see Fig. 13. The modular character of this type of solution for a tensegrity structural system offers a possibility of expanding the structure by adding subsequent nodes.

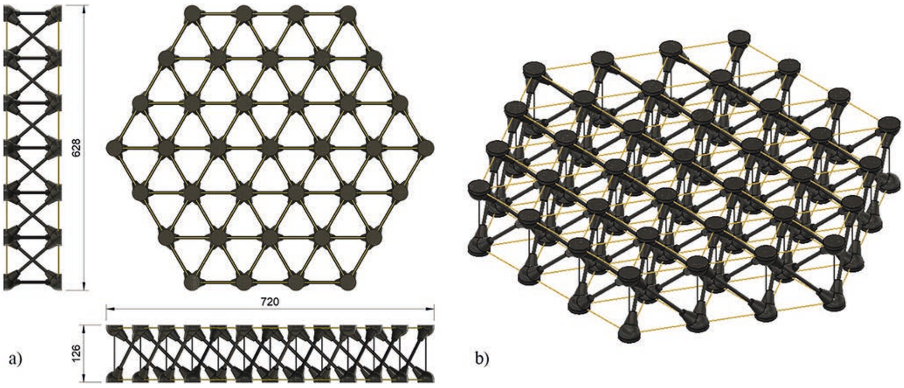

Fig. 13. a) Prototype design dimensions – mm, b) Orthographic view of 3-way tensegrity grid prototype design. Source: own study

In order to verify the correctness of the project assumptions, numerical simulations were conducted. A virtual model of the structure was developed in Autodesk Fusion 360. Static stress simulations were carried out in the simulation environment of the software. Next, the virtual model was subjected to a vertical force of 1 kN. The force was applied evenly to 7 central upper nodes of the structure, see Fig. 14b. The structure was supported on the bottom nodes of the structure, see Fig 14a. The materials properties used for simulations were for cables elements: *E* = 150 GPa, *v* = 0.35, Ultimate Tensile Strength (UTS): 3,000 MPa. and for nodes and struts: *E* = 133 GPa, *v* = 0.39, UTS: 577 MPa. The simulations of the virtual model provided grounds for further works on the 1:1 scale prototype, see Fig. 16a.

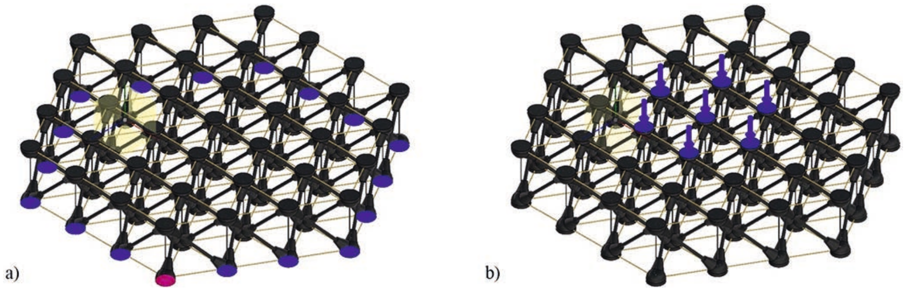

Fig. 14. a) Structural constraints: blue – frictionless, red – fixed, b) Load distribution. Vertical force of 1 kN equally distributed on 7 central upper nodes. Source: own study

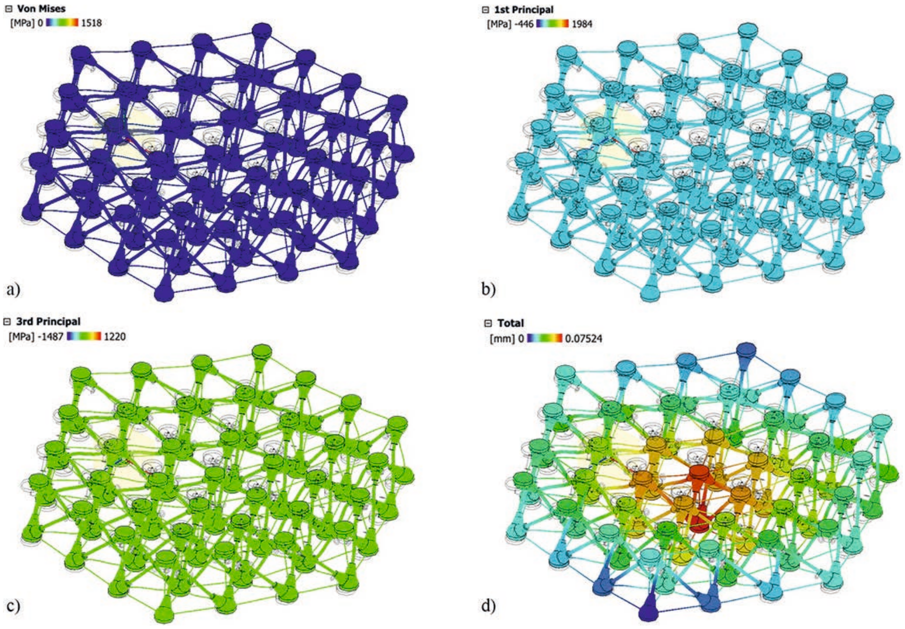

Fig. 15. Static stress simulation results: a) Von Mises, b) stress 1st principal, c) stress 3rd principal d) displacement. Source: own study

Table 1. Static stress study rapport of developed 3-way tensegrity structure under simulated load of 1 kN

Name	Minimum	Maximum
Stress		
Von Mises	7.416E-04 MPa	1,518 MPa
1st Principal	–446 MPa	1,984 MPa
3rd Principal	–1,487 MPa	1,220 MPa
Displacement		
Total	0 mm	0.07524 mm
Strain		
Equivalent	7.88E-09	0.02037
1st Principal	–6.964E-06	0.01893
3rd Principal	–0.0164	2.283E-06

In order to validate the form and the project assumptions after a virtual model design process and carrying out numerical simulations a 1:1 scale prototype of the structure was developed. The struts, which are the compressed elements of the structure, were designed as CFRP struts with the diameter of 6.4 mm. The 42 inside nodes were printed from high-impact thermoplastic PC--ABS by means of the Stratasys 3D Fortus 380mc printer. The 36 edge nodes were milled out of ⌀35mm PA6 aluminum rod. The struts were glued to the nodes of the structure with a high-strength epoxy glue 3M DP420. The nodes were connected with each other by means of cables – tensioned element –

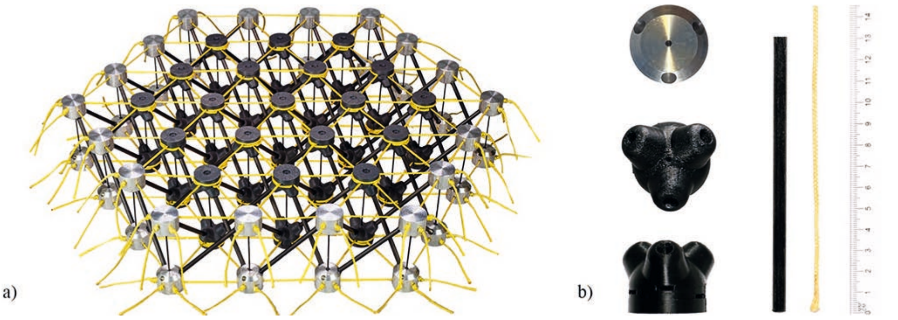

Fig. 16. a) View of the 3-way tensegrity grid prototype, b) Structure elements: 1) PC-ABS node, 2) aluminum node, 3) pultruded carbon fiber rod ⌀6.4 mm, 4) LIROS Dyneema SK75 ⌀2 mm braided cord. Source: own study

made of ⌀2 mm braided cord of the LIROS Dyneema SK75, see Fig 16b. These fibers are characterized by a low weight and very high strength. This material has a strength-to-weight ratios eight times that of high-strength steels with have comparable yield strength. The process of connecting the nodes of the structure consisted in interweaving and prestressing of the LIROS Dyneema cable through each of the nodes. This process was carried out in all three directions of the structural grid.

Thanks to the application of high strength and hence lightweight materials, the dead load of the prototype is 0,18 kN/m^2. For comparison, a 120 mm-thick slab of traditional reinforced concrete has the dead load of 3 kN/m^2. That is why structural solutions based on high strength composite materials could be used as a modular and easy to transport construction elements of a novel architectural design. One of the key characteristic features of tensegrity, high strength-to--weight ratio, combined with high strength composite materials, allows to develop lightweight and hence very durable spatial structures. The prototype is at the final preparatory stage for physical tests, see Fig. 17.

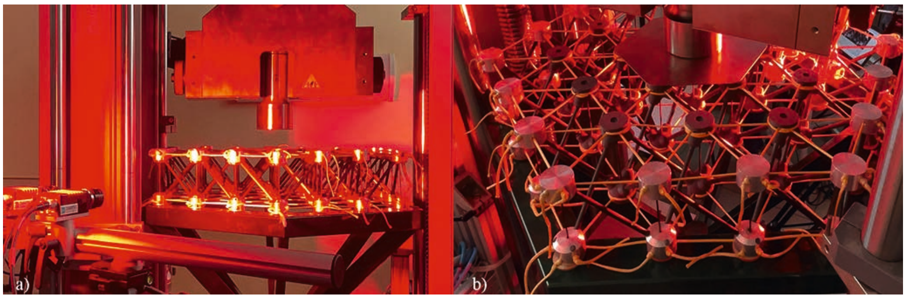

Fig. 17. a) Front view of the protype prepared for structural testing on the ZwickRoell Z250, b) View of the prototype and the steel plate on top (thickness 2mm) for load distribution on 7 central upper nodes. Source: own study

5. Results & conclusion

One of the main reasons why currently composite materials are not used on a large scale are their high production costs. As the interest of the construction industry grows, and consequently as the demand for such products increases, the production costs should go down. It will allow to use them more broadly. The research on implementation durable composite materials in tensegrity structures demonstrates their potential. Integration of tensegrity structures with ultralight and very durable composite materials offers a broad range of possible applications, which include ultralight modular building elements, light roofing, post-disaster emergency shelters, buildings locate in difficult climatic conditions, and perhaps even extra-terrestrial habitats. Restructuring of coal industry in favor of highly advanced carbon-based technologies may also contribute to the reduction of the currently negative influence upon the environment. Even today these technologies demonstrate enormous potential in terms of creating macro- and microstructures, from highly advanced carbon--based technologies of electronic systems through the architectural scale. Building an innovation-oriented industry truly moves with the times, creating new possibilities of improving the quality of our habitat.

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