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Architektonické řešení a integrace jednovrstvých membrán do nosného systému gridshell

Architectural solution of single- layer membrane integration into gridshell structures

DISERTAČNÍ PRÁCE

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Doktorský studijní program: Architektura a stavitelství

Studijní obor: Architektura a stavitelství

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Praha, 2018

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Název disertační práce: Architektonické řešení a integrace jednovrstvých membrán do nosného systému gridshell

Prohlašuji, že jsem uvedenou disertační práci vypracoval/a samostatně pod vedením školitele prof. Ing.arch. Miloše Kopřivy.
Použitou literaturu a další materiály uvádím v seznamu použité literatury.

V Praze dne ....

....
podpis

Acknowledgements

There is an interesting story line behind this dissertation, which happened during my PhD studies, starting as an undergraduate on my first specialized conference in 2011, continuing with the Master´s program Membrane Lightweight Structures on TU Wien and finishing with experiences from realized structures.

I would like to thank to my family and friends, primarily to:

My wife, Markéta Vaňková and the whole family, who supported me with making an important decision for further studies and for the tolerance they maintained during the work.

Many thanks to professor Miloš Kopřiva, who was my mentor and advisor, Robert Roithmayr for leading the Master program Membrane Lightweight Structures, sharing knowledges and sources, and the course lecturers - especially to Jürgen Hennicke, who initiates me into the mystery of Gridshells and helped me to design the experimental structure, Julian Lienhard for supervising my Master´s thesis on TU Wien and to share all necessary knowledges and experiences about lightweight architecture and engineering,

Many thanks to the company Matrix a.s., especially to the CEO, Mr. Libor Burian for the confidence and support by the realization of the pavilion in Třebešov, Radek Podorský and Christian Bartl for design collaboration on this project,

Lukáš Kurilla for continuous consultations about the problematics in general, Jaroslav Hruška, for supporting me by testing ETFE foil, Jan Vecko for design collaboration, project completion and manufacture of the eight-point sail for gridshell pavilion in Třebešov, Miroslav Kiška for helping with English grammar,

collective of Czech Technical University in Prague students and friends for helping to organize workshops, conferences and projects, preferentially to Dmitri Borisenko, David Salon, Stephan Töngi, Tereza Zhekova, Jan Paclt, Jiří Kolář, Jaroslav Hůzl, Pavel Janků, Jakub Seif, Matěj Sova Adam Pospíšil, Radomír Vaněk, Vojtěch Wágner, Přemysl Halámek, Tomáš Gloser and others.

Abstrakt

Cílem této disertační práce je výzkum a syntéza membrány a nosného systému na principu lehké konstrukce. Práce se zaměřuje na oblast vývoje lehkých membránových konstrukcí, zejména jejich nosných prvků, zkoumá aktuální stav tenkostěnných konstrukcí, popisuje jejich historii, dokumentuje vybrané případové studie od koncepčního návrhu až po realizaci.

Po celkové analýze existujících projektů (světových a vlastních) a na základě autorových vědomostí a zkušeností byl jako vhodný nosný systém pro další postup zvolen gridshell – mřížová skořepina. Jde o lehkou konstrukci, využívající potenciálu dvojitého zakřivení a membrána je zde přirozeně integrovanou součástí nosné konstrukce.

Jako výchozí bod vlastního výzkumu bylo uspořádáno několik seminářů a workshopů pro fyzické modelování se použilo mnoho různých materiálů a byla úspěšně navržena a postavena první reálná konstrukce.

V roce 2015 přišel skutečný projekt většího rozsahu – zastřešení dočasného divadla Menteatrál v Neratově, kde se konstrukce poprvé vyzkoušela a realizovala v reálném měřítku, vzápětí se v roce 2016 realizoval pavilon Matrix v Třebešově. Autor průběžně dokumentuje vývoj tohoto projektu lehké konstrukce od první fáze návrhu až po realizaci.

Abstract

The aim of this dissertation is the research and synthesis of membrane and supporting systems on the principle of lightweight structures. The thesis focuses on the development of light membrane structures, especially their supporting elements, examines the current state of thin-walled structures, their history, documents selected case studies from conceptual design to the implementation.

After a comprehensive analysis of existing projects (world´s and own) and based on author's knowledge and experience, a gridshell was chosen as a suitable system for the next process. It is a lightweight structure that uses the double curvature potential and the membrane acts as a naturally integrated part of the load-bearing structure.

As a starting point of the own research, several seminars and workshops were organized. For building physical models many different materials were used and after all, the first design was successfully designed and built.

In 2015, a real project of a larger scale has been built - the roof of the temporary theater Menteatrál in Neratov where the structure type was first tested and realized in real-life. Suddenly the Matrix Pavilion in Třebešov was realized in 2016.

The author continuously documents the development of this lightweight design project from the first phase of the design to the realization.

Contents:

1. INTRODUCTION: LIGHTWEIGHT STRUCTURES

Light-weight structure (also possible to name as *little weighing*) represents a structure which in fact is not heavy. At first glance, this definition may sound somewhat in general and ridiculous, but it must be added that the boundary between light and heavy is difficult to define and depends on many factors and angles of view.

The goal of this dissertation is not to define the boundary, because it would be a very complex topic that can only be speculated. The intention is to deal with the consciousness of light and material architecture, which clearly points to the development of architectural structures and documents significant progress whether building philosophy, space perception or material progress, given by the developmental difference of several centuries.

The issue of membrane and foil structures is increasingly seen in today's modern world as a legitimate competitor of already well-established and proven structures. It is a way of designing forms of double curvature using contemporary materials. Tensioned systems in architecture do not work without a supporting structure - in most cases, they are steel but wood, bamboo, PVC, composites or a combination of different materials can also be considered.

The dissertation workflow is focused on finding new architectural forms of supporting structures for modern fabric materials, in essence, it is a mutual interaction of the structure with the membrane. These structures must be able to capture significant horizontal forces of membranes to provide sufficient support for the proposed shape of ideally double curvature. It is also possible to cover surfaces by coating the membrane on the top or apply multilayer foil pneumatic elements into prepared structures.

The unique gridshells do have a great potential in modern architecture due to its rich shaping capabilities and interesting history where various uses of structural materials such as steel pipes, wooden laths, composites, bamboo, pressurized PVC membranes, or rigid PVC tubes are evident. These structures can be designed and erected in different ways and methods, but as a shell made only from raster, it must be ensured against weathering and collisions to meet its functional load. In order for the design to fulfill all the requirements of lightweight structures and to take full advantage of its architectural potential, the covering layer should be suitably chosen. In the case of the correct use of a single-layer textile membrane, it is in parallel with the aesthetic function that the static-shut off textile membrane is able to somewhat brute the structure.

The gridshell is kind of separate lightweight chapter that has significant advantages over other vendors, such as shape diversity, relatively low material costs, mold cleanliness (this is a self-supporting construction, elements such as supports or drawers in the case of single-ply drawn constructions), when using natural materials, they are recyclable, sustainable and environmentally friendly.

A certain disadvantage of these structures is the time required for the construction process, which requires certain procedures, each new building being original. Although these structures have been used massively in history (most probably in the form of a portable dwelling - yurt), today they are not very much used to them.

At the same time, they represent a great potential, for the climate of the lightweight belt combined with a single-layer drawn membrane, it is particularly suitable for the construction of various forms of shelters, pavilions, summer houses, public areas and sculptures. This dissertation is trying to define ideal membrane materials suitable for interaction and co-operation with a gridshell.

2. HISTORY OF LIGHTWEIGHT STRUCTURES

2.1 THE INITIATIONS OF FIRST LIGHTWEIGHT STRUCTURES

The history of lightweight structures in general comes up to the time of human origin existence, when first dwelling out of caves has been built. Very first structures were built up from natural materials, which were easy accessible in the surroundings. The main requirement was to shelter from adverse conditions, sun, animals and last but not least ensures a sense of security.

"The tents of the Nomads provide a unique look into the origins of human shelter and its subsequent evolution. Since nomads occupy the marginal areas of the world, they have been less subject to change than many settled people, because of their ability to move they have remained a free people. When outside forces encroached, the nomads simply rolled up their tents and moved on.

The tent is not man´s earliest dwelling, for it is difficult to make a fully portable dwelling, but the simplest dwellings we know of – the windscreen and the but – are very close to being tents. Most of the materials used for these types of shelters are easily moved so that the windscreen or the hut can quite easily be covered into a tent. In fact, it is impossible to draw a clear line between the moveable tent and the stationary hut. Many tents are only "semiportable" – that is, the frame is left in place and only the cover is moved. [1]

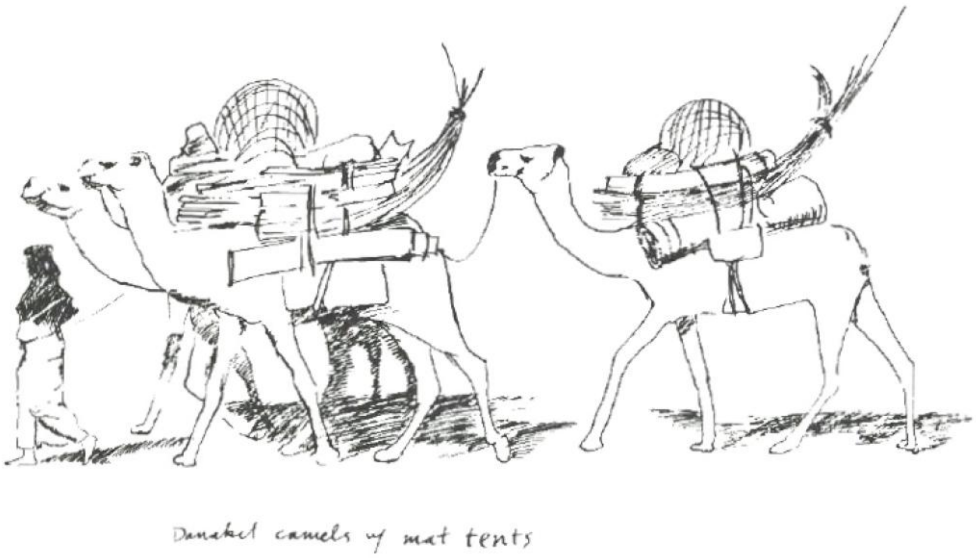

Fig. 2.1 Dwellings easily transported by camels [1]

It is very interesting that ancient proven methods also manifest themselves today, when their principles are used for current development. A tent as the simplest form of shelter created by man has survived to this day, especially due to its functionality and ease of construction. It is also easily demountable and transportable. Living in a shelter today means, as well as in the time of the emergence of this type of dwelling, being in close contact with nature, able to move easily and while under any circumstances one can be hidden in a "protective envelope".

“The nomad lives not so much in his tent as in the desert, the steppe, or the tundra. The tent is important as shelter, hut not in the same way as our homes and workplaces are important to us. The nomad spends a great deal of time living and working under the Open sky, for herding is by nature an outside activity. Clothing is often more vital to survival than shelter.

In the desert and the mountain, it had been their home, their temple and sanctuary. Without this tent the people of the Middle East might never have ventured into the desert.

The birthplace of the black tent is probably somewhere near Mesopotamia. Its origin is tied to the domestication of goats and sheep, the animals that provided the material for the tent cloth and permitted the early nomads to begin their break from settled agriculture. They moved their belongings donkeys, and thus the distance they could travel was limited. But with the domestication of the camel, a final break was made. The nomad could roam the desert, find pasture for his flocks, and never again till the soil. The camel could carry greater loads than the donkey, so the tent increased in size. The black tent and the camel moved together into the new lands so that their respective territories roughly coincide today.” [1]

Textile structures have been known for more than 2,000 years. At that time they appeared in the form of primitive shelters, and they are still in almost unchanged form like Bedouin tents and Mongolian yurts. Military and circus tents are still visible virtually all over the world. The reason for use today is mainly flexibility of shape and at the same time a relatively favorable price. The popularity of architects and investors has gained membrane design thanks to its elegance and unusual shapes and lightness of expression.

At this point, it is also necessary to mention the term “Extreme lightweights” (“Ultralights”), which arose due to the need of a really minimal shelter. If we compare these shelters with today's material possibilities, we would certainly achieve lower weight values, but at that time they were a vital minimum necessary supplement with acceptable weight. The shape and structural solution was given by its purpose.

“Although it usually took only a day to build a traditional stick-framed house, for Nomadic people, who needed to move quickly in pursuit of their livehood and take their dwellings with them, this was too long. Accordingly, they adopted lighter structures that were more transportable and could be erected anywhere in not much more than an hour.

The Tuaregs of the western Sahara desert, for example, reduced the composition of their stick-framed domes to a minimum number of arches, and covered their frames with mats or animal skins which could be rolled or folded into small packages. Similar movable dwelling systems were common in many other parts of the world. Among the best known are the yurts used by the Turks, Tatars and Mongolians. Yurts were the housing units used by Genghis Khan and his troops as they conquered large parts of Europe and Asia.” [2]

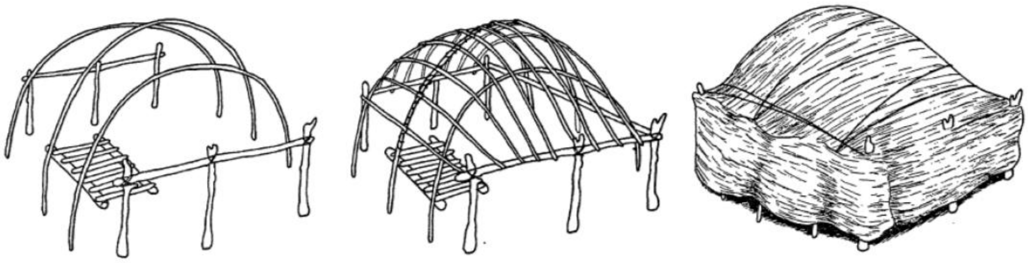

Fig. 2.2 The dwelling of the Tuaregs, minimal number of frame members needed [2]

2.2 HISTORY OF MODERN LIGHTWEIGHT STRUCTURES

2.2.1 Tensile structures

Talking about modern structures means to take into account the unstoppable development in architecture and building process. In the middle of 20th century there were developed several amazing realizations based on natural structural principles. The father of modern lightweight membrane structures became Frei Otto during his well-deserved lifelong research and experimentation that led to succesful realizations, which can stil be seen today.

These are based on the principles of double curvature and documenting modern progress, particularly with regard to the materials used. Frei Otto experimented with steel meshes, tensile membranes, pneumatics, gridshells and other lightweight structural principles, which became known again. He basically described the general core of lightweight structure problematics.

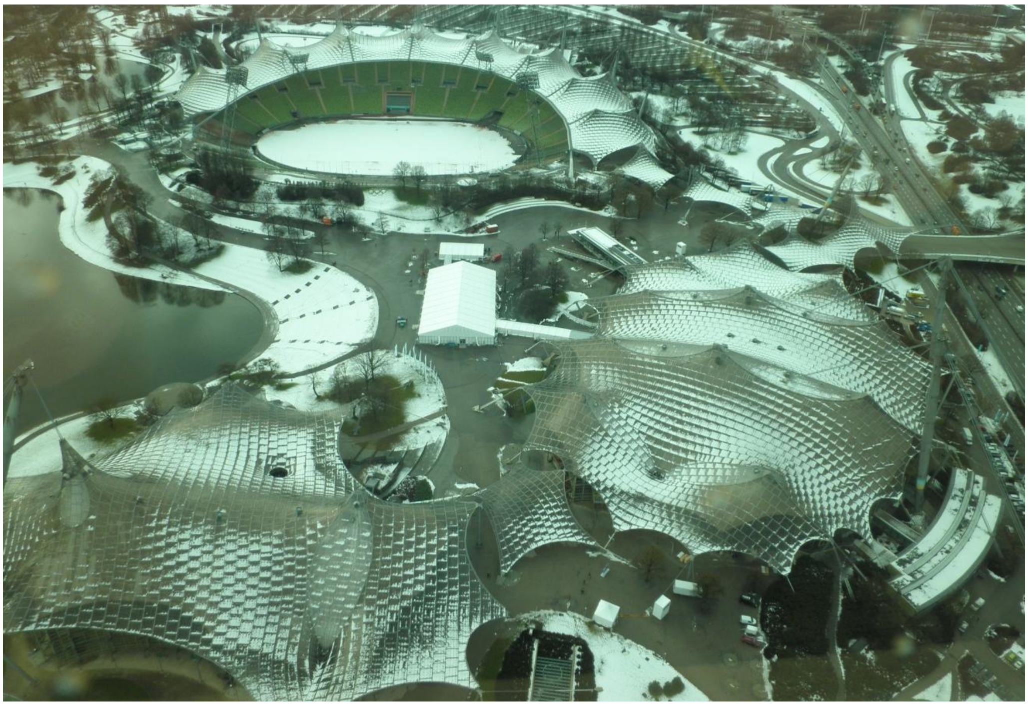

Fig. 2.3 Olympic stadium 1972, Munich, Germany [by author 1/2014]

Another very interesting structure is the workplace of ILEK in Stuttgart (Institut für Leichtbau Entwerfen und Konstruieren), originally designed as an experimental structure for German pavilion for the EXPO 1967 in Montreal. The pavilion has been used as a scientific institution and documents the beginning of the work of Frei Otto in the field of lightweight structures. Working in the free circuit which is in the circle substance can be any arrangement according to the specific needs. The large loop – eye window creates a beautiful structural element, which allows enough light to entrance the building. The object itself is surrounded by trees and garden, increasing the physical models of experimental light structures.

Fig. 2.4 ILEK Institute, Frei Otto, Stuttgart, Germany [3]

Another interesting building is the Eissporthalle, which is also located in the area of the Olympic Park in Munich. Basically it is a tensioned cable net structure, suspended using an arched steel truss construction on outside the building. This is an ideal solution for its purpose as it provides free ground plan without columns. The roof cladding is made of wooden laths, which are fixed on the top of the cable mesh and covered by PVC membrane. In the ridge "seam" there is led an illuminated belt, supported by the arc.

Nowadays, the space functions as a sports ground for ball games, especially for futsal, divided using nets for several separate playgrounds. It is a big pleasure to play a game there, because the space has its unique atmosphere due to the wooden ceiling and due to daylight coming through the middle "seam".

Fig. 2.5 Eissporthalle, Frei Otto, Munich, Germany [by author 11/2015]

2.2.2 Air supported / inflated structures

The concept of pneumatic structures is based on the overpressure of the internal air within the packaging of a lightweight and flexible material - an airtight membrane. In essence, two types of these structures are distinguished – Air supported and Air inflated. The first one provides high volume spaces, the air pressure required to stabilize the whole system is relatively small. For example, in the case of a typical enclosure, as an example a tennis court envelope, the air pressure values are about 50 Pa and in the case of a pneumatic element measuring four by four meters the value is about 10 times higher. In reality it is necessary to ensure constant air supply.

“The concept of using air-supported structure in building came from the car pioneer F. W. Lanchester. He obtained a patent on it in 1918. The largest of the airhouses he envisaged had a diameter of 650m and contained all of the features today. Unfortunately there is no record of construction and it is thought he couldn´t produce an adequate membrane. It wasn´t until the latest 1950´s that pressure supported domes to cover the early warning screens were developed by Birdair in the US. Birdair has been at the forefront of the field ever since. It´s estimated that more than 40.000 have been erected thoughout the world. Recently, however, by employing volumetric shaping to reduce wind loading and using a primary cable net infilled with PTFE coated glass fibre panels, Birdair have been covering span greater than 200 m with an anticipated life of around 50 years. An interesting quality of the Airhouse is that every aspect of flexible structure design is covered to some extent in such a problem – it is archetypal for all tension structures.”

Fig. 2.6 City in the Arctic [4]

By the end of 1960´s some research had been carried out on air supported structures but when one of the authors worked with the professor Frei Otto on a project for a City in the Arctic he became aware of the disparity between recorded measurements and the existing theory. Further design work in both tents and airhouses led to further questioning and an awareness that all published loadings related to profiles which were not in use and all stress calculation methods appeared to depend on an overall constant internal pressure, which is correct yet of limited value. Most research seemed to be carried out in isolation from reality and there appeared to be a need for an ordered and broad behavioural investigation.” [5]

An Arctic Town, covered by transparent material was designed by Frei Otto and Ewald Bubner together with Kenzo Tange, It proposed a large-scale dome of the span about two kilometers and enclosing the artificially made environment of the circular groundfloor. The foundation was to be built and then the dome structure was to be laid and inflated. Inside the dome the construction of the city could take place in a conditioned environment. The dome consisted of a double-layered transparent foil retained by a steel cable net, pressurized air in the dome providing the structural support of the dome. The shape of the dome would prevent the accumulation of snow and resist intense wind, and provide ventilation of fresh air and heating through atomic energy.

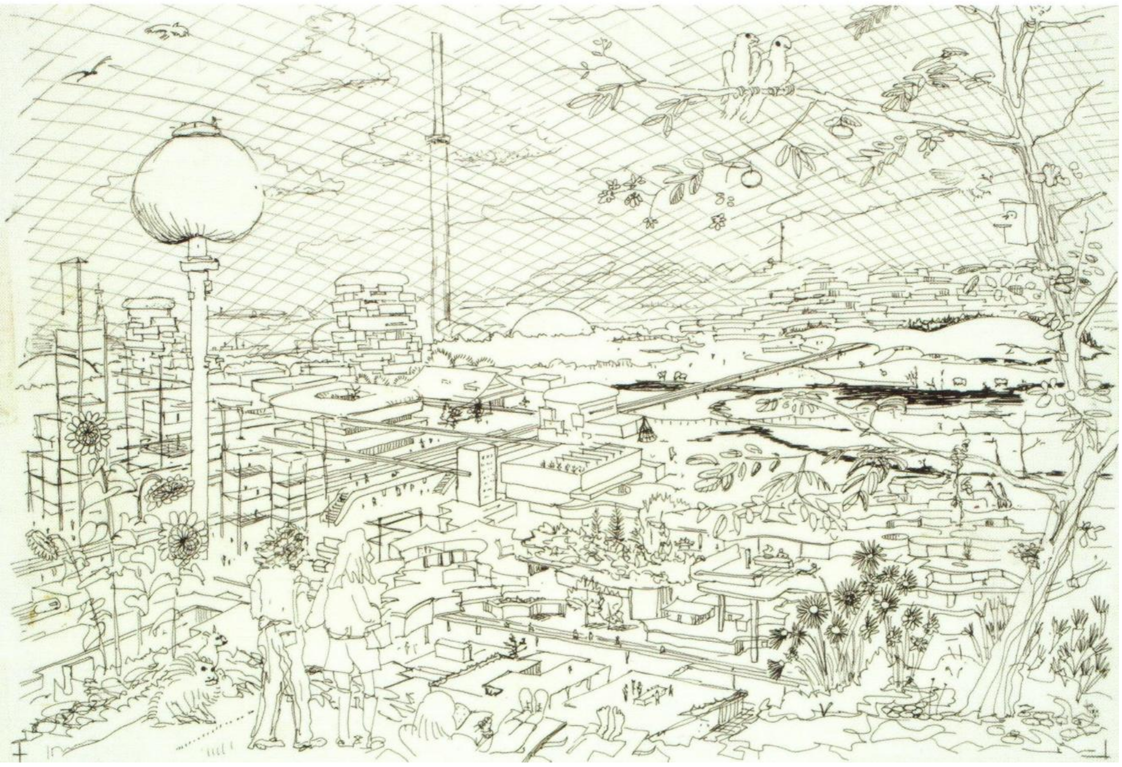

Fig. 2.7 The living space of city in the Arctic [4]

As an example of air inflated structure there is mentioned the pavilion Fuji for EXPO 1970 in Osaka. The shape of the pavilion was formed by 16 arches, made of shaped air iflated tubes, each tube measuring 4 m in diameter and 72 m in length). The tubes were arranged along the circumference of a circle having an outer diameter 50 m. When erecting the structure, the air-tubes, inflated in a row, were bound together with horizontal belts measuring 50 cm in width. Even tough it held an organic shape, it could still be made into a three dimensional geometric form.

Fig. 2.8 Fuji pavilion, EXPO Osaka 1970 [6]

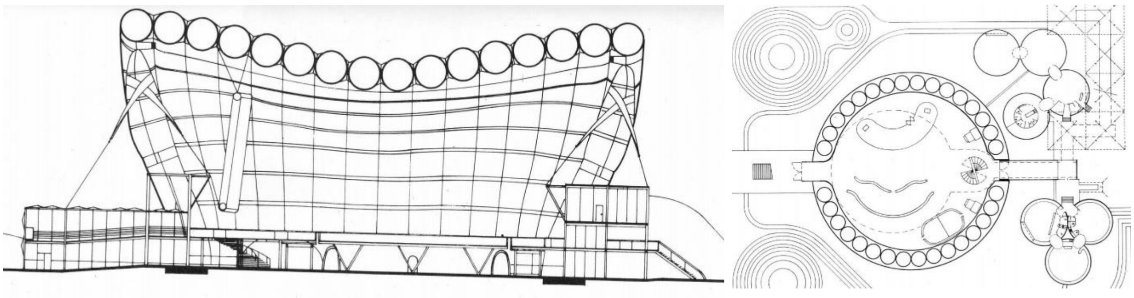

Fig. 2.9 Fuji pavilion, section and floor plan [7]

2.2.3 <u>Pressure – stressed structures</u>

The third considerable group in the field of modern lightweight structures is thin-walled shells, which act as pressure-loaded structures. These can be made of concrete, timber, plastic, composite, bamboo, paper or even steel. The very first gridshell structure was made of steel tubes by the Russian engineer Vladimir Shukhov in Niznij Novgorod in 1894.

As an example of a modern pressure – stressed structure one must mention Buckminster Fuller, who was the pioneer of several lightweight principles. Fuller was most famous for his lattice shell structures – geodesic domes, which have been used as parts of military radar stations, civic buildings, environmental protest camps and exhibition attractions.

*"Their construction is based on extending some basic principles to build simple "*tensegrity*" structures (tetrahedron,* octahedron*, and the closest packing of spheres), making them lightweight and stable. The geodesic dome was a result of Fuller's exploration of nature's constructing principles to find design solutions. International recognition began with the success of huge* geodesic domes *during the 1950s."* [8]

Fig. 2.10 Richard Buckminster Fuller´s Geodesic dome structure [9]

It is well known that the spherical surface of geodesic domes encloses the maximum volume for a given surface area. But the volume of a sphere, or even a segment of a sphere, while ideal for material storage, is not very useful for many other activities, and could result in wasted land or space.

3. CLADDING MATERIAL FOR LIGHTWEIGHT STRUCTURES

Membranes are referred to as the fifth building material - besides concrete, glass, wood and clay. Diaphragm structures have a very wide range of use - the most common is protection against sun and rain, which is most desirable since the very beginning of very first lightweight structures. Sports buildings, traffic buildings, atrium overlays, facades, but also small shading techniques or architectural accessories, textile artifacts. There textiles are most common.
Talking about modern lightweight structures, there is much more about nowadays, which is given by wide purpose range, modern materials and structural principles.

3.1 TENSIONED SINGLE LAYER FABRICS

Tensioned single layer fabrics are due to the wide range of realizations worldwide considered as a main market in the firld of lightweight membrane structures. The material follows multiple advantages (including rain and sun protection), its lightness, flexibility and elegance really supply an architectural work.

For an interior purpose, it is possible to use the simple membrane materials, which doesn´t need to carry additional loads from wind and snow.

Fig. 3.1 Interior atrium ceilings, CTU Prague [by author 10/2013]

Fig. 3.2 Interior ceilings, CTU Prague [photo by Jan Bartoníček 3/2018]

On the other hand, there are much higher requirements for the quality of the material and the design of the supporting structure for outdoor use. Especially with regard to year-round operation, where the roofing or facade must resist direct sunlight and unfavorable climatic conditions - wind, rain, snow, ice and, last but not least, sand. The wind load is, in most cases, the largest one that affects the membrane structure during its lifetime. For the purpose of external structures, there is a PVC coated fabric most widely used.

For woven sails, glass fibers coated with PTFE (polytetrafluoroethylene or teflon) and PES (polyester) fibers coated from both sides with PVC (polyvinyl chloride) are strong durable fabrics, translucent and waterproof and can withstand extreme environmental conditions, humidity and UV-radiation.. To achieve better properties it is also possible to apply coatings or lacqueurs, for example dirt repelents.

“PVC/PES fabrics are the most economic material in tensile fabric and membrane architecture. The price coupled with the availability of dirt repellent surface lacquers makes it attractive for a variety of permanent and temporary architectural applications.” [10]

Fig. 3.3 Wellness centre, Bad Wildbad, Germany [photo by Robert Roithmayr 5/2017]

Sails generally have a greater bearing capacity in the direction of straight fibers (warp direction) than in the direction of the threads (weft direction), i.e. they are orthotropic material.

Sheets with approximately identical load capacities in both directions are now being produced, which can be achieved by transverse prestressing of the basic warp of the fabric at all stages of production. The material characteristics of these materials are, as far as the maximum strength is concerned, given by the manufacturer, the most desirable conventional glass fiber and PES fabrics achieve a tensile strength of about 180 kN/m.

3.2 FOILS

The film, compared to the woven textile membrane, forms a film having the same properties in all directions. This material is extremely thin (about 0.3 mm) and stiff. The representative and most used is the ETFE foil.

"Architectural interest in ETFE was sparked by the first oil crisis in 1973-74, when Europe began to focus on harvesting solar energy to replace fossil fuels. Extruded ETFE film was developed at Hoechst, where researchers significantly advanced production techniques and market applications, including use as a replacement for glass in greenhouses and, in metalized form, for thermal solar collectors. Realizing the potential benefits of this material that weight only a fraction of glass, and which, for greenhouses, can produce food with the same color and flavor as when grown in the open air, Hoechst submitted ETFE to weathering tests both in Germany and in Arizona in 1984 after a decade of field testing. ETFE showed no change in its optical or mechanical properties, and these results provided the assurance that paved the way for architectural applications."

"The architectural use of ETFE films was pioneered by Vector Foiltec in Bremen. The first applications were for plant houses at Burger´s Zoo in Arnhem in the Netherlands. Vector Foiltec, at the time a sailmaker for yachts, was contacted in 1982 to rectify a building failure. Shortly after completion, the original cable-supported FEP (fluorinated ethylene-propylene) envelope of the Mangrove Hall in Arnhem collapsed, a result of FEP´s tendency to creep, become thin and rapidly propagate tears. The ETFE replacement – stronger, lighter and resistant to tear propagation. Reusing the original steel mast and cable structure, the three-layer ETFE cushions provide a well insulated environment flooded with daylight." [11]

Gulliver, Galery of Arts DOX, Prague, Czech republic

Fig. 3.4 View from the roof terrace, front view [by author 4/2018]

The airship is 42.2 m long with its diameter 9.35 m at the widest point. The total indoor floor area of 162 m² accommodates at least 80 spectators and the envelope has a volume of 2050 m³. The base of the structure is a steel bridge, which is laid on two supports anchored on the piloted foundations in the courtyard underneath. The airplane itself connects two roof terraces that are of varying height. This created the inner space of the auditorium, which is slightly inclined to the point of the airship and is divided into horizontal wooden terraces. A total of 14 larch trusses made of larch wood are connected to the longitudinal axis, which are interconnected by a longitudinal supporting wooden structure.

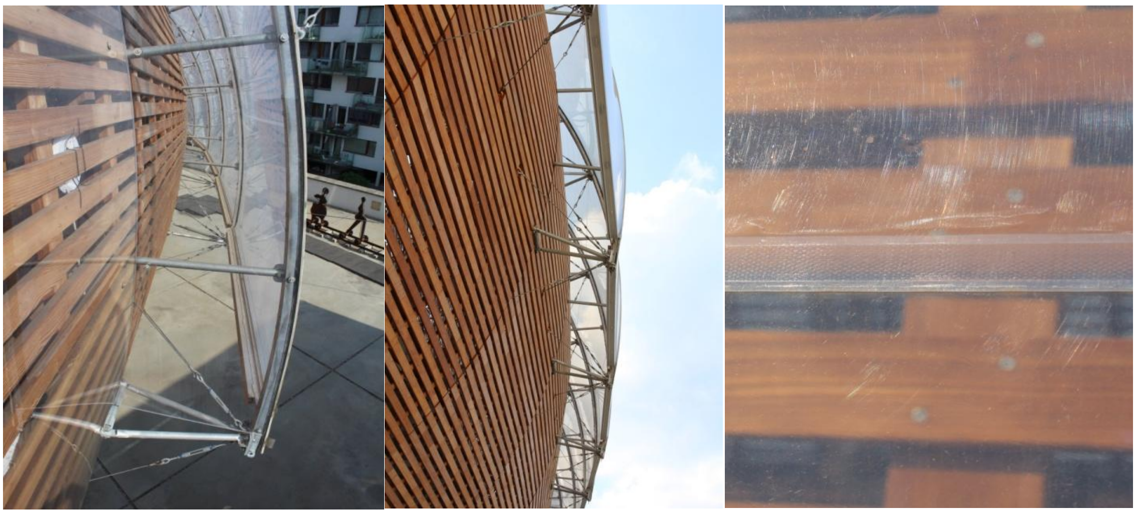

Fig. 3.5 Detailing of the ETFE foil application [by author 6/2018]

MULTIPLE LAYER FOILS

Pneumatic element – cushion, constitutes the most known example in the field of multiple layered foils, mostly used in two or three-layer modification. ETFE film is very thin (just about 0.3 mm), very strong, stable and resistant to UV radiation and adverse weather conditions. The perfect smoothness of the surface then ensures self-cleaning ability

EDEN Project, Cornwall, England

Fig. 3.6 Bird view of botanical garden in Cornwall, England [photo by Stanislava Šulcová 3/2018]

One of the most interesting ETFE projects worldwide, The complex consists of two large enclosed units, each unit is created of four smaller connected domes, consisting of hundreds of hexagonal and pentagonal inflated ETFE cushions, attached on carrying steel structure. In the whole complex, there are grown thousands of plant species, each of the smaller parts mimics the natural biomes.

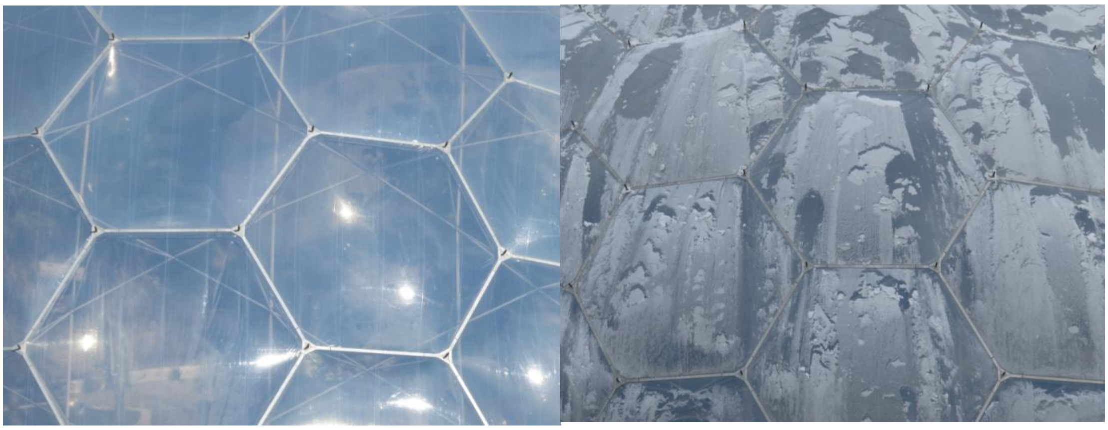

Fig. 3.7 Exterior view on façade in different weather conditions [photo by Stanislava Šulcová]

Fig. 3.8 Interior view on façade subtle structure [photo by Stanislava Šulcová, 4/2018]

<u>Allianz Arena, Munich, Germany</u>

The Allianz Arena Munich is one of the most prominent buildings in the world of membranes. The 2.816 double layer air supported ETFE cushions are equipped with led lights to create a colorful facade of approx. 65.000 m2. The lenght of the pillow edges range from 4 to 8 m and span from 2 m up to 4,25 m and the diagonal reaches of approx. 16 m, the span of the supporting steel cantilever trusses reach approx. 50 m. The ETFE film has a light transmission 95 % and a specific light balance membrane was installed below the ETFE cushions.

Fig. 3.9 View to the façade of Allianz arena, Munich, Germany [by author, 10/2012]

There does exist another material, which is suitable for use as an air inflated element. TPU film in the hands of the architect Thomas Herzig can transform into elements that is used especially for the purposes of constructions for temporary buildings. The product name is Pneumocell®.

There are often durable structures that are able to withstand adverse climatic conditions throughout the year, but in many cases they are temporary realizations that serve a short-term purpose, aim at making the place more pleasant and lively, attracting visitors, last but not least function as a functional roofing or shading element.

"Pneumatic windows based on Pneumocell-technology consisting of 4 layers of polyurethane membrane. The heat insulation and light transmission is equal to argon filled insulated glazing, by only 1/5th of the cost for glazing. Furthermore unlike glass larger panels with free curved geometry can be produced and easily transported and mounted. The pneumatic windows could be cut by a knife, but they are hail safe and break proof on the other hand" [12]

FIg. 3.10 Workshop of the architect Thomas Herzig, Austria [12]

The feeling from the interior space when using pneumatic elements instead of walls and windows greatly supports a high degree of clarity. If necessary, it is possible to unlock the whole element by means of zippers, thus complete linking the interior with the exterior.

The originality of the design favors the contrast between the existing wooden construction and the transparent TPU material, which greatly improves the structure and adds value to it.

The great value of these structures is then the possibility of efficient lighting in the evening. This added value is now commonplace. There is an interesting example of using extremely lightweight structures in context to present ones.

FIg. 3.11 Pneumocell® pavilion – side view and interior view, Thomas Herzig, Austria [12]

Customized pneumatic pillows are able to replace the glass. The advantage is freely configurable geometry, larger possible individual formats and a lower, more advantageous price. The pillows could be cut off by a knife, but they cannot break, unlike glass. The building shown here has exposed concrete flooring and an internal stone wall for storing solar energy. On a sunny day, even at outside temperatures below zero, 25°C is achieved inside without heating.

"Pneumocell elements are made of 100% recyclable TPU (thermoplastic polyurethane). Unlike PVC, this material burns residue-free and without toxic fumes. In addition, TPU is free of plasticizers and chlorine, substances that are permanently separated from other films in the form of the typical PVC so called plastic odor".

3.3 MEMBRANES CLADDED ON THE SURFACE

In this chapter, the author merely mentions the possibilities and difficulties of membrane application on the porch of a double curved surface. With regard to gridshell constructions, this issue is discussed in more detail in Chapter 8 (Membrane Protection Application).

Covering a membrane construction is not a simple matter, and the membrane is not enough to lay simply on the surface. This must be sufficiently stretched to ensure cohesion between the surface and the membrane, and in the case of synclastic shapes it can additionally stabilize the entire structure. The second type of surface is the surface anticlastic, where a transition occurs between the concave and the convex shape.

If the surface is directly covered by the membrane, in addition to the suitable material to cover, it is necessary to solve the main grid joints to which the membrane is attached. As for the screwed joint, the most advantageous, and in the course of the author's research, is the threaded bolt whose rounded head interacts well with the diaphragm and does not tend to break it. This bonding method was also tested by ETFE gridshell coating.

Another possible hurdle is moisture, which can be manifested by condensation or degradation of the wood by simple application of the gridshell-membrane. The gridshell designs in conjunction with the membrane are in most cases used for open pavilions or shelters, where we expect continuous sufficient ventilation.

Airshell -Air filled supporting structure

The realization of the humanitarian shelter demonstrates how flexible grids of high performance structures are able to cover big spans using a very small amount of material or built-in energy. The natural property of these structures is the ability to create double curved shell-like surfaces of thin profiles. While in its erected state it is durable and efficient, existing building methods are usually associated with significant complexity, cost and time.

Fig. 3.12 Exterior view of finished structure, interior view [13]

3.4 POLYCARBONATE

An exemplary example to cover the light structure using polycarbonate: The roof of the Olympic Stadium in Munich, which is presented in this dissertation several times, from different angles of view.

At the time of the designing and construction it was necessary to find a suitable roofing - sufficiently light and durable to solve all the necessary details - especially drainage of rainwater and adequate attachment of the roof to the construction of tensioned steel cables. Polycarbonate slabs are embedded in aluminum profiles - frames. Due to the curvature of the structure, the water can flow into prepared rubber grooves.

Fig. 3.13 Detailed view to the Olympic stadium roof, Munich, Germany   [by author, 1/2014]

3.5 MATERIAL COMBINATIONS

Sometimes, but not so often, there is possible to combine different membrane materials to achieve required properties that would otherwise be difficult to achieve. Mostly, however, these are rare cases as a result of research in the field of improving mechanical properties, efficiency of use, aesthetics. Costs can be more demanding, however, due to the more elaborate design and implementation process.

SIDEWALK COVERING IN LONDON

An unique example of cooperation between a translucent tensioned membrane and a cushion made of foil. The air-inflated cushion serves there as a stabilizing element, which reduces the demands on the perimeter edge of the hypar and serves for a uniform roofing of the entire sidewalk, which would be complicated feasibility by using only the shapes of hypar.

Fig. 3.14 Roofing over a sidewalk, London, 2006 [14]

4. MATERIALS OF MAIN SUPPORTING STRUCTURES AND EQUIPMENTS FOR MEMBRANES AND FOILS

4.1 STEEL

4.1.1 RIGID STEEL ELEMENTS

Steel support structures can be found on the vast majority of membrane structures. This type is particularly suitable for single-layer drawn membranes and single or multilayer ETFE films. Steel can be applied to all types of membrane structures in the form of pushing elements (columns, arches, frames, tubes of different cross-sections) or drawn elements (peripheral ropes or ropes in the area).

Fig. 4.1 Khan Shatyr entertainment centre, Astana, Kazachstan [15]

In the field of membrane lightweight structures, there is the need for a visual impression of lightness. In large-scale embodiments. In many cases, the construction from another material would be much more robust and worse, the whole would then be too massive as a result of a reduction in aesthetic quality.

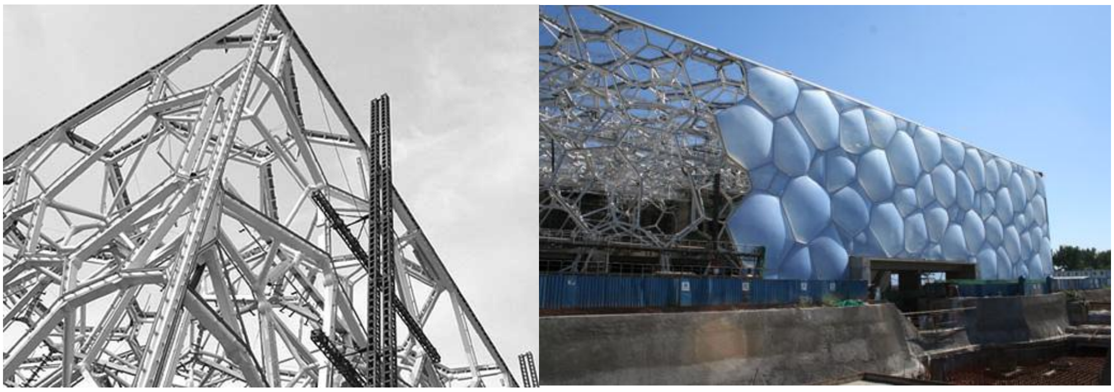

Fig. 4.2 "Watercube" for Olympic games in China, Peking, 2008 under construction [16]

4.1.2 STEEL CABLES

OLYMPIA STADIUM IN MUNICH, 1972

the use of steel cables in a large scale is still visible at the Olympic stadium in Munich. Cables in tension are capable of transferring tremendous tensile forces, which was needed to realize the roofing of such dimensions.

Fig. 4.3 Olympic stadium in Munich, Germany, 1972 [by author 11/2013]

Fig. 4.4 Olympic stadium in Munich, Germany, 1972 [by author 11/2013]

4.2 WOOD

Non-homogeneous, recyclable material, for the complete realization, auxiliary components (joints, drawers, anchors) are needed in practice. From the architectural point of view, wood is a very welcome ecological material and, in combination with the membrane, works very visually, but larger cross-sections have to be considered to ensure sufficient bearing capacity.

For the purpose of lightweight structures it is possible to use several types of wood. To the author´s experience, one of the most suitable species of wood, accessible in the middle Europe is larch thanks to the high resin content, which guarantees a long life of the structure and relatively good flexibility of the wooden laths by building. Larch is also not as branched as other conifers and therefore, in comparison with them does not contain too many knots, as is the case with spruce. The structure of Matrix pavilion in Třebešov is made of larch timber, which sufficiently flexible and resistant to moisture and pests. Individual laths were thoroughly stained with a colorless primer prior to the realization, the lifetime of this open structure is provisionally estimated at 20 years.

Fig. 4.7 Gridshell Matrix pavilion, made of larch timber [by author 8/2016]

"In the past two decades, new high-performance wood construction materials have replaced many traditional building products. In the building industry these advanced materials are referred to as engineered wood products (EWP). They are variations of plywood – a material first made in ancient Egypt and China, though modern versions first appeared in the nineteenth century." [17]

The roofing structure of Centre Pompidou in Metz is made of glulam wood, designed using parametric modeling method.

Fig. 4.5 Centre pompidou Metz, France, both finished structure and under construction [18]

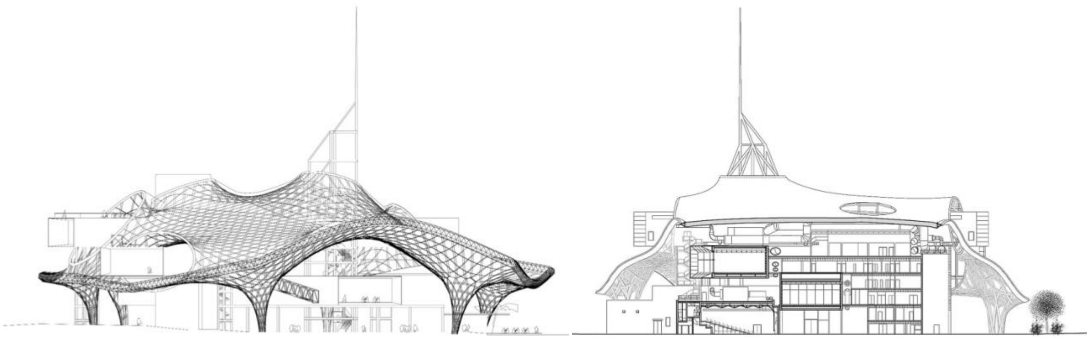

Fig. 4.6 Centre pompidou Metz, France, both finished structure and under construction [17]

4.3 CONCRETE

Rigid material, mostly used for groun fitting of tensile membranes. The other posibility to use concrete as lightweight material is for concrete shells.

At this point is mentioned a concrete shell structure from Heinz Isler (born in Zürich in 1926), his first research was connected with natural principles. In his life he built hundreds of shells for covering garages, Industry halls, accompanied by many prototypes. His largest shell spans 58 x 54 meters. In the figure below a concrete shell covers the natural theatre in Grötzingen near Stuttgart.

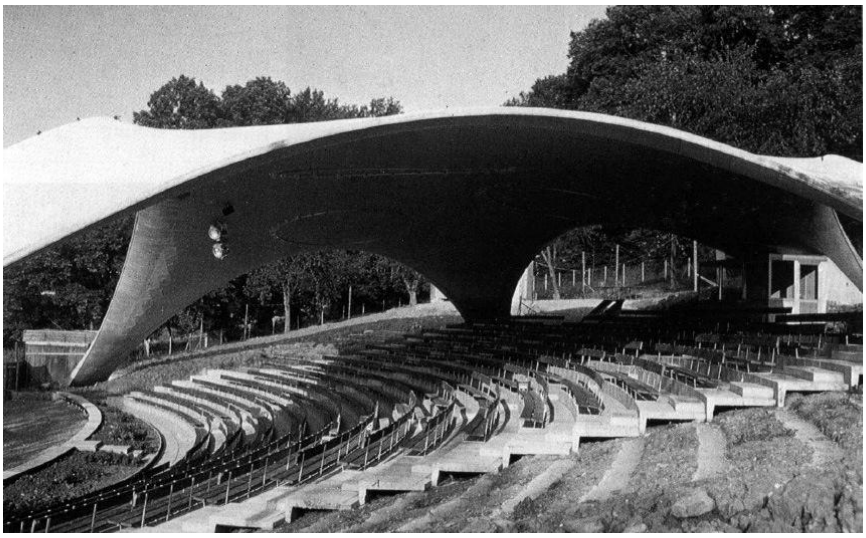

Fig. 4.8 Concrete shell made by Heinz Isler [19]

4.4 ALUMINIUM

Aluminium as a material for lightweight structures is mostly used for construction profiles (even specialized and complicated cross sections). On the example below: Rectangular cushion made of ETFE foil, application on Allianz Arena roofing / façade.

Fig. 4.9 Aluminium profiles for ETFE cushions - Allianz arena façade, Munich, Germany [by author]

4.5 BAMBOO

An Exotic material grown in the middle Europe, widely used in Asia. The other advantage is high strength at low weight, easy accessibility (natural material) and recyclability.

"There are many reasons for bamboo´s appeal: It is inexpensive, it is intensely renewable (growing up fifteen meters in its first year); its cultivation can prevent soil erosion; and it converts more carbon dioxide to oxygen than many other plants. The plant is suitable for construction use within five to eight years, and it has a yield twenty-five times higher than timber." [17]

4.10 Experimental bamboo gridshell structure [17]

"Today, the use of modern building materials has meant that bamboo no longer has the significance it traditionally had as as a construction material. The craft of building with bamboo is a subject of neglect almost everywhere.

In spite of this trend, it is highly probable that building with bamboo will become more popular again in the years to come for a number of reasons. On the one hand, these are due to the rapid rate at which it grows and the large quantities in which it is available, thus making it easy to obtain, and on the other hand the favourable material properties which it has almost without exception, such as low weight, high resistance to tension, compression and deflection, easy of processing and, last but not least, the ever-increasing need for housing for the ever-growing population of the world. This is further supplemented by the fact that the regions in which bamboo grows are by and large identical to those regions with the highest population growth rates.

There are two particular reasons why less consideration is given to building with bamboo today as compared with other building methods, namely the relatively short life of bamboo buildings and, to a greater extent, the fact that this construction method does not contribute a status symbol." [20]

Nowadays, there is no experience or practical knowledge given to the author of this dissertation about building with bamboo, but there is a big challenge to realize an experimental structure in the near future.

4.6 PAPER

An unusual natural building material that came into the subconscious thanks to several successful realizations of the Japanese architect Shigeru Ban, who realized small and simple but also large and complex structures based on paper tubes.

„Shigeru Ban has used paper, an inherently weak material, in the form of tubes, honeycomb panels, and membranes to construct dozens of structures over the past two decades, from exhibition installations and temporary shelters to monumrntal pavilion. Ban refers to paper as „evolved wood", implying that wood and paper share certain similaritioes – the most obvious being that one is the source for the other. Paper´s multistep manufacturin processs begins with wod pulp saturated in water, Paper tubes, the form of paper most associated with Ban, actually began with rolls of recycled paper. These are cut into strips, saturated with glue, and wound spirally around a short metal rod that creates the hollow core of the tube. The tube can be made in any diameter, thickness and length, depending on its use. And used tubes can be recycled, creating an endless reincarnation cycle." [21]

4,11 Japan pavilion, EXPO 2000 [17]

4.7 MASONRY

For the purpose of membrane structures anchoring, masonry is a suitable material mainly because of its strength and the fact that many membranes are realized near masonry walls. In most of cases membrane uses properties of masonry walls to transfer mainly tensile forces.

A little different is the case of historic walls, which are often not homogeneous, and therefore it is not possible to determine precisely whether they are strong enough to interact with the membrane structure. Another problem is monument protection - in these cases a support structure is made of another material, which can be placed in close proximity to the historic wall.

CASTLE RAPPERSWIL COURTYARD COVERING

For any structures that are additionally connected to historical objects, their anchoring is problematic. In case of tensioned membrane structures, this is far more complicated, especially due to the transfer of large tensile forces and the limited possibilities of fitting the anchor elements of the historic walls, which is also the result of heritage preservation.

The inner courtyard of the historic castle Rapperswil in Switzerland is used as a garden restaurant from April to October. The extremely light cover, made of transparent PVC film from the Swiss producer, company Bieri, is especially used to protect visitors from the rain. The lightweight structure is framed along the overhanging eaves by a steel pipe. The welding seams are nicely arranged to create an open and light atmosphere. In case of rain, water flows in the direction to the middle of the membrane surface through the inverted conical shape of the membrane and into the prepared drainage channel. The feeling of lightness, due to the material is extremely high and in case in bad weather conditions, the whole courtyard is well protected.

Fig. 4.12 Rain protection canopy over the castle courtyard [22]

REINHOLD MESSNER MOUNTAIN MUSEUM

An interesting shading structure in the field of tensile membranes is realized at the Sigmundskron castle in Firmian in Switzerland, which is home to the Mountain museum of world-famous writer and mountain lover Reinhold Messner.

This realization consists of 2 symmetrical pieces each of 9-point sail, which is an elegant solution for its purpose as a shading canopy over the restaurant terrace. The whole structure reminds of the open bird's wings inviting visitors to sit and enjoy the atmosphere. The feeling of lightness and double curvature is supported by the patterns layout.

If necessary (winter, predicted poor weather conditions), the membrane can be easily uninstalled and stored. in similar cases the use of a membrane structure is a seasonal matter, serving mainly as a protection against sunlight.

Fig. 4.13 Shading canopy over a restaurant terrace [23]

5. STRUCTURAL PRINCIPLES OF MAIN CARRYING STRUCTURES FOR MEMBRANES

There are many different kinds of structures, which are able to carry lightweight membrane material, especially if the material is cladded on the top of the structure. In the field of tensile membranes, supporting structure for the transfer of horizontal forces is needed as another structural element. In this case, single-layer membrane acts as covering structure, which is a rightful structure in collaboration with supporting rigid structure, suitable mainly for widespan structures. These are, because of its ability to cover sizable areas, mainly used for sport, social and industrial buildings. In a smaller scale, they are often used as protecting structures for housing purpose (rain and sun protection).

5.1 SUPPORTING STEEL STRUCTURE

Nowadays the most commonly supporting system used single-layer membrane is a steel structure, the pressure-loaded columns being supplemented by tensile elements to stabilize them. The solution the solution has its undisputed advantages, in particular the stiffness of the support element with the minimum thickness, where, when the structure is correctly designed, high architectural quality can be achieved because the interaction of the steel and the membrane produces an impression of lightness and subtlety.

The steel elements are used both in the form of anchors, perimeter, ridge and ridge cables, both in the form of structural elements and anchoring. However, tensioned membranes are often incorporated into the larger main supporting steel structure only as a secondary element.

Fig. 5.1 Shading structure for Aquacolors Porec, Istria, Croatia [photo by Jan Vecko, 2015]

5.2 PNEUMATIC STRUCTURE

As already mentioned, the concept of “pneumatic” structures is based on the overpressure of the internal air within the packaging of a lightweight and flexible material - an airtight membrane. There are basically two types: Air supported and Air inflated.

Air supported structures, commonly referred to as “bubbles,” are typically used to provide protection of high volume spaces as tennis courts, swimming pools and athletic fields. Air is used to "support" the membrane and creates tension.

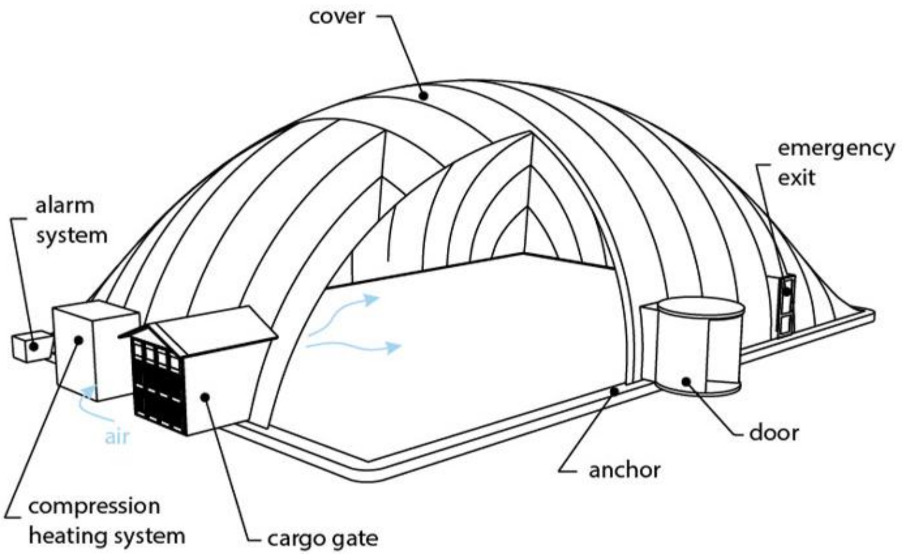

Fig. 5.2 Functional scheme of Air isupported structure [24]

Air inflated structures are often pleasing to the eye through their "friendly" appearance, widely known from applications like inflated boats or air mattresses. But our focus is on the architectural purpose of these structures. The space created is unique and so we can find beautiful sculptures and art installations.

The structural integrity comes from the internal pressure of the air within a structural fabric envelope. The span is often limited as additional structural elements are needed eg. rigid element or cable nets.

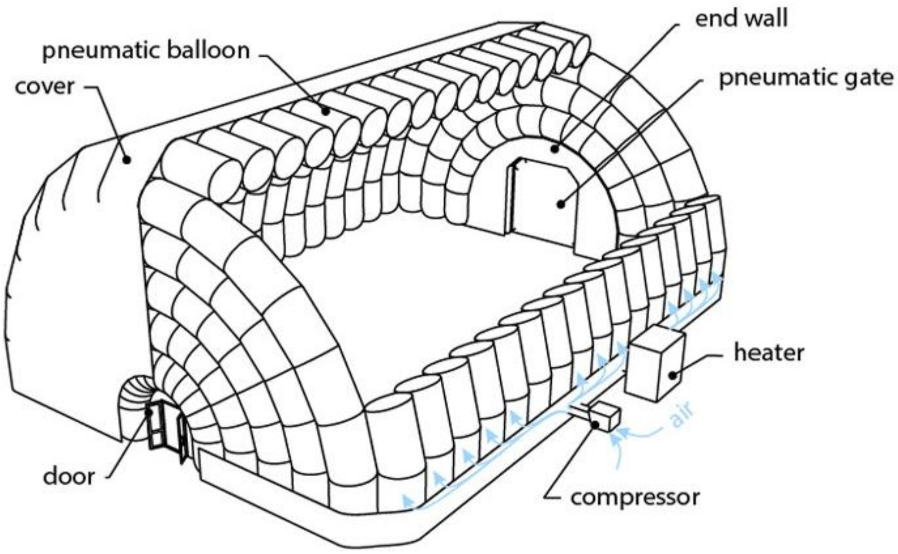

Fig. 5.3 Functional scheme of Air inflated structure [24]

5.3 PARAMETRIC DOUBLE CURVED SURFACE

Fig. 5.4 Interior and exterior view of Centre Pompidou, Shigeru Ban, Metz, France [25]

Center Pompidou-Metz is a French museum in the city of Metz, a branch of the Paris Center Pompidou. The construction of the building was launched in November 2006 and the museum was inaugurated in May 2010. Shigeru Ban as the architect was inspired by a Chinese hat that the architect found in Paris. The museum, after its opening, became one of the most visited cultural facilities in France.

"The roof of CNC-machined laminated timber beams evolves a language developed in Ban's earlier projects. From numerous examples, the architect's elegant Japanese pavilion (AR September 2000) for Expo 2000 in Hanover, which employs his trademark structural paper tubes, particularly stands out. Though Metz is geometrically more complex, this wooden iteration, though beautiful, looks leaden by comparison. Furthermore, the membrane allows only 15 per cent light penetration. In the day the roof is opaque. Press photographs show an appealing glowing mass, but these surely mourn the loss of the initial proposal's fundamental transparency." [26]

5.4 TENSEGRITY

The term "Tensegrity" was first mentioned in the 1960´s as the expression of "tensional integrity" by Buckminster Fuller. "Floating compression" was then used, as another expression of tensegrity, by Kenneth Snelson.

"Tensegrity, tensional integrity or floating compression is a structural principle based on the use of isolated components in compression inside a net of continuous tension, in such a way that the compressed members (usually bars or struts) do not touch each other and the prestressed tensioned members (usually cables or tendons) delineate the system spatially." [27]

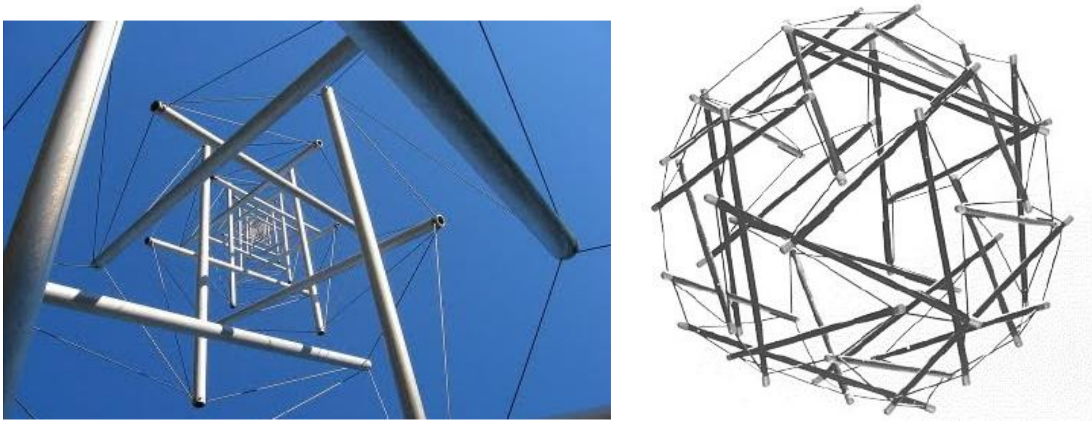

Fig. 5.5 Interior view of tensegrity tower structure [28]

TENSEGRITIC MEMBRANE STRUCTURE by Kazuhiro Kojima

Architectural students at the Tokyo University of Science developed an experimental pavilion, which load-bearing structure is extremely lightweight. The pavilion is 26 meters long, 7,5 meters wide at the broadest point and 4,25 meters high. The volume is self-supporting and comprises only two kinds of components: The metal bearing elements and a delicate space-enclosing skin consisting of a membrane of an 0,7 mm thickness, made of elastic polyester fabric. The membrane is tensioned over the metal tubes and the whole creates a tensegrity system and forms the tension element.

Fig. 5.6 Interior view of tensegrity tower structure [29]

“The 131 compression bars are 25-mm diameter aluminum tubes of various lengths and there is no contact between them; instead, they are connected to the skin by sliding the ends into sheaths sewn on. The membrane is anchored at the base like a conventional tent with pegs consisting of aluminum tubes with tips pressed together to form a point. The compression members are pushed into these pegs and fixed in position by means of steel pins. With a weight of only 600 kg, this airy structure covers a ground area of 146 square meters.

The overall structure was tensioned on all sides, pushed upwards at the same time in the interior and finally fixed to the ground. The convex and concave forms resulting from this create an animated surface and a lively interplay of light and shade. Since the membrane screens off 80% of the UV radiation, but allows 50% of the daylight to pass through, the softly filtered light creates a fascinating spatial impression internally. When illuminated, the translucent pavilion has the appearance of a lighted sculpture.” [29]

5.5 TENSAIRITY®

“Tensairity® (registered trademark is a light weight structural concept that uses low pressure air to stabilize compression elements against buckling. It employs an ancient foundational splinting structure using inflated airbeams and attached stiffeners or cables that gains mechanical advantages for low mass. Pneumatic structures using tensairity are solving problems.” [30]

The structure modality has been particularly developed by Mauro Pedretti.

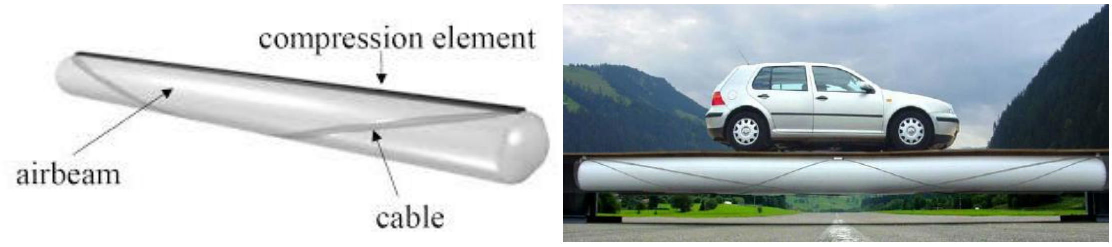

Fig. 5.7 Tensegrity® structure principle [30]

There are several realizations made using Tensairity airbeam, for example roof beam, mobile advertisement pillar with 20 meters height, exhibition stand, bridge with 52 meters span, entrance canopy, complete roof structure and experimental retractable structure.

As a sample example there is mentioned Tensairity roof structure with up to 28 m span for a parking garage in Montreux in Switzerland, realized in 2014 by Luscher Architectes & Airlight.

Fig. 5.8 View to the element, Interior view of Tensairity roofing structure [30]

5.5 SHELL STRUCTURES

The following two examples may are not continuous shell structures which are milestone projects in the field of lightweight shell structures.

Fig. 5.9 Pantheon, Roma [by author 7/2013]

The Pantheon in Roma, Piazza della Rotonda, belongs to the most significant and well preserved historical buildings. It shows structural skills of architects and engineers in beginning of 2nd century (built 114 – 118). The cathedral´s interior circle diameter measures 43,3 meters, which is enormous even to today´s standards. Even with its massive stones the cupola roofing radiates lightness, which is intensified with the rounded hole in big span space.

At this point is mentioned a concrete shell structure from Heinz Isler (born in Zürich in 1926), his first research was connected with natural principles. In his life he built hundreds of shells for covering garages, Industry halls, accompanied by many prototypes. His largest shell spans 58 x 54 meters. In following figures a concrete shell covers the natural theatre in Grötzingen near Stuttgart and a roof of the garden center Wyss in Zuchwil, (1962).

Fig. 5.10 Concrete shells made by Heinz Isler [19]

5.6 HYBRID STRUCTURES

Hybrid structures in building and architecture are created by combining the materials used, the construction procedures or the principles of static behavior and co-operation. In the case of tensile membranes, the support structure for the application of the diaphragm and the membrane itself is needed to bring the tensile forces into the breakdown structure.

In the case of following examples, a combination of two basic systems for the application of the hybrid structure has been used – Tensioned membrane and the pneumatic element (arc) that is loaded by tensioned membrane in compression, .

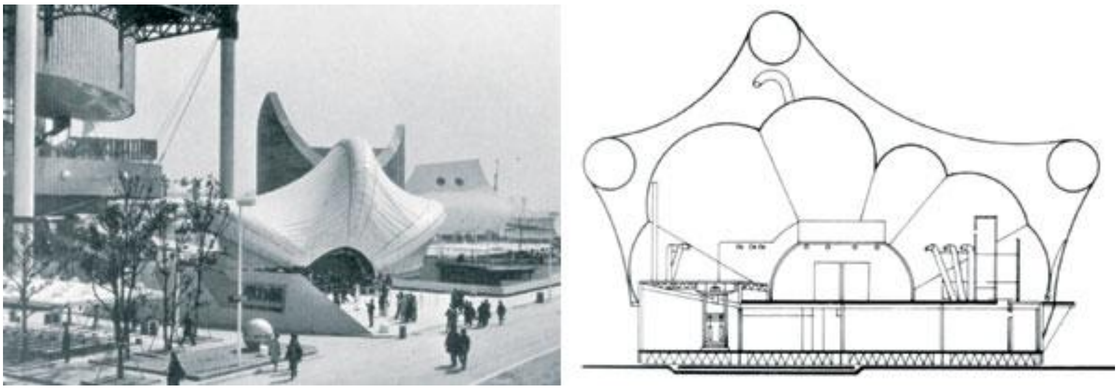

Fig. 5.11 Floating Theatre, EXPO Osaka 1970 [31]

Floating theatre represents the combination of air-supported, air-inflated and tensioned membrane to cover a cultural space. The upper layer combines three air inflated arches with a tensioned membrane on the top of them, which stabilizes the arches. Insid the structure an air supported membrane is used as the ceiling.

The Tubaloon, Kongsberg, Norway

Snøhetta designed the Tuballoon to serve as the main stage at Scandinavia's reputable Kongsberg Jazz Festival. The annual musical event is one of the oldest and most highly regarded festivals in Europe, headlining acts from the international jazz scene.

The mounting of Tuballoon recurs annually and stands for three weeks time before returning to storage in standard containers for the rest of the year. The pneumatic tension membrane structure measures 20 meters in height and approx. 40 meters in length.

The structure seems poised to break away and drift skyward from the tethers which hold fast to its historic site. Its geometry is suggestive of natural acoustic forms such as musical wind instruments and geometries of the inner ear.

Base area of the Tubaloon covering takes about 800 m². For the festival stage is this area sufficient and for an event like this effects very light and friendly.

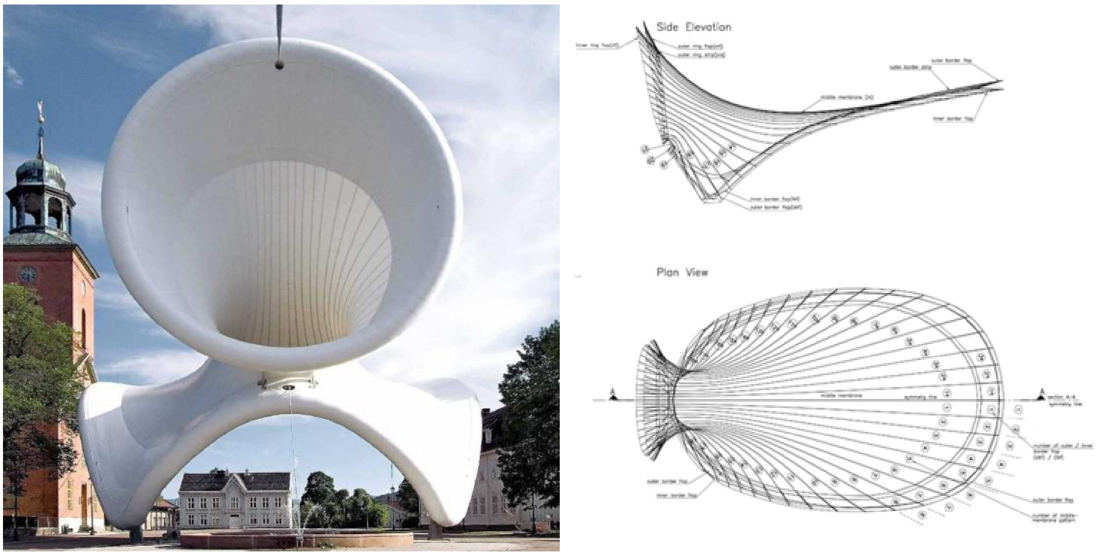

Fig. 5.12 Tubaloon, jazz festival pavilion, Kongsberg, Norway [32]

The space property is strongly supported by great accoustic gualities, variable lighting possibilities and also because of used structures gives the impression of something unique, original, modern and truthful. This project was born with the idea to creat a big ear fo all real jazz music fans.

Fig. 5.13 Installation of the Tubaloon, Kongsberg, Norway, 2006   [32]

Fig. 5.14 The Tubaloon, Kongsberg, Norway, 2006   [33]

6 GRIDSHELL – SUPPORTING STRUCTURE FOR MEMBRANES AND FOILS

6.1 DEFINITION OF GRIDSHELL

Shell structures may rely on natural principles which can underline a particular impression of lightness. Although these structures may look simple, it is a science to find the right form and to realize the same to scale. The realization must be done step by step with high requirements on the whole process.

Gridshell is a structure which derives its strength from its double curvature (in a similar way as a fabric structure), but is constructed of a grid or lattice. Synclastic / anticlastic double curved shapes (mostly made of timber laths). Rectangular plan shape is during erection process changing into a double-curved shape. This is possible due to the elements bending and twisting and the possibility of changing the rectangular grid to a rhombus.

“Shell structures will always have a role for architecture and engineering. More so than any other structural systems, shells have the ability to create eye-catching forms, to provide freedom for design exploration and to resist load efficiency. The grid shell is a spatially curved framework of rods and rigid joints. The rod elements form a planar grid with rectangular meshes and constant spacing between the knots. The form of a grid shell may be determined by inverting the form of a flexible hanging net. To invert the catenary so that it becomes the thrust line of an arch free of moment is an idealization. Analogously, inverting the form of the hanging net yields the support surface of a grid shell free of moments.” [34]

6.2 HISTORY OF GRIDSHELLS

6.2.1 Forerunners of gridshells

This chapter presents and introduces a few examples which are documenting the evolution of grid shell. A yurt, which was the traditional dwelling in the middle Asia since approx. 3000 years ago, as a predecessor could be considered a Tee-Pee structure. In case of yurt the grid is curved in one direction.

“A traditional yurt (from the Turkics or Mongolian) is a portable, round tent covered with skins or felt and used as a dwelling by nomads in the steppes of Central Asia. The structure comprises an angled assembly or latticework of pieces of wood or bamboo for walls, a door frame, ribs (poles, rafters), and a wheel (crown, compression ring) possibly steam-bent. The roof structure is often self-supporting, but large yurts may have interior posts supporting the crown. The top of the wall of self-supporting yurts is prevented from spreading by means of a tension band which opposes the force of the roof ribs. Modern yurts may be permanently built on a wooden platform; they may use modern materials such as steam-bent wooden framing or metal framing, canvas or tarpaulin, Plexiglas dome, wire rope, or radiant insulation.” [35]

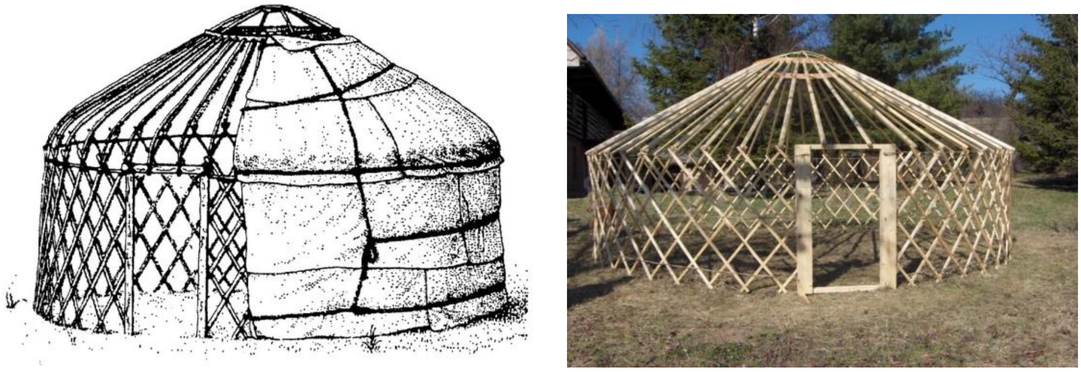

Fig. 6.1 Mongolian Yurt – structural solution – design sketch [35] and realization [36]

As the example of modern gridshell builder there must be mentioned the Russian engineer Vladimir Shukhov, who was the pioneer in the field of lightweight structures in general.

Fig 6.2 Exhibition pavilion, Niznij Novgorod, Vladimir Shukhov, Russia, 1894 [37]

6.2:2 <u>Gridshell case studies</u>

There are many structures existing, for the purpose of this dissertation there were choosed preferentially covered structures, which best describe the essence of lightweight form resistance structure.

<u>WEALD AND DOWNLAND MUSEUM</u>

The Museum's award-winning Downland Gridshell Building was the first timber gridshell building to be constructed in the UK. It is regarded as an iconic building made of oak timber and both architects and other interested visitors travel from across the UK (and further afield) to view this unique example of the technique, completed in 2002.

"Material testing at the University of Bath in England proved that oak is a suitable material for this kind of construction. Oak turned out to be the stiffest kind of wood tested, therefore, it took more forces to bend it in the required form. Thanks to its high bending strength oak wood has a small radius of curvature before it breaks. [38]

Fig. 6.3 Weald and Downland Museum - building procedure .[39]

Fig. 6.4 Weald and Downland Museum - completed structure [40]

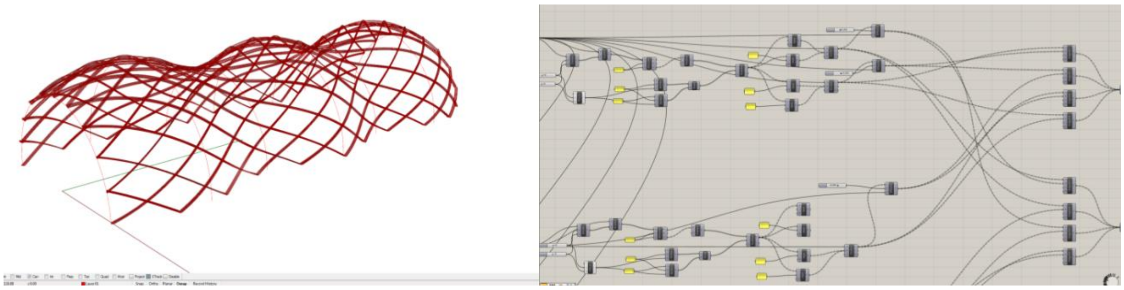

Fig. 6.5 Computer-aided 3D model, Grasshopper definition [41]

This original and unique structure takes its place in a beautiful historical village. This building gives the impression of freedom and dispassionate icon in the green. Wooden cover is made very precisely and the facade creates in collaboration of the horizontal roof curved line an effect of a wave.

<u>*HOUSE OBU*</u>

Gridshell structure originally designed as a living house and architectural studio by Erwin H. Zander in Hahnwald, Cologne, Germany (1976–82). Haus OBU is considered as a lightweight experimental building complex of 3 buildings, which are owergrown by wine and other plants.

Fig. 6.6 House OBU, outside view [42]

The concurrently research project served to verify if grid shell organic structures are suitable and comfortable for living. Covered area makes a space for 160 m² living place and 80 m² atelier. The unique structure did serve successfully for several years, after that was demolished when the parcel was bought by a new owner who decided to remove the gridshell and replace it with another building for housing.

Fig. 6.7 House OBU, nterior view [42]

Dome shaped buildings complex signifies a reached dream of non-traditional cozy by the author. Experimental buildings are in the whole interesting, new techniques, details and used procedures makes it really exciting. Erwin H. Zender made his dream real and pushed the problematic of these unique structures further. The house consists of a big window opening as well as of rigid body, which makes it statically stable and creates comfortable inside space. A higher quality level makes the green part of the roof, which correspond with green surrounding. These structures should provoke a new impulse for the architects and become the new way of thinking about what is the meaning about the quality of living.

<u>MULTIHALLE MANNHEIM</u>

An iconic grid shell structure, made for the Federal Garden Exhibition in Mannheim, which was brought on the light in 1975. An unique modeling system, which exactly describes final designed shape. In reality it is a huge structure with several saddle-shaped areas and one valley. For the grid the dimensions of 0,5 x 0,5 m were used, because it allows a convenient walking on grid even on the roof skin. However, by working on the structure, mountaineers use securing cables, because of danger of slipping down when it is wet.

"The form-finding process was supported by a wire model followed by a suspended net. The Multihall covers an area of 7.500 m^2. The grid shell is build with wooden laths in a dimension of 5 x 5 cm. The distance between the laths is 50 x 50 cm and they are arranged cross laminated double or quadruple. The longest span is 85 m lengthways. The assemblage of the Multihall, which laid out flat first, was managed through lifting the laths with scaffolding towers." [31]

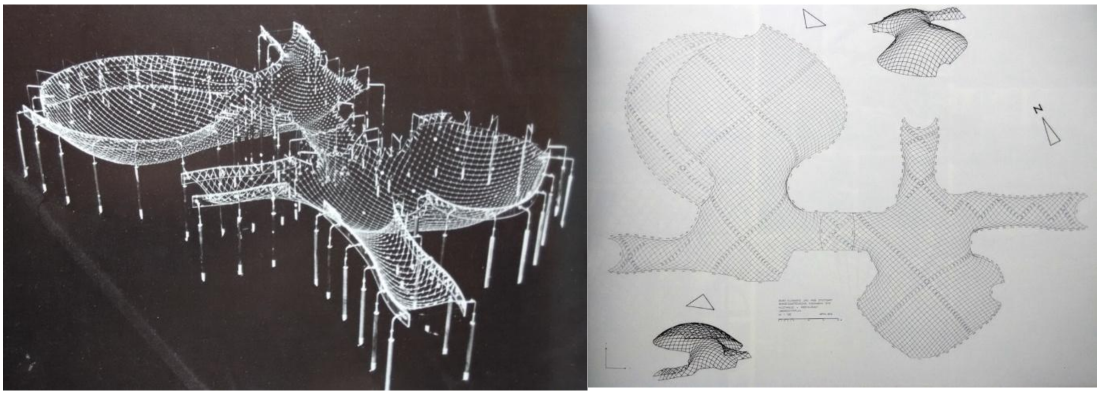

Fig. 6.8 Suspended net model of the Multihall in Mannheim [43]

"Demonstration models and first form-finding models (1:200) made of wire grid fabric. Suspended model (1:100) on marble plate with measuring grid (= pattern model): net made of element chain, every third grid rod represented as net line. On edge: small springs in each net line to control net forces." [44]

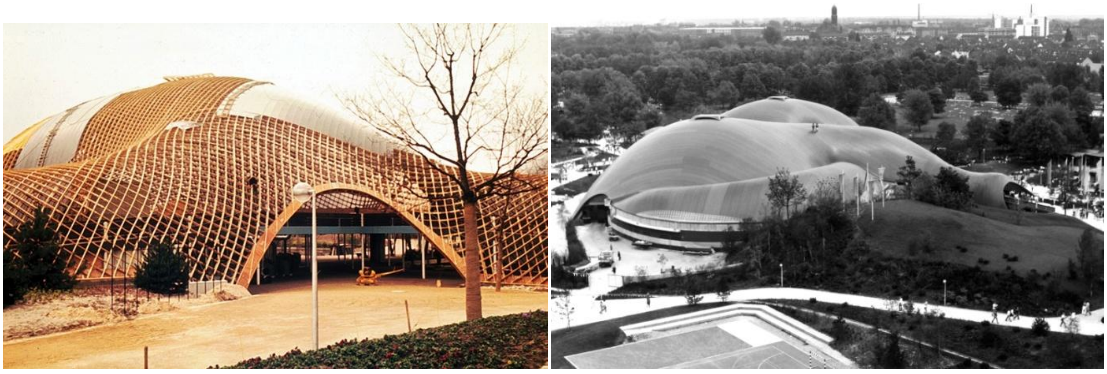

Fig. 6.9 Realization of the Multihall in Mannheim, 1972 [45]

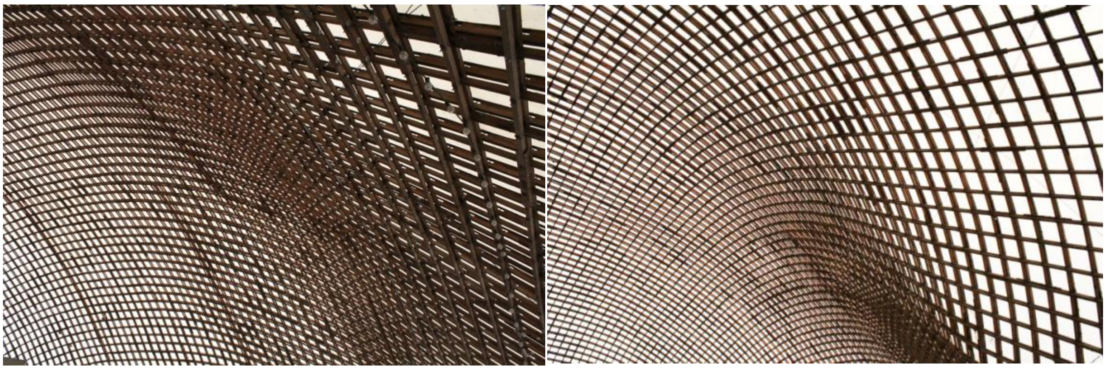

Fig 6.10 In the structure, both synclastic and anticlastic forms are visible [picture by author 11/2017]

Fig 6.11 Roof embrane cover after decades [by author 11/2017]

Fig 6.12 Roof membrane cover after decades [by author 11/2017]

Fig 6.13 Roof membrane cover after decades [by author 11/2017]

<u>*LSRU PAVILION*</u>

An exciting example of a small scale grid shell structure enriched with a yellow membrane cover. In case of small scale structures there´s a problematic point of enormous bending forces impacting to the structural elements. This was well done and the final result is really impressive, having inspiration in some kind of opened shell.

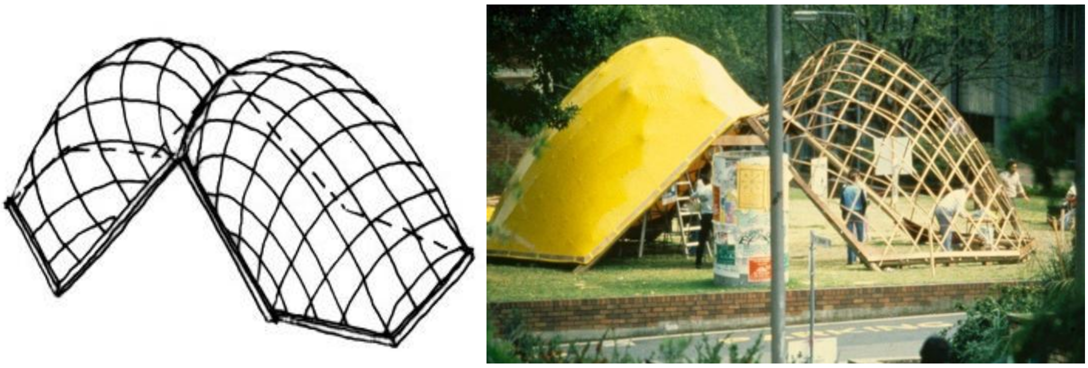

Fig. 6.14 Sketch of expected result – one shell leaning against the other one [46]

"First grid shell structure in Australia constructed from plywood stripes. designed as a study prototype and for display purposes, assisted by sponsorship from industry. It consisted of twin PVC membranes form- cut to a synclastic shape and stretched over two grid-shells on timber log edge beams with footings arranged as a double hexagon in plan. Each shell was initially a 500 mm square two-dimensional loose-bolted grid of paired 32 x 8 mm plywood laths distorted and shaped according to a prior chain-net suspended model into a domical form with lath ends screwed to the log boundary. Preserved logs 125-150 mm diameter, 3m and 3.9m long formed a pair of adjoining skewed hexagons. All logs bolted together using 25 mm thick plywood gusset plates. All footing logs were secured to the ground by 800 mm long hooked reinforcing rod earth nails. Each membrane cover was fabricated from 0.35 mm unstabilized chrome yellow PVC foil cut to pattern and glued along 50 mm wide seams with PVC glue. Both membranes were lightly stressed with edges secured under timber cover strips nailed to the edge and footing logs and with local slack taken out at selected locations over the surfaces by adjustable neoprene pads." [46]

Fig 6.15 Roof embrane cover over an experimental pavilion [46]

POLYDOME LAUSANNE

"The structure is designed to house permanent and temporary exhibitions. It raises 6.85 meters above the ground level at its highest point in the centre, reaching 3 meters in the middle point of every side wall. The structure of the building consists of four perimeter glue-lam arch beams, which provide structural support for 2-way grid shell and are restrained at their ends by concrete buttresses." [47]

The grid is made of transversely laid, continuous timber cords which are joined at intersections with steel bolts to form efficient load transmitting grid knots.
The structure made in 1991 of square floor plan of size 25 x 25 meters is stabilized with series of continuous timber braces running diagonally through the apex and terminating at corner buttresses.

The perimeter of the roof was reinforced with continuous 27 mm thick boarding which was nailed directly onto the grid shell to resist shear and compression forces within the structure. Weather resistant PVC membrane was applied on top of the structure allowing light access to the interior and protecting the building against weather conditions, especially wind, rain and snow.

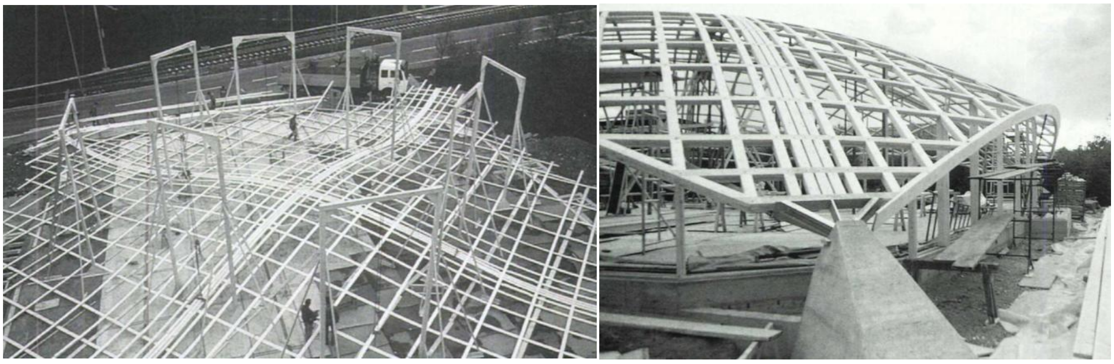

Fig. 6.16 Polydome Lausanne – form at the exterior border [48]

In the design of grid shells can be advantageous to create symmetric shapes due to substantial facilitation in the whole design procedure and higher level of feasibility.

A mesh could be symmetrical in one or two axes. When erecting such structures, symmetrical shapes behave more predictable and it is more easy to fix horizontal forces because of balanced vertical forces when erecting.

An interesting structure from the technological procedure point of view. At first, there was made a simple grid of timber planks, which was erected to the final position. As a next step, the middle parts between the joints were completed with additional elements, each exactly made for its position (many different pieces were done because of different grid rhombus).

WOODOME 1.0 – Pavilion in the courtyard, Italy, Lecce 2009

An example of a workshop realization. Made in 2006 in the courtyard in Lecce, Italy. The pavilion is the result of lifting a square mesh, creating a two-sided symmetrical gridshell. The advantage of this solution is the even distribution of weight and internal forces of the structure, which leads to a relatively simple implementation process. Very effective addition is caused by the ceiling membrane, which gives the whole structure life and functionally serves as a shading element.

Fig. 6.17 Woodome 1.0 – Interior view [49]

MATRIX PAVILION, TŘEBEŠOV

The unique structure, as a representative multi-purpose pavilion was created thanks to the successful cooperation between the company Matrix and architects from the SMA (Studio of Membrane Architecture) Studio. Design was created with the support of austrian colleagues - architects and statical analytics with the help of specialized software.

This newly created and unique gridshell design represents the beauty of natural material and its new options. It is made of 3x5 cm cross-section larch roof laths with a total length of more than 1.8 km. The Pavilion in the Matrix company area is the dominant feature of the newly established natural park and serves primarily for cultural and social events. The opening ceremony of the new pavilion on August 28, 2016 was connected with the mortal mass of the Czech Cardinal Dominik Duka.

Fig. 6.18 Matrix pavilion – Holy Mass of the Czech cardinal Dominik Duka [by Christian Bartl, 9/2016]

The assignment was to create an original structure as a representative building associated with a useful function - for the purpose of organizing cultural and social events, in the newly emerging nature park in the southwest part of Matrix a.s. in Třebešov. The pavilion, as a multipurpose building, responds to the given place in its organic dilapidated form, opening up to three semicircular entrances.

The gridshell design represents the beauty of natural material - larch and its new possibilities. It is basically a type of lightweight structure, the basic motive is the double curved surface with a smooth transition of the facade - roofing, which enhances the feeling of grace and naturalness. The three entrances then provide airiness and openness, the impression of lightness underlines the seasonal suspended translucent membrane of 42 m^2. It serves as a shielding element and also protection against rain.

As part of the implementation of the project, a full-faced larch terrace was installed and the parter was sensitive to the changes - the whole is harmonious and logically connected to the surrounding roads. The design is fitted with RGB LED panels that give it a special charm in the evening and early morning hours.

Fig. 6.18 Gridshell pavilion – from beginning up to realization [by author]

Fig. 6.19 Gridshell pavilion – from beginning pu to realization [by author]

6.3 STRUCTURAL PRINCIPLES OF SHELLS

„Structures canbe classified in many ways according to their shape, their function and the materials from which they are made. The most obvious definition of a shell might be through its geometry. A structure or structural element may be a fully three-dimensional solid object, or it might have some dimensions notably smaller than others. A shell structure is a structure defined by a curved surface. It is thin in the direction perpendicular to the surface, but there is no absolute rule as to how thin it has to be.“ [50]

“A shell is a type of structural element which is characterized by its geometry, being a three-dimensional solid whose thickness is very small when compared with other dimensions, and in structural terms, by the stress resultants calculated in the middle plane displaying components which are both coplanar and normal to the surface. Essentially, a shell can be derived from a plate by two means:

- *by initially forming the middle surface as a singly or doubly curved surface*
- *applying loads which are coplanar to a plate's* plane *which generate significant stresses”. [34]*

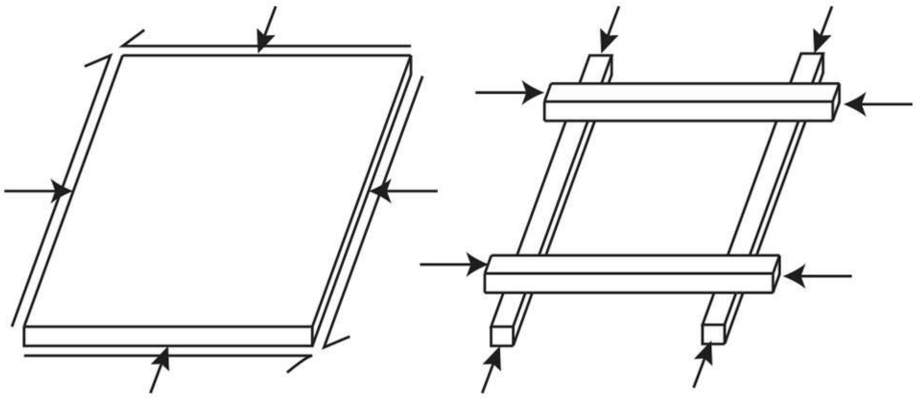

Fig. 6.20 Structural principle of shell and gridshell structure [51]

6.4 FORMFINDING - PHYSICAL MODELING

A substantial part of this chapter was taken from the author's master´s thesis, which deals mainly with physical modeling.

Creating lightweight architecture, there is always the need of cooperation with many experts and specialists, architects, engineers, craftsmen etc., in the whole process from designing point to realization. In order to be able to create meaningful and reasonable concepts, here is no better way to start a lightweight structure design than using a physical model. In case of tensile membrane structures we are able to feel the tension from a stocking model and decide for the best solution – a convenient concept for further analysis.

Computer tools may be less in the first step of the design, because they could form find many different shapes, which are not feasible in a next step of the design procedure.

This is similar when designing grid shells. Holding a sheet of plastic grid, one may observe an infinite number of double curved shapes which are formed from one and the same grid. However, not every shape is easy or even possible to be built. It is essential to test many materials and techniques to be able to select the best grid material for building physical model.

In the problematics of gridshells a physical model is of high value (in every even simple design), because it is able to demonstrate the real structural properties. Creating physical models keeps the designer close to a possible, reasonable and feasible form. There are two basic model building procedures – hanging chain model and push up method.

Building physical models constitutes an interesting topic, which lies at the core of designing such structures. Physical models are also important from educational point of view as they are literally „touchable" and thereby facilitate communication between structural engineer and the designer.

For physical modeling a large number of considerable materials and techniques are available. From built structures it is apparent that we have to consider material properties, which may be diverse in case of timbers or fiber reinforced plastics. For the realization of non-homogenous material as timber, the main goal is to achieve a first class timber with high breaking strain. In all cases the aim is to minimize bending and especially torsion stress which may be achieved by controlling global shell geometry and local grid orientation.

The latest research of the author in the field of grishells is concentrated on the optimization of the erection process. This is often the subject of discussion, always proposing an original design using a different elementary element in the grid (due to its cross-section and the material used.

Computer design and simulation of grid behavior in the air, even using state-of-the-art methods, may be different in practice, and should always be verified using physical model before implementation.

This chapter includes an overview of the author's evolution in physical modeling, when some real-time designs have been implemented. Physical modeling is considered by the author to be one of the pivotal components of a lightweight design, with a correctly designed and manufactured model being true regarding the scale, static effect of forces in the design, the shape of double curved surfaces, and deformation behavior. In addition, it has an educational effect, while the creator realizes a lot of practical experience.

6.4.1 HANGING CHAIN METHOD

To verify the designed shape hanging chain model was made. It is a big challenge to work with hanging chains and it needs to be really precise, because there is a high level of sensibility. With this modeling procedure one can experience an important property of grid shells: when changing one point position even a little bit, the whole structure will react to this by changing the total shape. This is really essential to know before a grid shell design is done.

Hanging chain model: A net of chains is attached to given edges and lowered into an inverse shell shape. The resulted form-finding process is reversed. This procedure is very powerful because it helps form finding an efficient global shell geometry and local grid layout at once. The base with a suitable grid must be first prepared, after that the challenge of form finding begins as changing even only one point position, the whole grid reacts and change.

Hooke´s hanging chain

"The shell designer seeks forms to carry the applied loads in axial compression with minimal bending forces. The earliest example of structural form finding for an arch was published by English engineer and scientist Robert Hooke (1635 – 1703). In 1676, Hooke published ten „Inventions" in the form of anagrams of Latin phrases in order to protect his ideas. The third invention would later become known as Hooke´s law of elasticity, for which he is most known." [52]

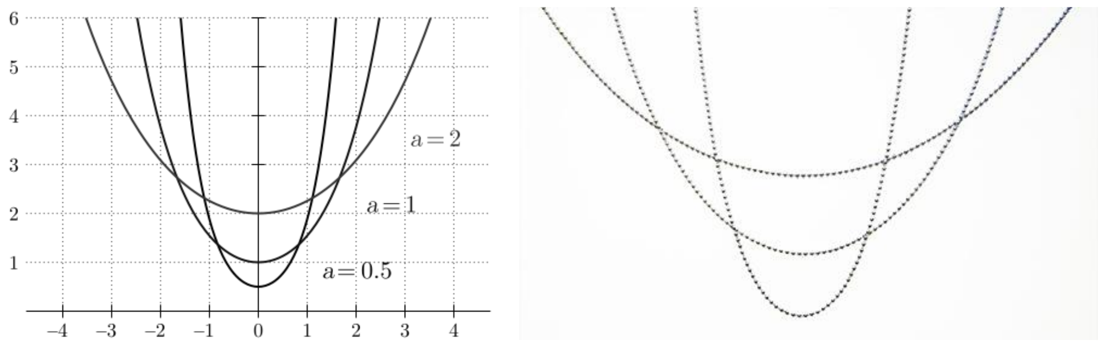

Fig. 6.21 Hooke´s hanging chain principle [by author]

The idea of the hanging chain is simple: Invert the shape of the hanging chain, which by definition is in pure tension and free of bending, to obtain the equivalent arch that acts in pure compression. The form of the ideal arch will depend on the applied loading. For a chain of constant weight per unit length, the shape of a hanging chain acting under self-weight is a catenary. But if the load is uniformly distributed horizontally, the ideal arch would take the form of a parabola and the chain would take different geometries according to the loading. In addition, the span the span/rise ratio (L/d) can vary widely, though most shell structures occur in the range of 2 < L/d < 10. Thus, even a simple two-dimensional arch has infinite possible forms which would act in pure compression under self-weight, depending on the distribution of weight and the rise of the arch.

To continue the analogy with Hooke´s hanging chain, a three-dimensional model of intersecting chains could be created. This hanging model could be used to design a discrete shell, in which elements are connected at nodes, or the model could be used to help define a continuous surface. If hanging from a continuous circular support, the model-builder could create a network of meridional chains and hoop chains. By adjusting the length of each chain, various tension-only solutions can be found when hanging under self-weight only. Once inverted, this geometry would represent a compression-only form. Such a model would quickly illustrate that many different shell geometries can function in compression due to self-weight. [53]

"Italian mathematician and engineer, Poleni, drew on Newton and the principle of force diagram which he had formulated for dynamics and which Poleni applied to the field of statics. At the same time, he arrived at the explanation of the thrust line as an inverted catenary, according to which he determined the correct section of arches and domes."

Robert Hooke's hanging chain. Robert Hooke (1635-1703) described the relationship between a hanging chain, which forms a catenary in tension under its own weight, and an arch, which stands in compression". [54]

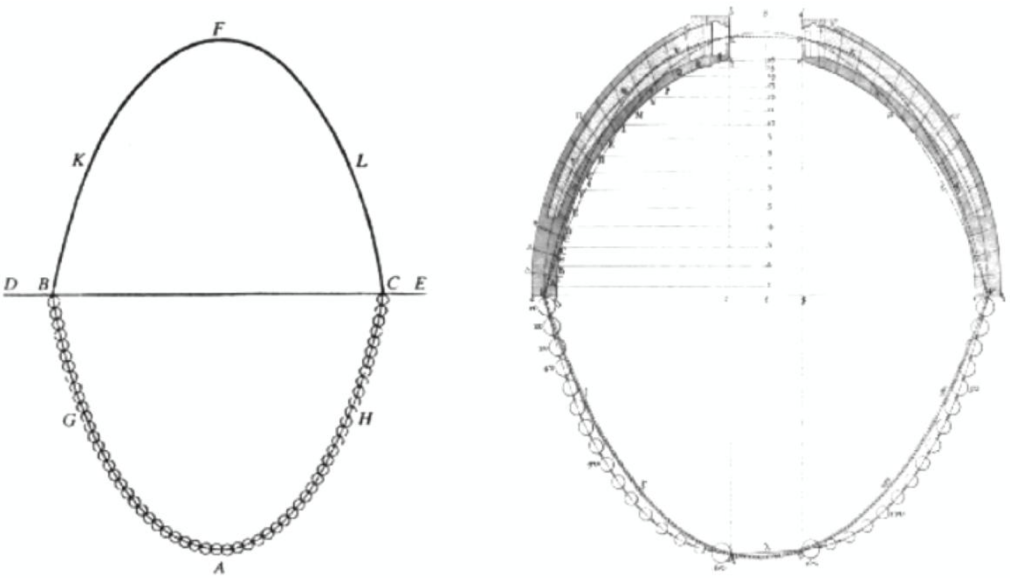

Fig. 6.22 Drawing of analogy between an arch a hanging chain, made for analysis of St. Peter´s Cathedral in Rome, 1748, Poleni [54]

"A thrust chain consists of chain links which roll on top of each other without rolling free of each other. The roll radius of the roll hinge is greater than half the chain length.

In conclusion, the model experiments of Frei Otto are mentioned, in 1950 and 1951 he developed a model to illustrate thrust lines. This arose out of the consideration, that a rod is stable only when the rod radius of its supporting surface is as large as possible, at least larger than half the length of the rod." [55]

"The hanging chain model principle, or Hooke´s law of inversion, is known to be one of the oldest form-finding methods for the design of arches and domes that are in pure compression by being free of bending. This principle allowed coping with the low- or no-tension material of masonry as the only available construction material at that time. By inverting the shape of the hanging chain, which by definition is free of bending, an equivalent arch that is in pure compression is obtained" [50]

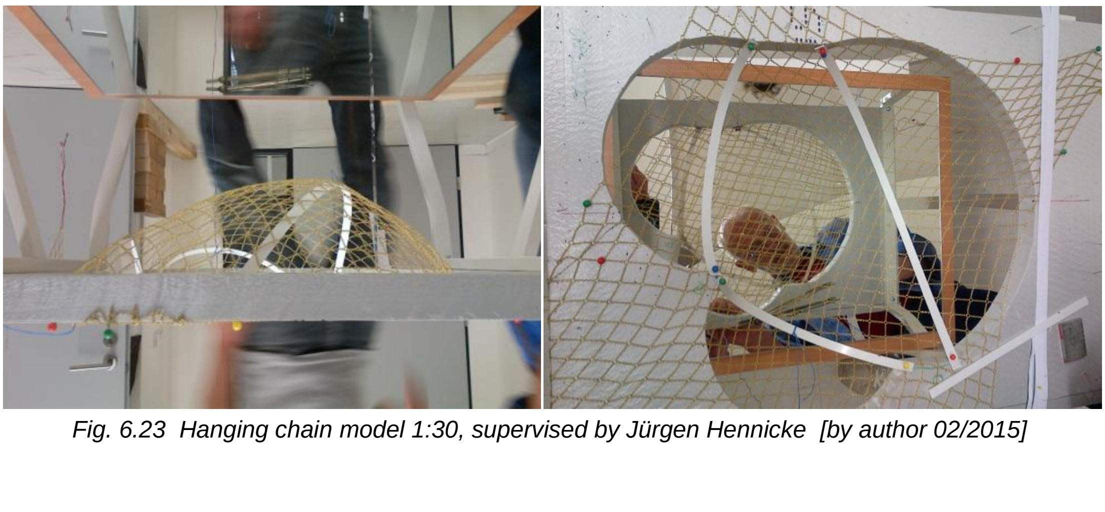

Fig. 6.23 Hanging chain model 1:30, supervised by Jürgen Hennicke [by author 02/2015]

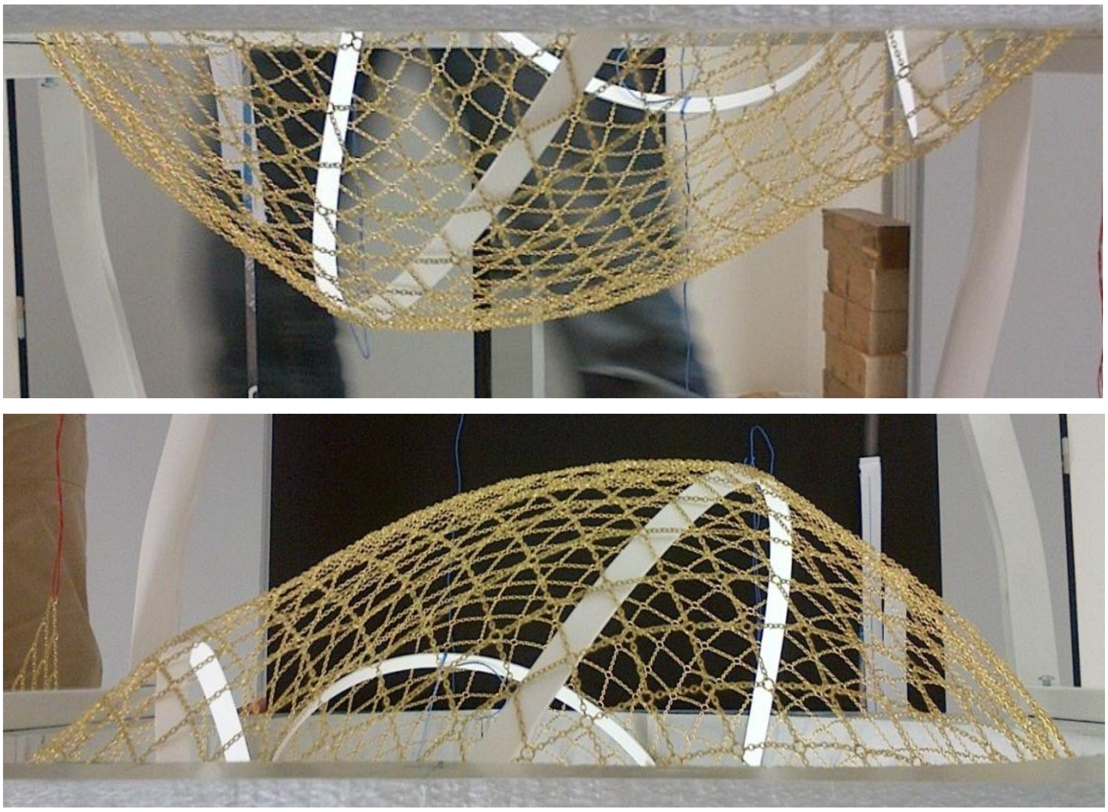

Fig. 6.24. Hanging chain model – inverted using a mirror [by author]

6.4.2 PUSH-UP MODELING METHOD

During the author´s research and developing process, several modeling materials were used. For the very first ones paper and plastic stripe were used. These are suitable for the purpose due to its flexibility, lightness and well

Problematic locations are grid joints, which must be movable by rotating in crossing joints. To reach this were found solutions with punching pliers and metallic pins. This works well, the only disadvantage is the scale of cross-sections, which is not realistic in horizontal direction (individual pieces are thin enough, but too wide because of the pin size). For the final shape model were used hardened polystyrene stripes with 12 mm width, cut out from a board size of 1000x700 mm, thickness 1 mm.

The very important step to verify feasibility especially of timber material is material testing. The aim of testing is to verify, if the material is applicable for the structure. The test is based on bending of connected timber laths, measuring reached height until the breakdown. The testing result gives us the minimal bending radius using the formula below:

$$R = (S^2 + 4h^2) / 8h$$

R – radius, S – horizontal floor length, h – arch height

Because of inhomogeneous timber behavior we use the safety factor of 1,5. This results with the value of R, which can be taken into account (bigger radius = smaller curvature). This value depends on type of wood, its humidity, thickness and joints length.

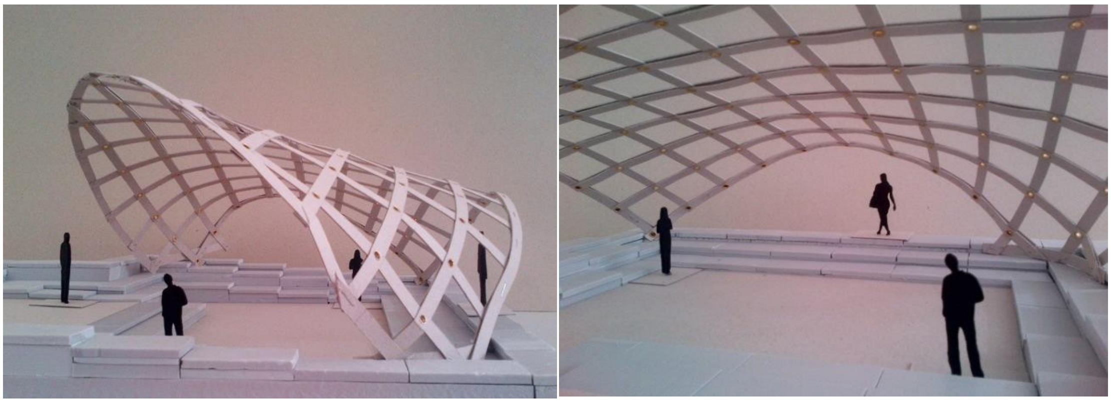

Fig. 6.25 The very first physical model from paper [by author 02/2015]

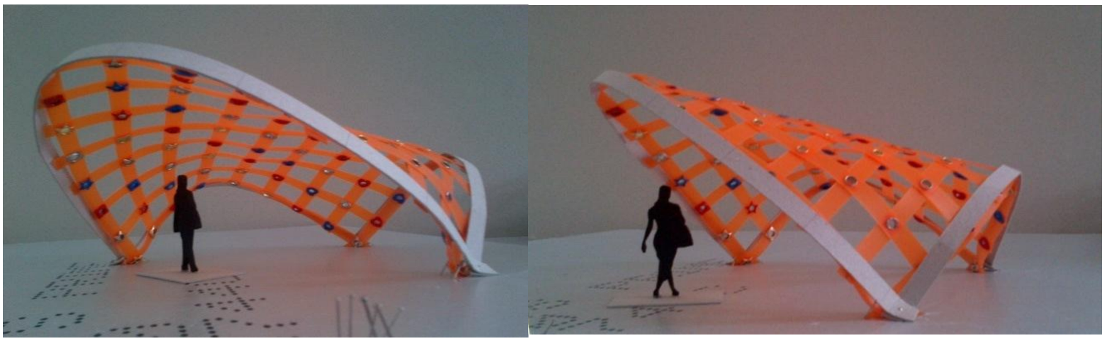

Fig. 6.26 Physical model from plastic stripes [by author 02/2015]

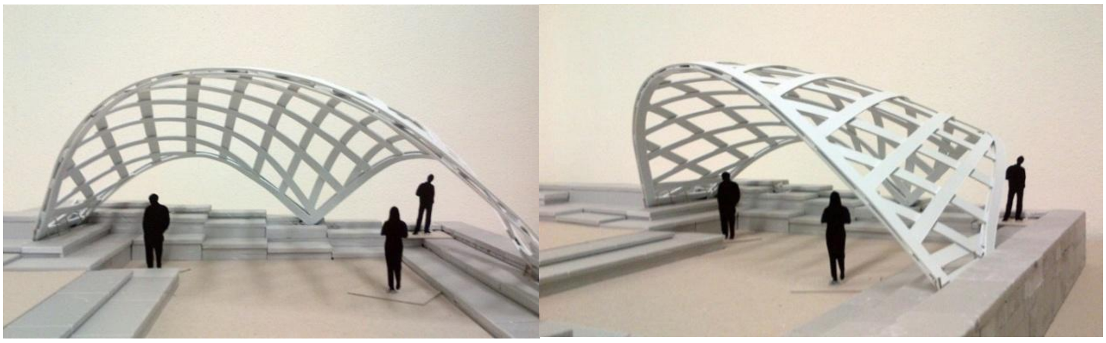

Fig. 6.27 Final shape physical model made of HIPS (hardened polystyrene) [by author 03/2015]

Fig. 6.28 The very first physical model of spruce timber laths [by author 4/2015]

Fig. 6.29 Realized structure – The result of design in real scale [by author 9/2015]

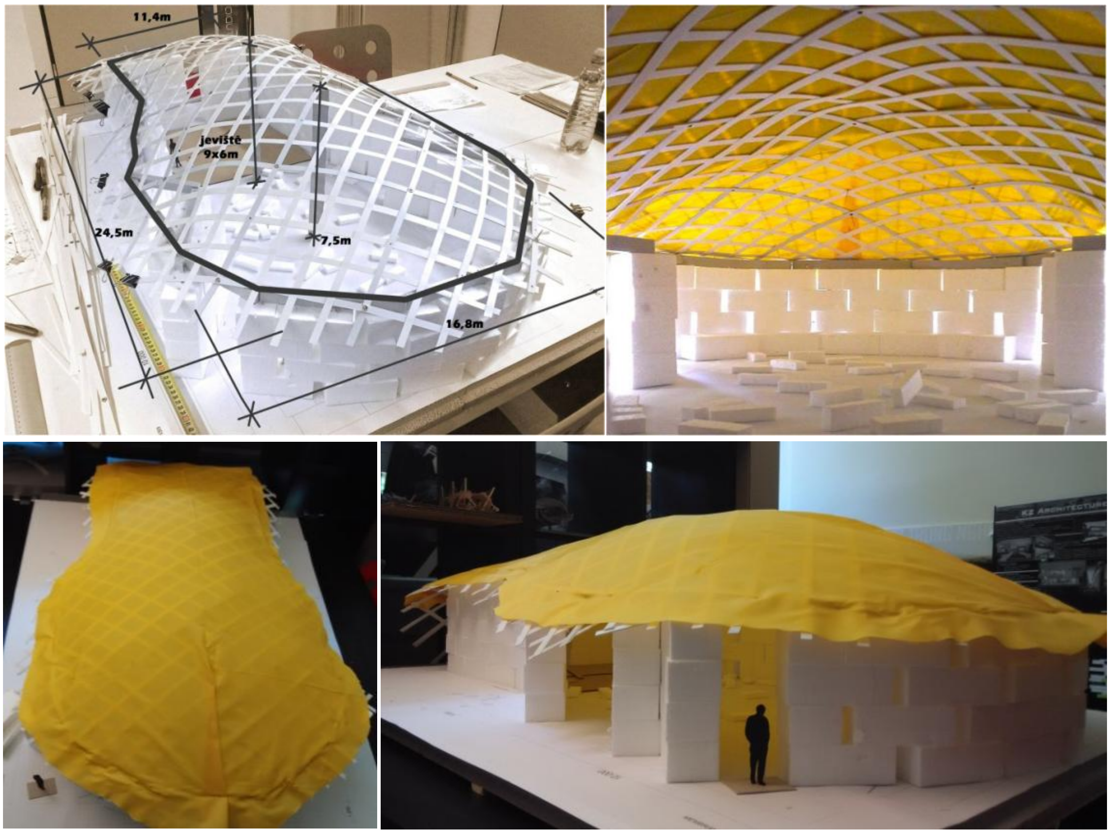

Fig. 6.30 Physical model for the theatre Menteatrál, made of HPS [by Radek Podorský 2/2015]

Fig. 6.31 Experimental shading structure for the Hojda® seesaw [by author 07/2015]

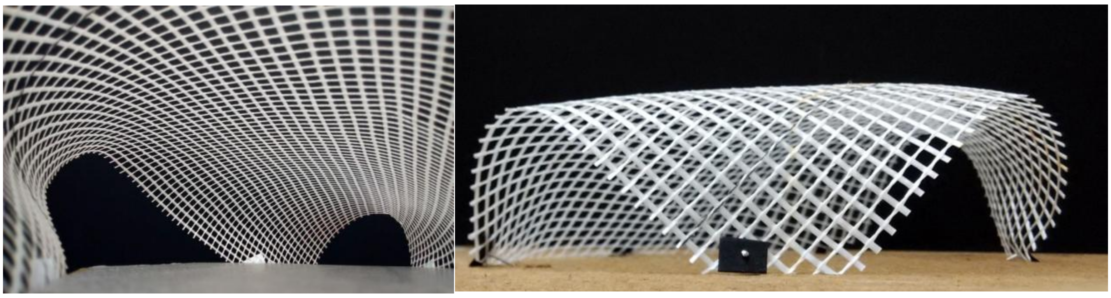

Fig. 6.32 The very first physical model made of wall reinforcement mesh   [by author 10/2015]

Fig. 6.33 Final shape physical model of Třebešov pavilion   [by author 10/2015]

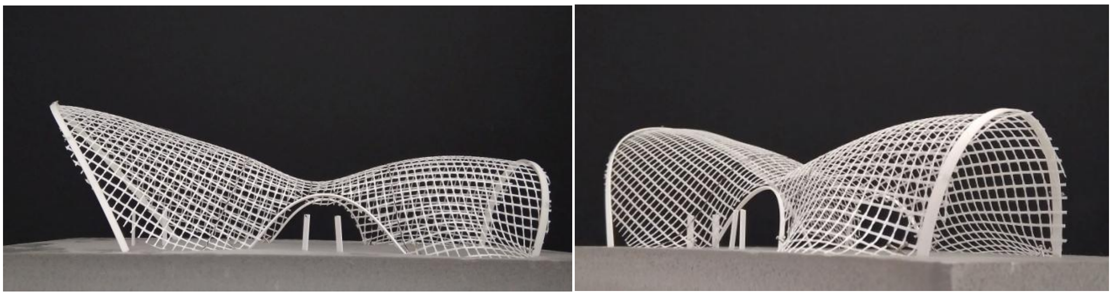

Fig. 6.34 Physical model of 1st variant of Třebešov pavilion   [by author 10/2015]

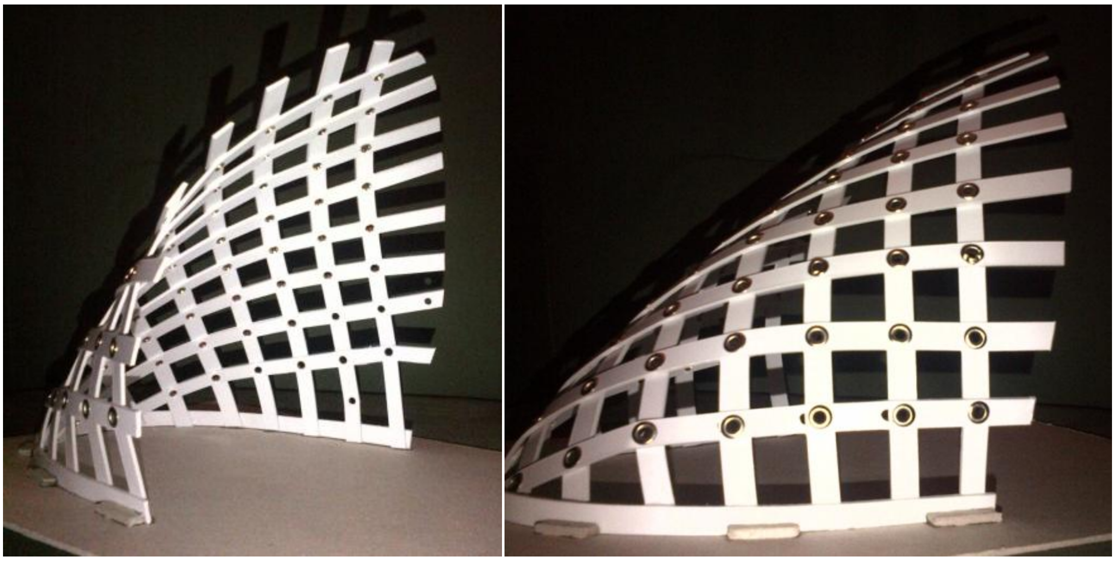

Fig. 6.35 Experimental physical model made of HPS [by author 10/2014]

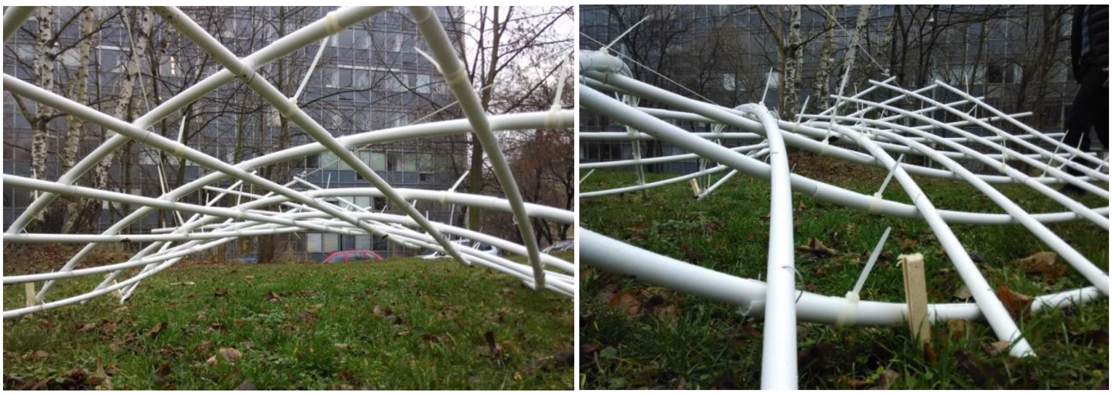

Fig. 6.36 Physical model of Třebešov pavilion made of PVC tubes Ø 25 mm [by author 2/2016]

Fig. 6.37 First physical model from plastic tubes Ø 16 mm [by author 02/2015]

Fig. 6.38 First physical model from plastic stripes [by author 02/2015]

The design of Matrix pavilion was a complex issue and, in particular, the physical model of the pavilion was given a lot of attention, as it was necessary to understand the behavior of the asymmetric construction and subsequently to select the most suitable material, cross-section and work progress of the realization.

During the research and design there have been four physical model built for ongoing verification of design accuracy and construction behavior.

The design of a trade fair representative pavilion for the company Matrix was made purely on the experiences and author´s given knowledge during the research. A physical model was built as as the default design, and on the basis of which the grid and the erection of the structure were assembled.

The construction was different from the previous realizations by the fact that the gridshell formed a kind of lid, which was retrofitted up to a pre-built structure. It consisted of a wall, a doorway, a totem and a dungeon. The horizontal forces were captured by a 5 mm diameter steel wire. At the design point, a membrane application was considered, finally rejected because of costs and much more time needed for the realization. The pavilion was realized only just for four days.

Fig. 6.39 Real scale structure based on simple physical model [by author 02/2015]

6.5 COMPUTATIONAL FORMFINDING

Designing a grid shell is easily possible without using any kind of software, but it is very helpful to have one for further structural analysis. First step of the design should comprise building a proper physical model in an adequate scale. It is necessary to optimalize the . After that the grid is projected to the ground plan and transformed to the digital form.

The dissertation is based on the previous research of authors Master´s thesis on the topic: Generating design, manufacturing and erection experience from full scale grid shell prototypes, which was mainly focused on physical form-finding methods. However, in 2015, there is not possible not to mention a numerical optimization process, which is the basis of computational form-finding.

"What makes numerical optimization especially useful for form-finding is the possibility of solving non-linear problems in a relative easy way. When deflections get large, structures can display

geometrically non-linear behavior, which means the deflection is not linear with respect to its loadings.

The fact that the models deviate does show that the computer model does not represent a shape that is optimized in structural behavior. The model should be of a more parabolic shape." [56]

6.5.1 FORCE DENSITY METHOD

"The force density method allows you to generate shapes of tension structures that are in static equilibrium. It is a method that uses a linear system of equations to model static equilibrium of pre-tensioned cable net under prescribed force/length rations. By assuming a constant ratio of force to length, non linear system of equations becomes linear and can be solved."

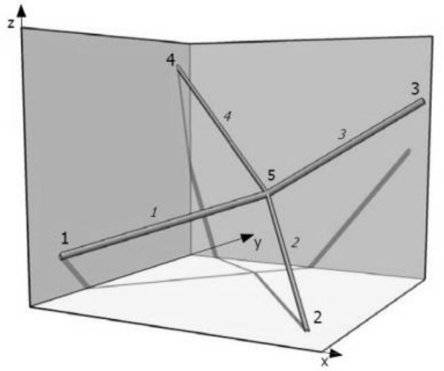

Fig. 6.40 Structure with four members [56]

With the Force density method the initial shape of cable nets and membranes can be generated with only the boundary coordinates and the force densities to be specified.

6.5.2 DYNAMIC RELAXATION

"In dynamic relaxation, form finding is performed by a pseudo dynamic process, which can be explained as follows. The mass of the structure is lumped in the nodes and oscillate around the initial position under influence of the out-of-balance forces. Due to artificial damping, the masses come to rest in an equilibrium position. In its original form, the iterative process uses viscous damping, where the movement of the nodes is damped by damping coefficients in its formulae." [57]

Following architectural shapes, created using Rhino+Grasshopper based on the final physical model of Matrix pavilion in Třebešov.

Fig. 6.41 Structural shape design [by Radek Podorský 11/2015]

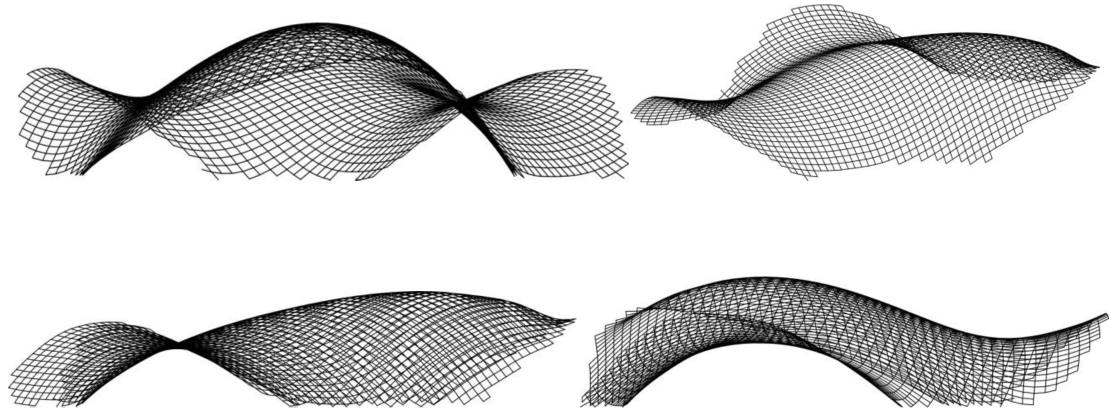

Fig. 6.42 Structural design – optimized grid shape [by Christian Bartl 11/2015]

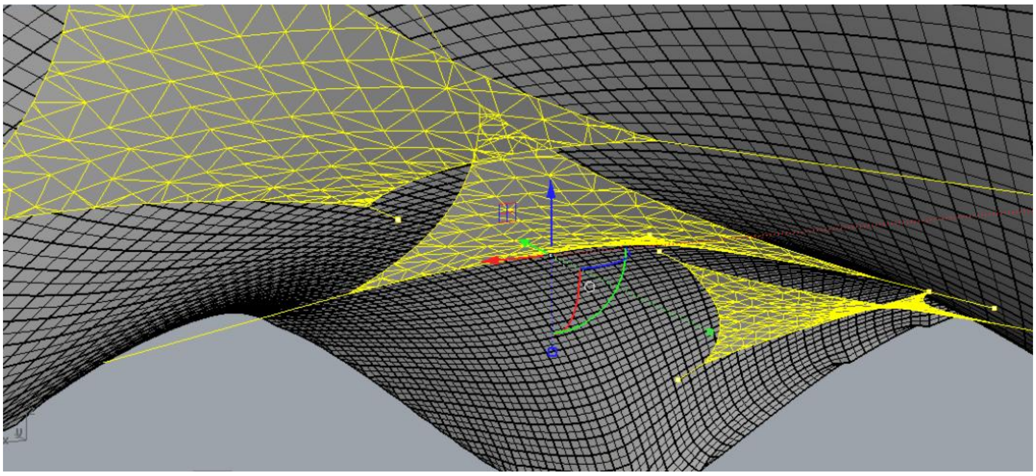

Fig. 6.43 Suspended membrane design – Variant I [by Jan Vecko]

The design of a membrane for gridshell structure was made in several varieties. At first, there were three hypars considered – bigger amount of membranes wirh smaller scale, which are overlapping each other. The advantage of such solution is to keep minimal distance between the membrane and gridshell surface.

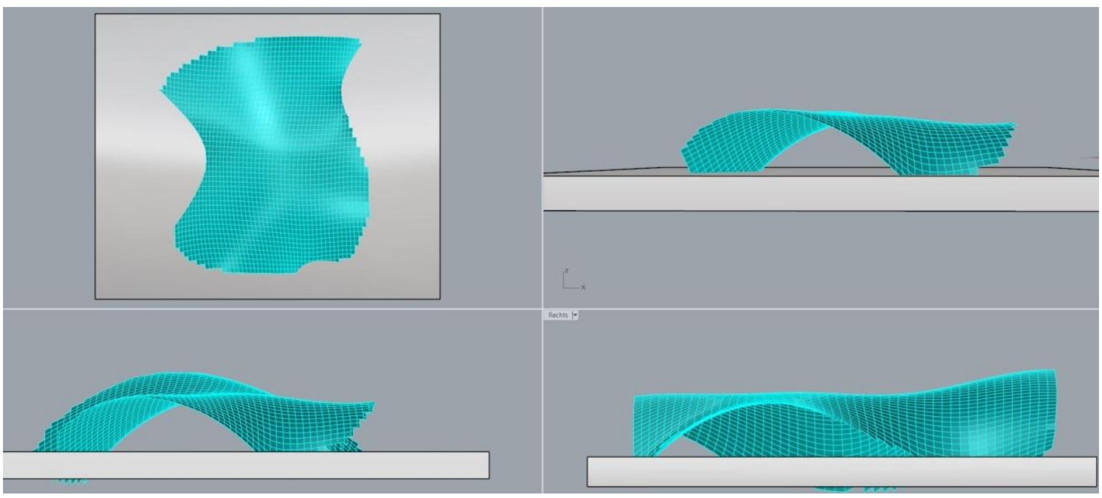

Fig. 6.44 Structural design –optimized grid shape [made by Christian Bartl]

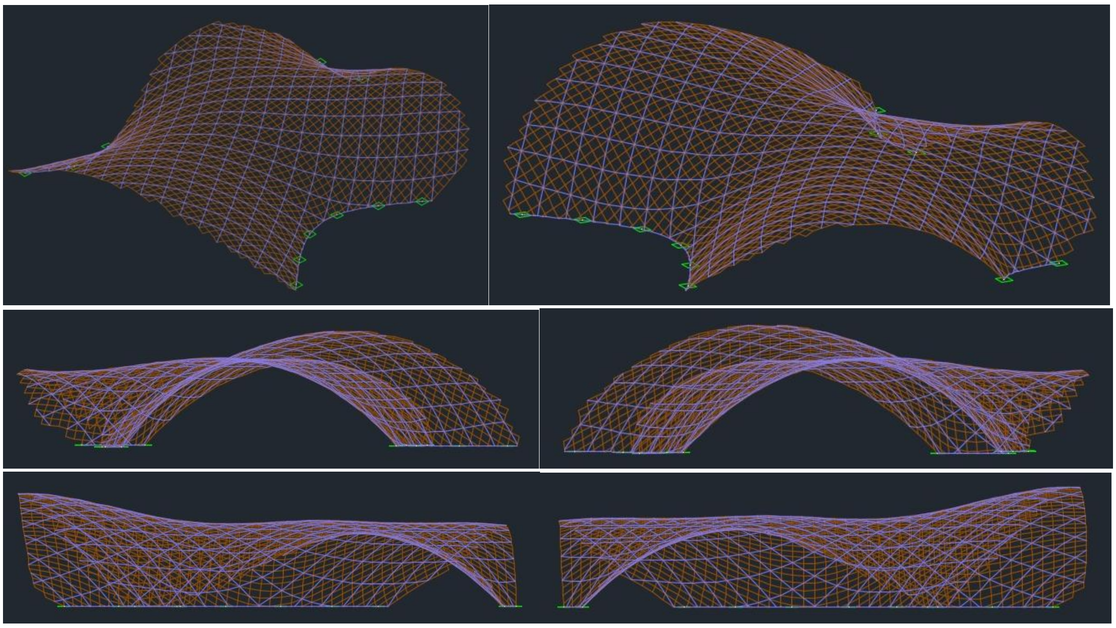

Fig. 6.45 Structural design –optimized grid shape in Autocad [made by Christian Bartl]

7. MEMBRANE PROTECTION APPLICATION

The collaboration between a gridshell structure and single layer membrane can be considered in the statical way as an important point due to the ability to stabilize such structure. Gridshells are in general extremely thin shells, which must have been additionally stiffened, mainly in the diagonals of the rhombic mesh. The possible way to achieve the stiffness, which was used in many experimental structures made by the author Is to add a third layer of timber on the top in diagonal direction, which is the most easy. The advantage of this solution Is that we can use thinner cross section of the basic grid elements, which allows easier forming. There is possible to add more than one additional layer afterwards, which could collaborate with design decision.

The other way, which lets stand out the beauty of simple gridshell is to use steel cables, fixed in diagonals of the bottom (much more compacted - sophisticated anchoring system using steel plates).

Cladding demands in general are depending on required inner space conditions, typology, weather conditions and usage requirements. In the case of gridshell structures mainly the protection against rain and sun is expected. When adding cladding to an open grid mesh it is necessary to assume additional wind load. As such the selected cladding system will have a big influence of the whole structure and its lightness. The combinations of following types of cladding are often used:

Combination of synclastic and anticlastic shape used on a single gridshell structure causes many difficulties and challenges by designing the whole surface covering, which is very often asked by clients.

When designing a partial covering, on a gridshell there are many snap points suitable for a corner plate anchoring. The distance between these points depends on the mesh density, due to experiences we can roughly estimate the biggest distance 50 - 75 cm (considering the mesh 50/50 cm).

This possibility offers many choices for the architect, who is form finding an optimal solution.

Second way to envelope the surface is to cover using single layer membrane or ETFE foil. This solution offers fully free interior space and it is well for structures with closed edge on perimeter.

In case of opened edges (entrances) we have to take in account the wind suction, which could generate high forces. These forces are the biggest enemy of such structures, because they can cause unvilling damages.

From the statical point of view, membranes besides its architectural qualities and functional properties are able to be a structural part of gridshells. To stabilize a gridshell structure in final position there is diagonal bracing needed, often made using steel cables or rigid elements as a third layer. It is also possible to fix the surface using membrane, which acts as a stabilizer in both directions.

The most important part of author´s research is based on realized gridshell structures. In this chapter, there are two pilot projects mentioned as the core of the research, which should show the possibilities of collaboration between supporting gridshell structure and a membrane structure itself. All of these exaples are already mentioned in some way in the dissertation.

7.1 <u>MEMBRANE TENSIONED FROM BOTTOM SIDE OF GRIDSHELL</u>

Gridshell as compression structure is due to its synclastic shape (in most cases) suitable to place the membrane from the bottom side as a ceiling. By anticlastic shapes there is a challenge to design a membrane. The structure can be on one side quite helpful, and suggestive the right placement of membrane structure from below. A big advantage is that we have a *forest* of possible anchoring points, which could have been used for placing a corner point.

Fig. 7.1 Seasonal membrane – mounting procedure, Matrix pavilion Třebešov [by author 4/2017]

Fig. 7.2 Seasonal membrane – dismantling procedure, Matrix pavilion Třebešov, [by author 10/2017]

In case of ceiling membranes we need to avoid a loose of walking height and on the other side do carry about membrane attaching the grid. Demands in general are depending on required inner space conditions, typology, weather conditions and usage requirements.

In the case of gridshell application the suspended membrane is space consuming. Due to the double curvature of the surface it is necessary to design the membrane with respect to the purpose of the space, especially to prevent undesirable elimination of the clear height at the expense of usability.

Fig. 7.3 Suspended membrane from the bottom [by author 8/2016]

For the purpose of Matrix pavilion, eight-point sail was used as the final solution. The design was optimized several times to the final form, finally it was able to hang a membrane with an area of 42 m^2 in total compared to the original three pieces of four-point hyperbolic paraboloids.

7.2 MEMBRANE TIGHTENED ON THE SURFACE OF GRIDSHELL

SQUARE MOCK-UP – COVERED ETFE

For the authorization of covered gridshell structure by ETFE foil, a square mock-up of the size 3,5 x 3,5m was used. The point was to apply the ETFE as a top layer without doing cutting patterns, which is basically used.

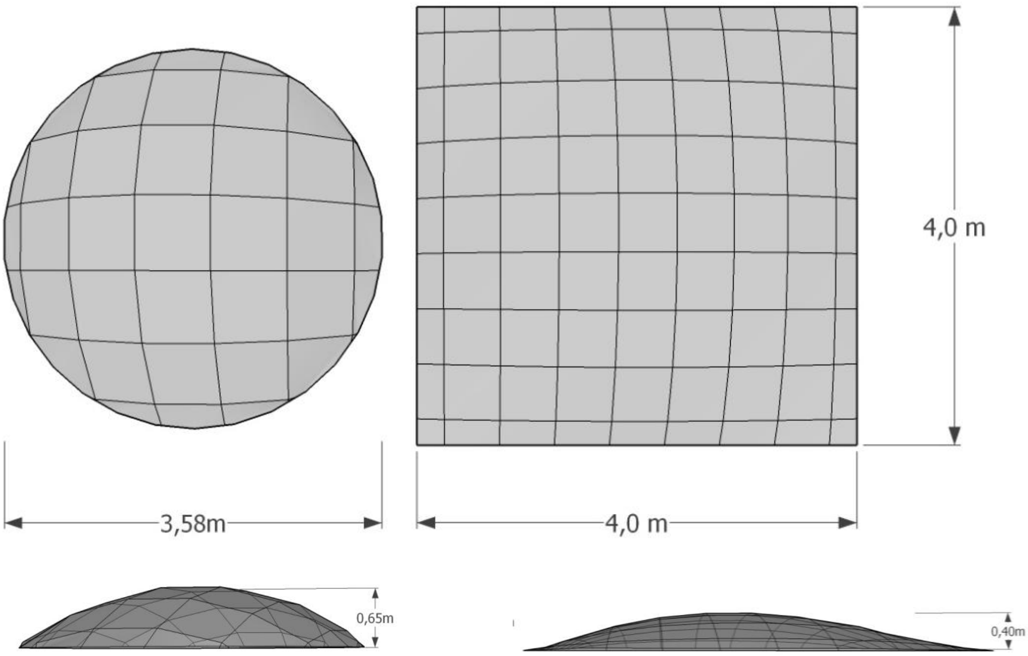

Fig. 7.4 Two variants of ETFE mock-up project [by author 3/2018]

In the case of pneumatic pillows, we consider the average width (at the widest point) as 20% of the cushion range (length). The aim of this experiment was to verify the elasticity of the foil, using rigid construction instead of internal air pressure. From the two variants considered (circular and square plan), the second option was chosen for the workshop at CTU in Prague. A square plan of dimensions 4 x 4 meters, later reduced to 3.6 x 3, 6 meters. The film was applied using modified aluminum profiles and sufficiently tensioned.

<u>Result of the application:</u>

ETFE film is a solid material that can be tensioned by air pressure, but it is not recommended to apply it to the gridshell. In the top surface area, an enormous tension occurs when stretching, by the middle circumferences decreases significantly and at the corners the value is minimal. The only possible solution is to create a “cap” using cutting patterns, which will be additionally tensioned by means of peripheral profiles.

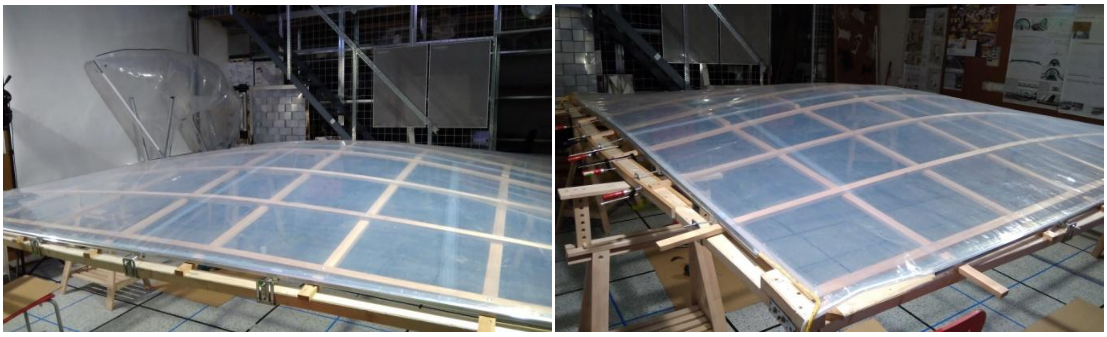

Fig. 7.5 Mock-UP 3,5 X 3,5 m, covered ETFE foil [by author 3/2018]

Fig. 7.6 Experimental mock-up 3,6 X 3,6 m, covered ETFE foil [by author 3/2018]

Fig. 7.7 Experimental mock-up 3,6 X 3,6 m, covered ETFE foil, detailed view [by author 3/2018]

7.3 UNDERPRESSURE INBETWEEN TWO FOILS

PLUSMINUS PAVILION

Membrane integrated into the gridshell – created using 2 membranes, first from the bottom and second from the top. After that the inner space is vacuumed, which causes the surfaces of both membranes to adhere.

In the Plusminus Pavilion by Studio LTA, a series of inflated "beams" arranged in a grid support a double-layered enclosure under negative pressure (reaching a total vacuum), which contracts, trapping the beams and giving stability to the whole assembly. Other roofing systems have been developed using hybrid solutions in which the main structure consists of a grid of pre-stressed cables, and the enclosure is a grouping of double-layered pressurized cushions, as in the case of the Khan Shatyr Tower by Foster + Partners.

A bold idea was the foundation for the unique design, which is using negative pressure to fix and reinforce the whole grid. One can consider this as the lightest possible way to realize such structure, especially in combination with air tubes. The solution is very clever, but needs a lot of caution and precision during the building procedure.

Fig 7.8 Airtubes as a grid shell structure before covering [58]

“The gridshell’s feet play an important role in the overall construction. Each individual element has several, integrative functions: a ball joint connects the tubes with the base elements and allows them to adopt any angle required. With the aid of various clamping mechanisms, the tubes are kept airtight and firmly fixed with the foot. The high inner pressure prevents them from slipping out“.

Fig 7.9 Airtubes as a grid shell structure before covering [58]

Fig 7.10 Negative pressure grid shell structure in the entrance hall, Stuttgart [58]

Unique design of Plus-minus pavilion is using negative pressure to fix and reinforce the whole grid which may be considered as the lightest possible way to built a gridshell or even similar structural type, especially in combination with air tubes. The solution is very clever, but needs a lot of caution during the building procedure.

7.4 CLADDING PROPERTIES IN TERM OF LIGHT TRANSMITTION AND SUITABILITY FOR USE

Every cladding does have its properties and usage meaning, some of them are common to all – as the limits of building covered area. Membranes and foils are, however they are strong in tension, thin and in some ways delicate material.

7.4.1 Opaque cladding

There are several cases, in which a grid shell structure covers a special kind of space, for example theatres which does not need lighting from above. Typically for long-lasting buildings or structures, the grid is covered with additional layer of rigid material as wooden planks and after that covered by common waterproof roofing.

It is also possible to apply natural green cladding though it could be a bit problematic in steep parts of the structure because of heavy material sliding down.
Opaque systems are considered to be mainly used for covered theatres and exhibition pavilions, housing etc.

Using opaque cladding is reasonable for some kind of buildings like theatres to prevent the light getting inside. As an example presented a theater roofing in Neratov.

Fig. 7.11 Opaque cladding [by author 7/2015]

Fig. 7.12 Double layered cladding – opaque and bright [by author 7/2015]

7.4.2 Translucent cladding

Added value achieved by using translucent cladding may be achieved with single layer membrane which has the ability to let the daylight inside. At night it is impressive and effective when the structure covered by translucent membrane is illuminated using artificial lighting, because it is possible to see the whole grid structure under the membrane.

For this purpose could be also used perforated single-layer membrane with different fiber mesh size or vegetation, which makes the whole more interesting and natural.

Fig. 7.13 Japanese pavilion EXPO 2000, Shigeru Ban [59]

Fig. 7.14 Earth Centre Doncaster, UK – 2010 Carpenter Oak & Woodland [60]

Matrix pavilion Třebešov, Czech republic

As a representative membrane structure of using translucent cladding, there is the seasonal membrane of Matrix pavilion in Třebešov mentioned, which is really playful because of used material Ferrari Soltis W96. Soltis Proof W96 protects against UV and bad weather, while preserving the level of natural light transmitted. This translucent, waterproof fabric is ideal for the purpose of multipurpose pavilion.

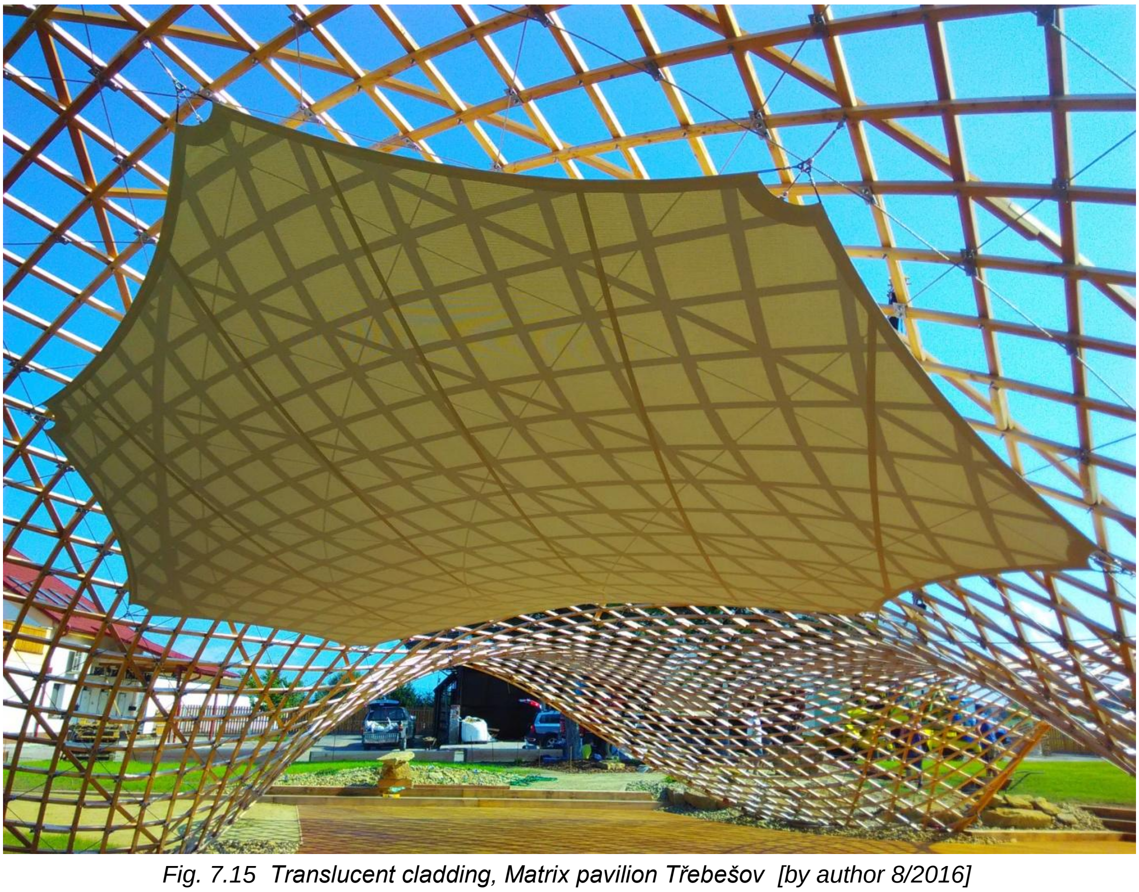

Fig. 7.15 Translucent cladding, Matrix pavilion Třebešov [by author 8/2016]

Fig. 7.16 Translucent cladding of the area 42 m^2, Matrix pavilion Třebešov [by author 8/2016]

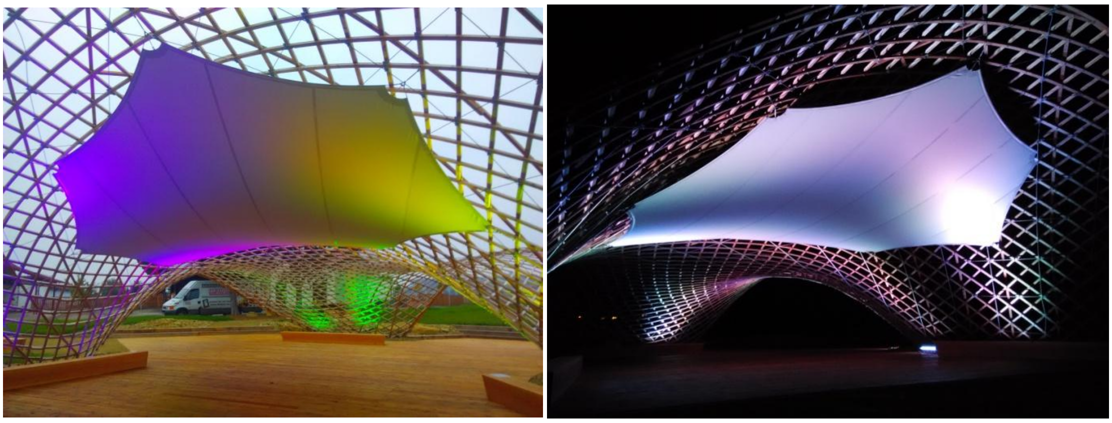

Fig. 7.17 Lightening effects [by author 10/2016]

The lighting of the gridshell and membrane is particularly impressive especially in the night hours, with the RGB LED panels that can be set to any color. The membrane itself acts as if it is floating in the space. From the inner view, it forms part of the ceiling so that it optically reduces the clear height, which is perceived rather pleasant and also defines the meeting point, which is protected from the rain or the sun.

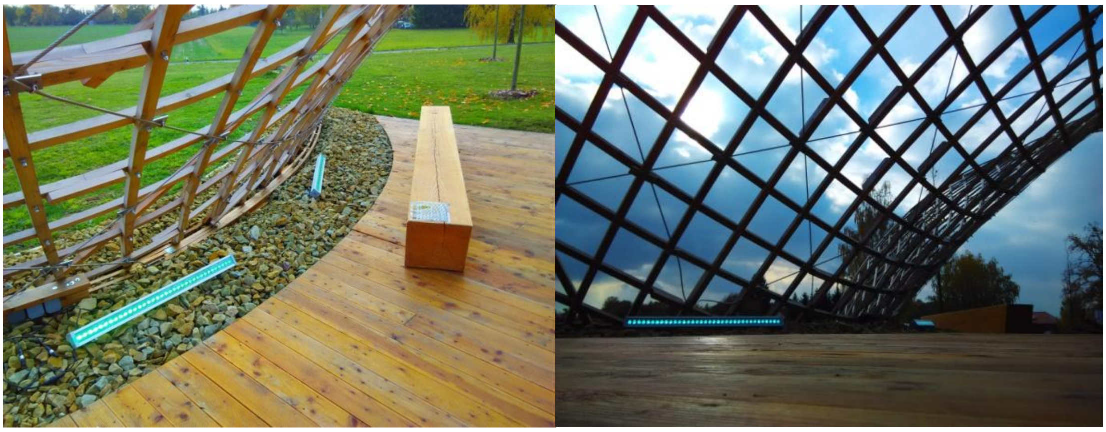

Fig. 7.18 Lightening effects – made by LED RGB panels [by author 10/2016]

7.4.3 <u>Transparent cladding</u>

ETFE foil is the most widespread transparent material in the field of lightweight structures and can be used as a single-layer membrane or in the form of multiple-layer air inflated cushions, depending on required envelope conditions.

ETFE cushions require an aluminium frame around the circumference to anchor and the whole system must be airtight. A big advantage using ETFE cushions is that there is possible to create a tempered inner space by almost 100% light transparency. If necessary, there is a system invented by Vector Foiltec, which can operate with the middle layer to create partial or complete shading.

Fig. 7.19 Leisure Centre, Neydens, France, 2009 [61]

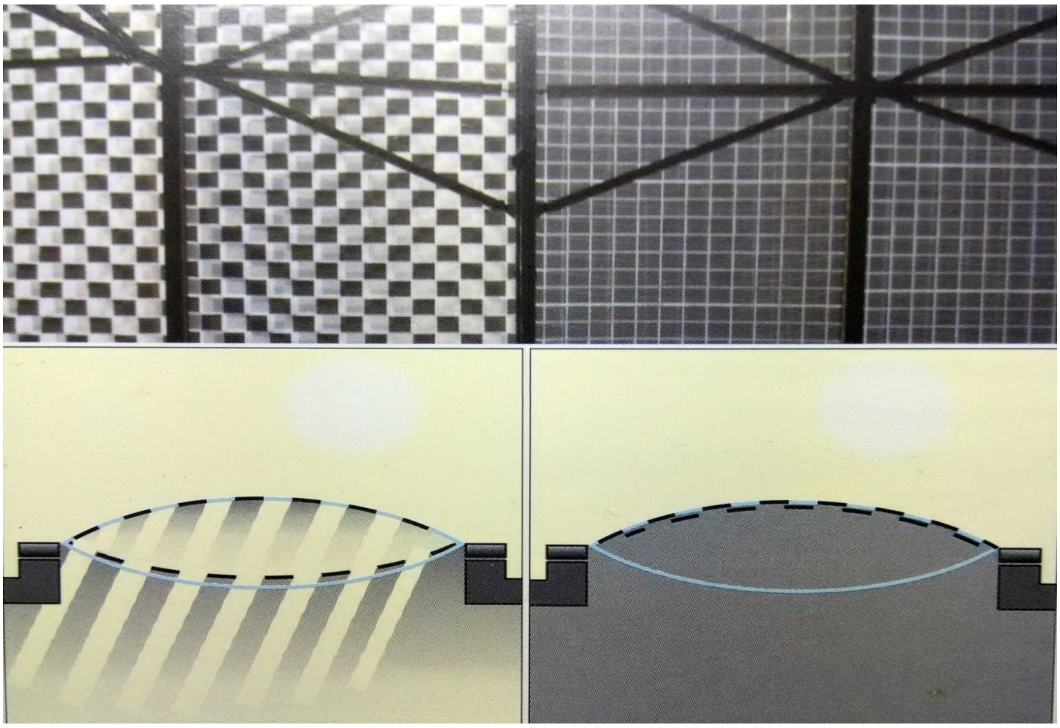

Fig. 7.20 Tripple-layered ETFE cushion – shading effects [Vector Foiltec catalog]

In the opened position (Fig. on the left): Solar and temperature sensors cause the upper air chamber to be pressurized allowing light to penetrate through the graphic pattern in the closed position (Fig. on the right): As internal temperature and solar gains increase the lower air chamber is pressurized reducing the level of light and solar gain penetrating the space.

7.4.4 Semi - transparent cladding

Shopping centre in Amadora, Portugal

Sophisticated use of the ETFE foil element, when using the element thickness. Respectively the difference between the layers, at the widest point it corresponds to twenty percent of the pillow span. In this case, with the dimensions of the 10 x 10 meter pillow equals the height about two meters.

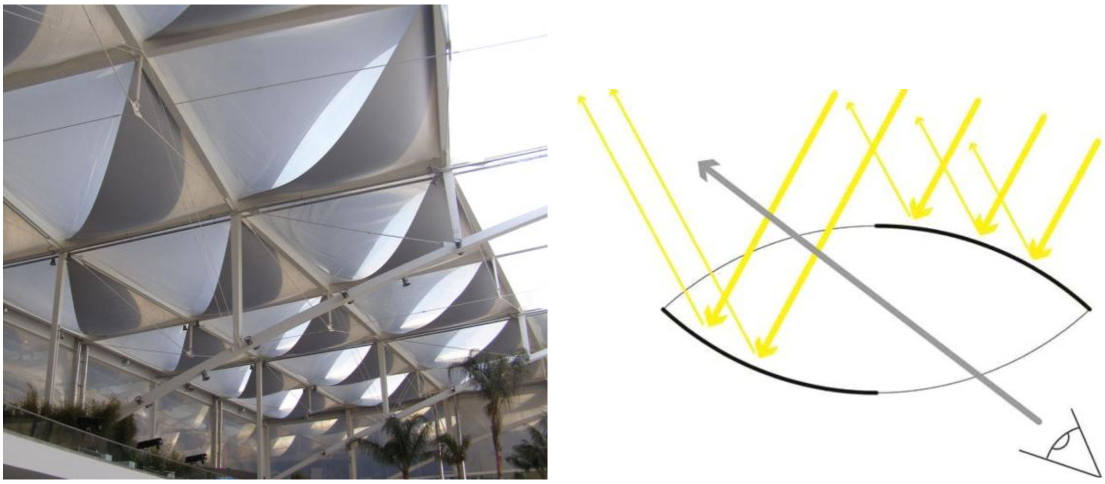

Fig. 7.21 Scheme of permanent partial printing on ETFE cushion, Amadora, Portugal, 2009 *[62]*

The design idea for the shopping mall in Lisbon (Portugal) was to realize a transparent foil cushion roof of the surface of 46.000 m². The main objective for the Climate-Engineering was to develop a solution, which would provide thermal comfort and high daylight availability at the same time.

“Due to the location of the site – Lisbon with above 1600 kWh/m² solar radiation and an average yearly ambient temperature of about 17°C, this was a challenge for the design team. The solution is different coatings on specific parts of the cushion roof, allowing low energetic north diffuse light to enter the mall, but provide shading from the direct sun. The mall area will be conditioned with a floor cooling system in combination with jet nozzles.
Louvers at the perimeter can be opened for natural ventilation, minimizing energy consumption.
Only with the combination of different design tools (daylight simulation, dynamic thermal simulation and CFD) it was possible to find an optimized the solution.” [61]

Transparent membranes often provide additional shading systems that prevent direct sunlight from entering the interior. These systems may be retractable or fixed, depending on the type of operation and the degree of shading required during the day. In the case of the Allianz Arena, it is a movable element that is capable of responding to the need for daily lighting.

In any case, there is the maximum possible care for a good lawn – unless the sunshine is off, it is irradiated by a mobile reflector system.

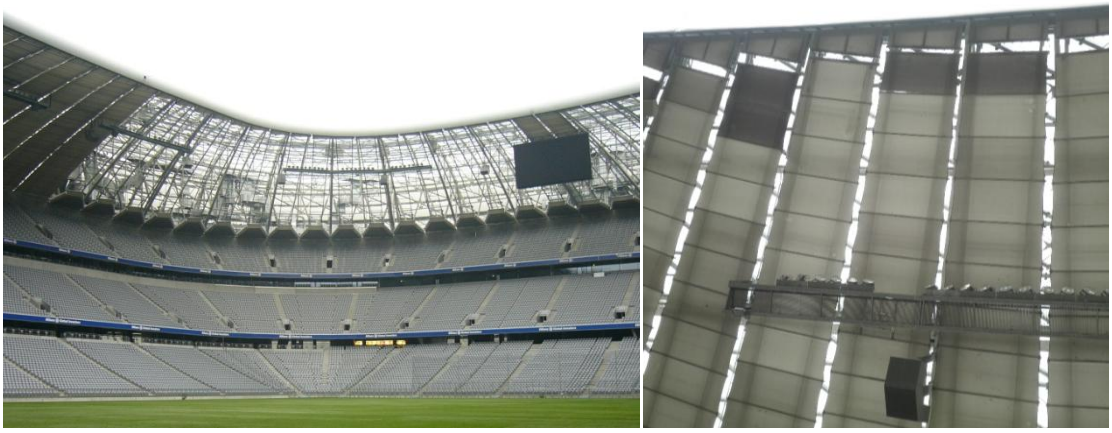

Fig. 7.22 Interior view to the shading ceilings installed from the bottom of the structure, Allianz arena, Munich, Germany   [by author 10/2012]

8. DETAILING

The solution of the details is an integral and extremely important part of every structure from the functional and aesthetic point of view. In reality, every even little detail in the structure must be precisely designed and assembled. This chapter introduces the design of gridshell details within the overall design, ranging from simple grid connections to more complex bracing and anchoring of the entire structure.

8.1 GRID MEMBERS – LONGITUDINAL CONNECTION

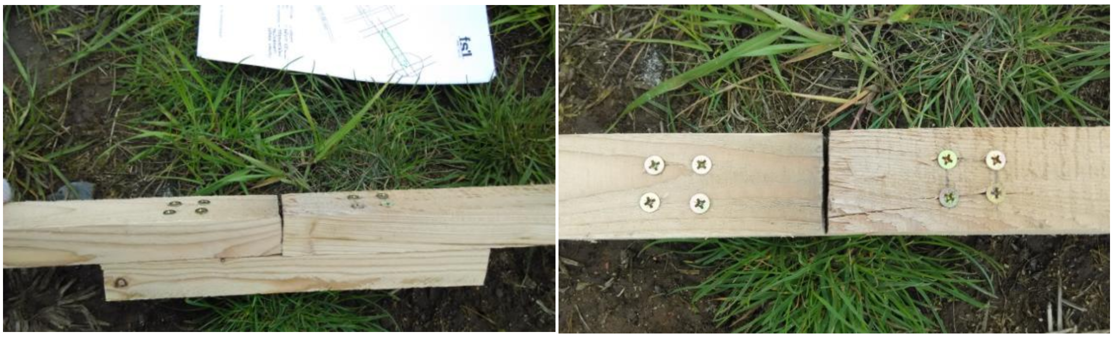

Fig. 8.1 Testing sample - Longitudinal connection of two larch timber laths [photo by author 3/2016]

The simplest structural joints include longitudinal joining of individual elements of the orthogonal grid. In his research, the author directly uses and verifies two types of joints in wooden strips, and also experiments with the connection of PVC pipes of 16 and 25 mm in diameter. The first chosen connection method is to screw one another when one bar is laid over with the overlap. This solution is not difficult, but the workability of the grid connection at the intersections is worse, since the element thus connected has twice the thickness at the joint.

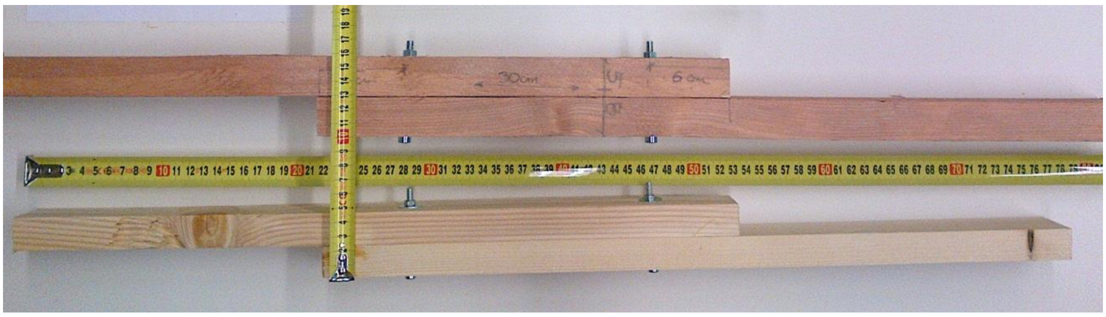

Fig. 8.2 Longitudinal connection with the overlap – testing sample [by author 6/2015]

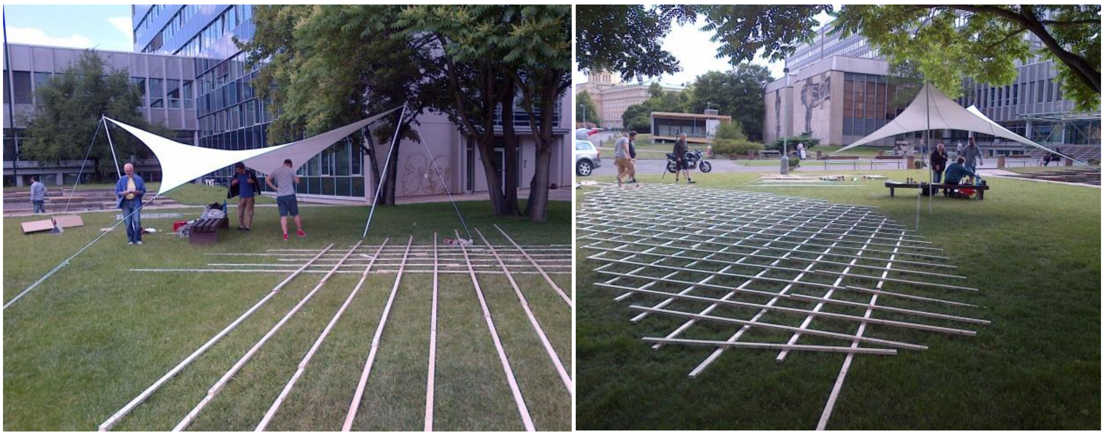

Fig. 8.3 Longitudinal connection with the overlap mountling process [by author 7/2015]

Fig. 8.4 Longitudinal connection with the overlap on a realized structure [by author 7/2015]

As the most elegant and effective solution of longitudinal member connection there is considered a finger joint. This connection type has the advantage due to the final grid mounting and erection process, as well it acts purely and gracefully in the final effect.

A certain disadvantage of the joint is its time and production demands. After the joint grooves have been milled, the parts are glued to each other and the optimum dry-out supply is 1 day. In case of bad weather, longer drying time, possible deterioration of the connection quality must be considered. It is also more complicated in case of additional adjustment of the length of the continuous laths. Also the devices for bonding joints are limited in length and mass capacity.

Fig. 8.5 Finger joint [by author]

8.2 <u>ANCHORING FOUNDATIONS</u>

Foundations anchoring of the gridshell structure has far lesser demands on the size of the resulting forces than a conventional tensioned membrane. As a result, the horizontal forces are relatively small compared to the forces exerted by the tensile membranes, but the design of the foundation must be considered in the course of the realization. Due to the pulling of the lower face of the gridshell to the base edge, considerable stress occurs during the realization. This process may be lengthy and inadvertent force deflections may occur during manipulation.

In the case of the design of the foundations for the Matrix pavilion in Třebešov, various options were considered, and finally, the system of earthworms was chosen as the best. Due to a small previous experience with a similar system, the twin screws were eventually twisted (as shown in the figure). In general, the whole foundation there consists of 22 earthworms, each two meters long

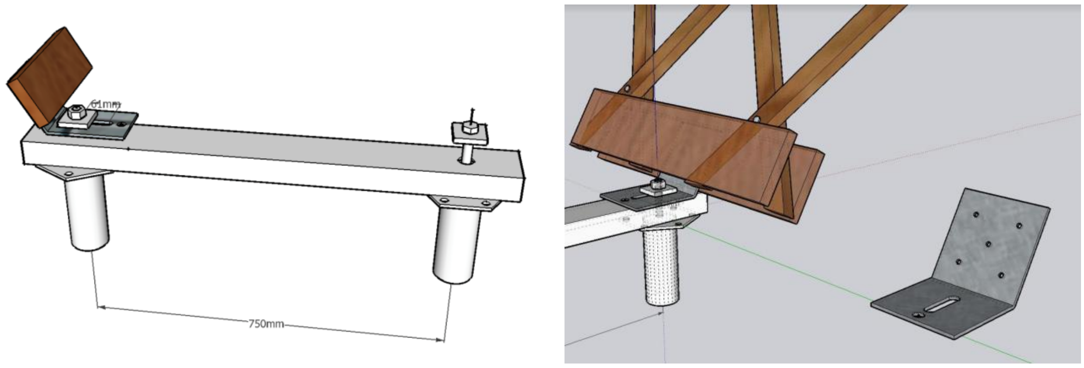

Fig. 8.6 Foundation anchoring design, Matrix pavilion, Třebešov [by author 3/2016]

Fig. 8.7 Foundation anchoring, Matrix pavilion, Třebešov [by author 6/2016]

Fig. 8.8 Foundation anchoring, Matrix pavilion, Třebešov [by author 6/2016]

The anchoring edge is made of the same timber laths as used for the grig, because there was the need to create a curved anchoring edge. This would be also possible using glulam, but the price would be extremy uch higher and not affordable for the client.

Fig. 8.9 Anchoring of the experimental structure, [by author 10/2015]

8.3 CONSTRUCTION JOINTS

Grid structural joints are the basic element for the functionality and stability of the entire structure and there is a number of ways to make the joint. In the case of a splinter joint, which is essentially simpler in the case of drilled joints, maximum junction precision is required. If the connections are not made exact (resulting from the bending of the elements during assembly), unwanted grid tension can occur before erecting the whole grid.

Fig. 8.10   Structural joints, experimental shading structure, [by author 7/2015]

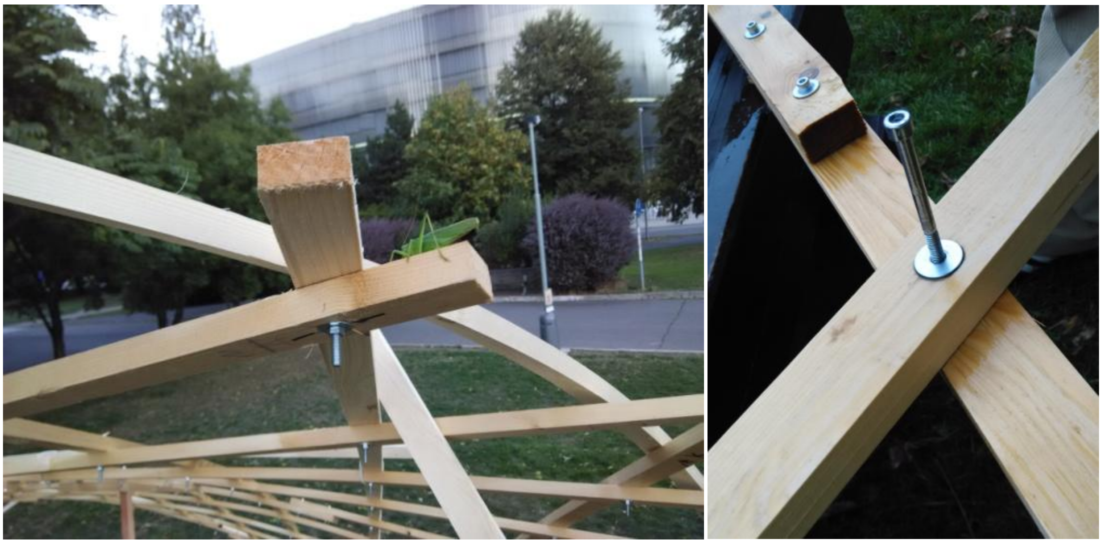

Fig. 8.11 Gridl joints, Experimental structure, Prague, Czech republic [by author 7/2015]

Fig. 8.12 Gridl joints – detail and finished grid before erection process [by author 6/2016]

Circular cross-section materials do have an advantage when forming the structure, as the circular cross section behaves in all directions equally to the square or rectangular cross-section (considering bending and twisting). The interconnection of circular cross-section elements is then more complicated due to the minimal contact area.

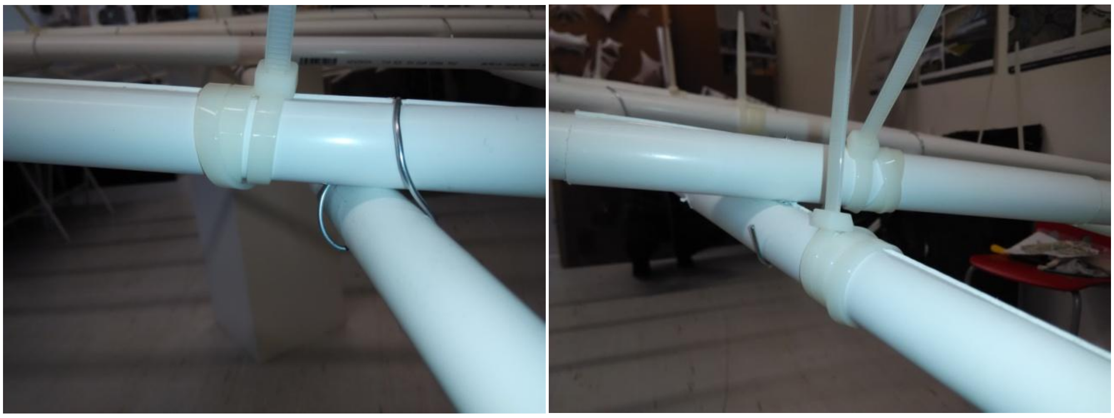

Fig. 8.13 Structural joints by PVC tubes Ø 25 mm, experimental mesh [by author 7/2016]

8.4 STRUCTURAL EDGES

In the field of double curved gridshells, structural edges are a demanding part, especially in the implementation when their quality is required..Depending on the position and the function, there are two types of edges mentioned - the lower edges of the anchor elements, which have one curvature, since they lie on a flat surface, and edges in the space that can be double curved.

Timber laths (as well as another materials) naturally twist when bending, and if we want to place them in the structure, we have to put them into the desired shape by pulling them out. Another option is beforehand prepared glued wood edges that have a higher design quality, but can also act materially when using laminated material.

8.4.1 Free edges in the space

Fig. 8.14 Structural edges realization, Matrix pavilion Třebešov, [by author 7/2016]

Fig. 8.15 Structural edges of Multihalle Mannheim [by author 11/2018]

due to the lack of funds on Multihalle in mannheim, it is not possible to maintain the old hall, which is why the accumulation of disasters arises. Mainly due to the moisture in the structure and the old lattice, which slowly but surely loses its strength. The edge is additionally supported by cable support, which is however not an extremely reliable way and therefore the construction is still supported by the beams.

Fig. 8.16 Structural edges of Multihalle Mannheim [picture by author 11/2018]

8.4.2 Edges in connection with foundation anchoring

Probably the most difficult part of the realization of the Matrix pavilion was to tighten the peripheral edge of the grid to the final position. Finally, this was accomplished by the gradual horizontal pulling of the opposite edges and vertical pushing to the prepared base edge.

Fig. 8.17 Foundation anchoring, Matrix pavilion, Třebešov [by author 6/2016]

the prepared anchor edge is strong enough to cope with the grid structure due to its curvature in one direction (we could also call it lightweight because it is made only from laths). Subsequently, the place of contact between the grid and the base edges was afterwards covered by larch boards from both sides and the whole joint was fixed using threaded rods.

Fig. 8.18 Foundation anchoring, Matrix pavilion, Třebešov, Czech republic [by author 6/2016]

Fig. 8.19 Structural edge anchoring, Multihalle Mannheim [picture by author 11/2017]

Fig. 8.20 Foundation anchoring, Experimental shading structure, , Czech republic [by author 7/2016]

Fig. 8.21 Anchoring made of steel plate, which is formed to required shape [63]

8.5 DIAGONAL REINFORCEMENT

The reinforcement of a gridshell in the design and final phase of realization is one of the most important components. The most effective way to do that is using diagonal bracing. Its application occurs in the process phase after lifting the structure and fixing it to the circumferential anchor elements. In order to properly construct the structure.

It is essential that all joints are allowed to rotate during lifting, but after joining, the joints must be locked to prevent spontaneous movement. Following there are several ways to achieve the reinforcement mentioned.

Fig. 8.22 Structural joints, Matrix pavilion Třebešov, [by author 7/2016]

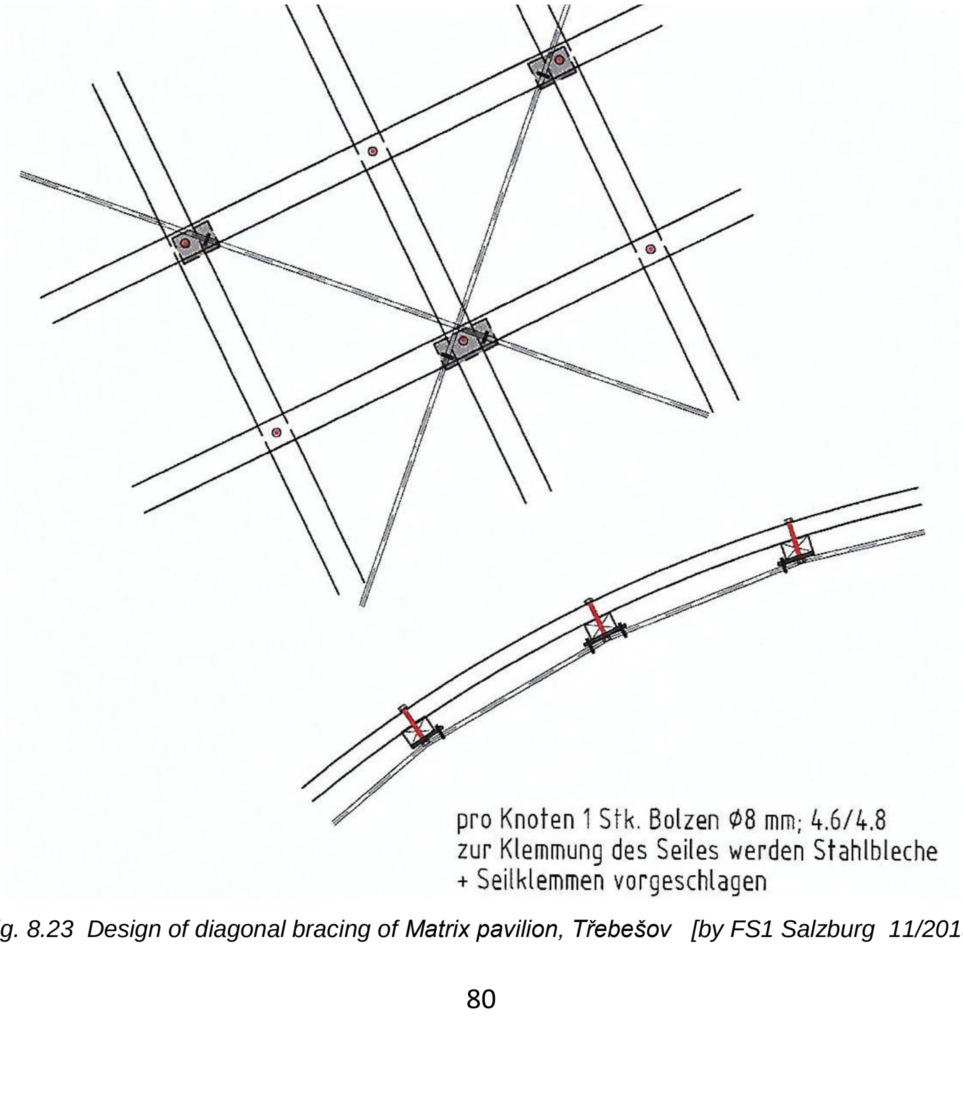

Fig. 8.23 Design of diagonal bracing of Matrix pavilion, Třebešov [by FS1 Salzburg 11/2015]

The diagonal reinforcement itself is possible to achieve The bracing of the surface of the gridshell construction is also possible without the use of diagonal elements that essentially provide for additional surface division by creating triangles by splintering diamonds. In the case of partially or ideally covering the entire surface of the structure preloaded by the membrane, stabilization of the structure occurs due to oblique or perpendicular pressure forces.

Fig. 8.24 Diagonal bracing using 3rd layer of timber, Trade fair Wooden structures 2017, Prague [by author 2/2017]

Fig. 8.25 diagonal reinforcement using steel cable [62]

One possible way of diagonal bracing is to cover the structura surface. Sufficient bracing is achieved if the membrane covers the entire structure. In this example, a stretch rubberized mat is used, which is preloaded on the structure due to its stretching just before application to the surface of the structure.

Fig. 8.26 Membrane covering experimental gridshell mde of PVC tubes [by author]

8.6 MEMBRANE ANCHORING

8.6.1 Membrane on the top of the gridshell

the surface membrane is most often anchored at the circumferential surface by the synclastic curvature of the surface, attracting the peripheral anchor edge, which makes it easy to shut off and stabilize the structure.

For anticlastic forms, this may not be an advantage, as it may cause the membrane to move away from the surface of the structure (for example, in the valleys) at certain points. In these cases, the correct direction of laying of the membrane belts is important to ensure smooth operation.

Another option is to produce a membrane made to measure according to the cutting pattern, which is recommended to do after reaching the final shape of the structure, since in the case of inaccuracies in the gridshell structure deviations from the proposed state may occur, even smaller deviations could result in wrinkling the surface of the applied membrane.

Fig. 8.27 Membrane anchoring to the perimeter made of steel plate [62]

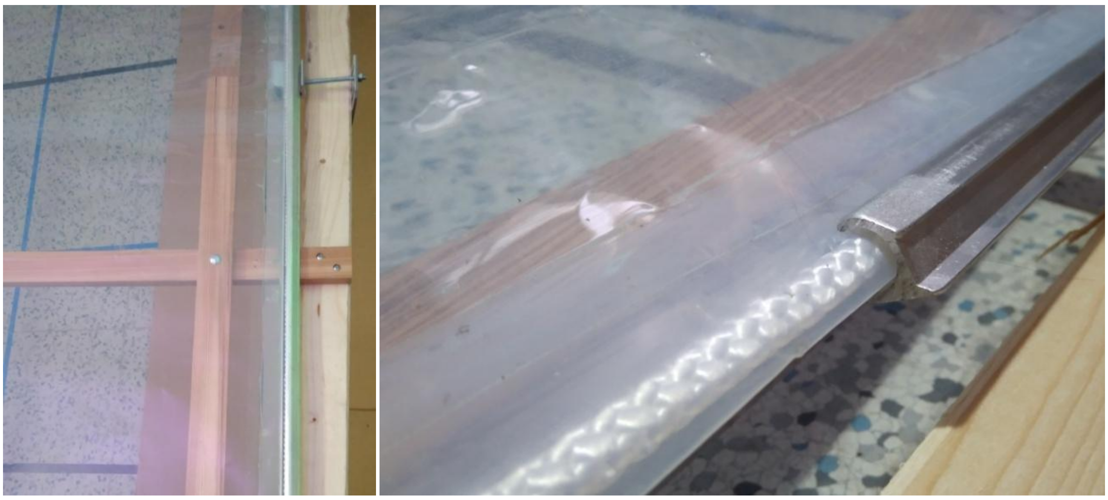

Fig. 8.28 ETFE foil anchoring to the perimeter using aluminium profile [by author]

8.6.2 Membrane suspended from below

The entrance roof for the Waitomo caves in New Zealand was realized in 2010 using a gridshell structure with implementation of the ETFE pillow system. The whole is transparent and air-friendly, protecting visitors from bad weather and the additionally flooded membranes also from the sun's rays and the resulting overheating of the interior. The hanging membranes are made as simple sails without double curvature and are easily demountable if necessary.

Fig. 8.29 Waitoma Caves Visitors Centre, 2010 New Zealand [63]

The possibility of anchoring at any point of the main lattice gridshell was used on the project of Matrix pavilion,. At these points is also anchored diagonal reinforcement.

In order to ensure the rigidity of the structure and reinforcement of the cross section at the point of greatest stress, a third layer of laths, diagonally to the given grid was applied.

Fig. 8.32 Membrane anchoring detail to the perimeter in points, 2016, Třebešov [by author]

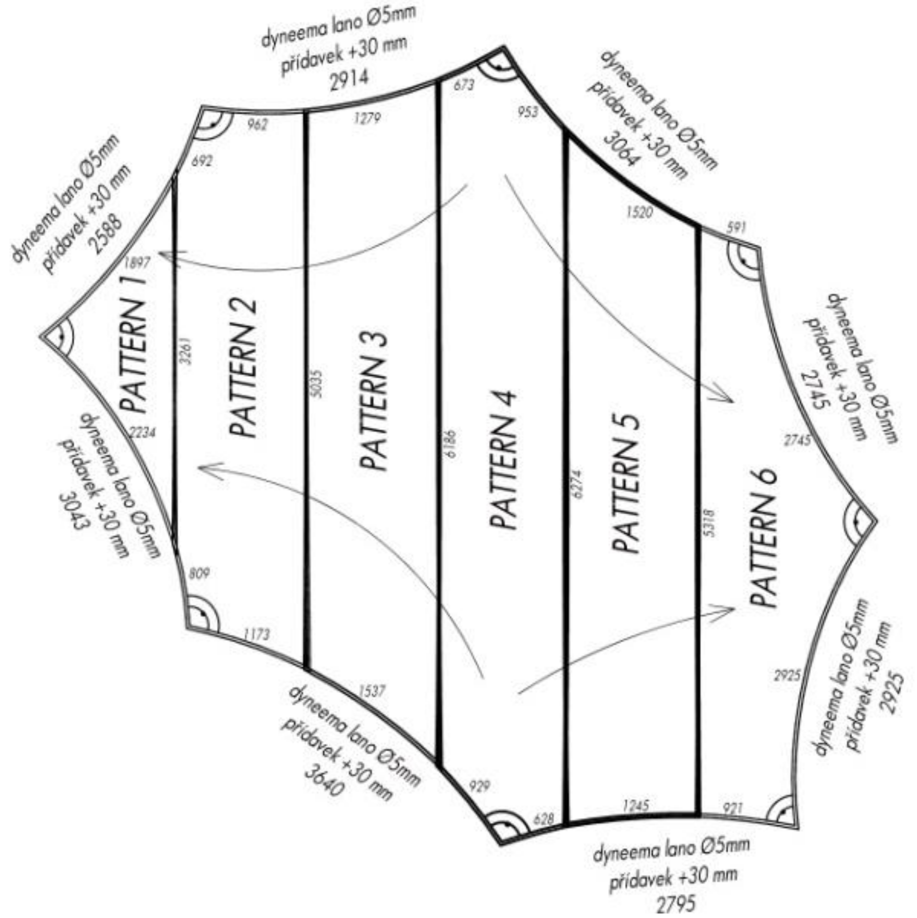

Fig. 8.30 Membrane pattern layout, 2016, Třebešov [by Jan Vecko]

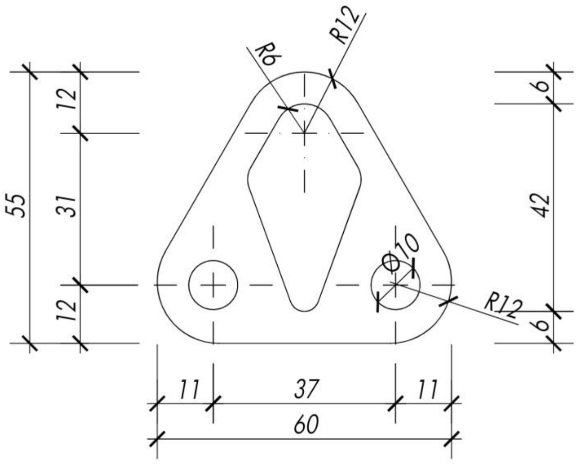

Fig. 8.31 Membrane corner anchoring detail, 2016, Třebešov, [by Jan Vecko]

8.7 CLADDING MEMBRANE – ADDITIONALTENSIONING

Students from London's Architectural Association have designed and built a lattice-framed shelter for seasoning timber at the school's Dorset campus, using short lengths of wood taken from neighbouring beech trees.

Fig. 8.33 Membrane tensioning made using rectificable wooden balls [64]

The ability of additional tensioning possibility of the membrane is very helpful in the subsequent optimal application of the membrane to the surface of the structure. If the membrane is stretched only circumferentially, there is an uneven distribution of forces within the membrane, the largest being at the very top where membrane damage or deformation of the supporting structure.

The tensioning from the inner side allows to additionally tension locally, which ensures an even distribution of forces throughout the area.

In the case of experimental gridshell made of PVC tubes, the additional tensioning was made from below using half- cutted tennis balls. This solution was quite helpful, defining the area of lower and higher surface tension.

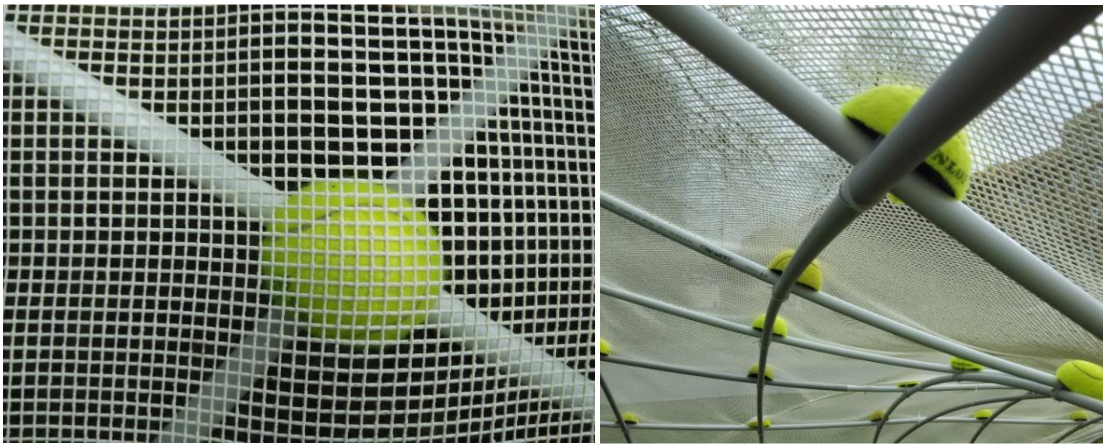

Fig. 8.34 Additional membrane tensioning using half-cutted tennis balls, 2016 [by author 10/2015]

9. DOCUMENTATION OF MATERIAL DAMAGE DURING RESEARCH

The chapter documents using pictures several material failures, which were adapted under the author's research. The whole research was preferentially based on making physical models in a real scale which involved testing the real material from which the designs are realized. This experience has helped to verify the details proposed and confirmed their accuracy and misconduct

Fig. 9.1 Bending tests made on spruce timber, cracking occurs most often in areas close to reinforced joints [by author 3/2015]

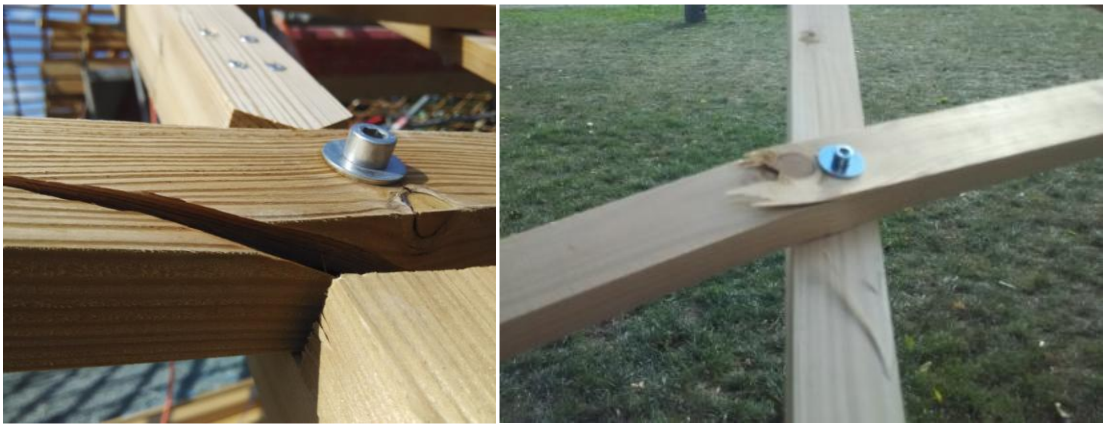

Fig. 9.2 Grid members cracking due to the worse local quality of non-homogeneous material, [by author 7/2016]

Fig. 9.3 The crackings of additional layer when erecting the grid during the building process of Matrix pavilion Třebešov. This shows the need to strengthen the structure before lifting [by author 7/2016]

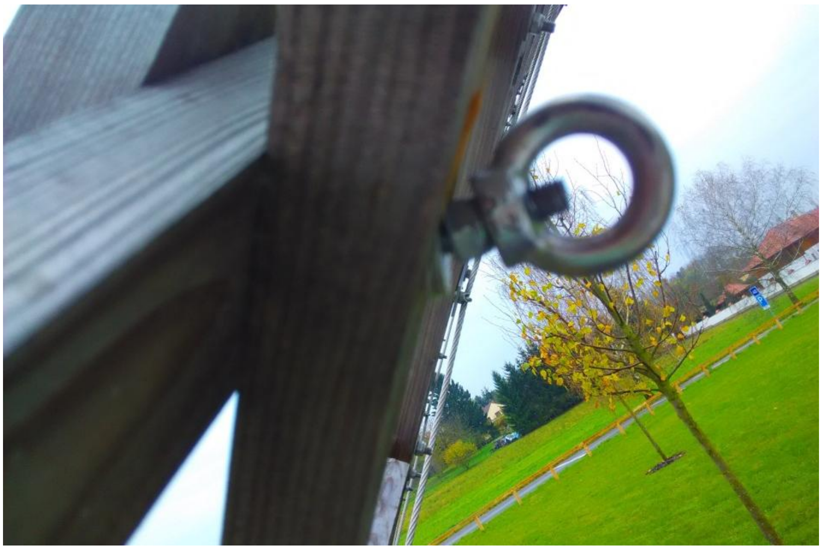

Fig. 9.4   Damage to the handlecaused by extreme tension force from the suspended membrane which happened during a strong whirlwind, [by author 10/2017]

Fig. 9.5   Membrane corner damage, which happened during a strong whirlwind. The membrane was designed for seasonal use, in case of unpredictable events one must expect this could happened [by author 10/2017]

Fig. 9.6   Extreme tension forces perpendicular to the glued joint in the surface of ETFE foil tensioned on the top of a gridhell sample, damage caused during the tests [by author 5/2018]

ZÁVĚR

Lehké konstrukce jednovrstvých tažených membrán či jedno- a vícevrstvích fólií ETFE tvoří součást konstrukčního systému, což dovoluje podpůrné konstrukci korekci materiálu nutného pro zajištění dostatečné tuhosti. S tím jde ruku v ruce možná finanční úspora, efektivita výstavby a v neposlední řadě osobitý architektonický výraz.

Cílem této disertační práce bylo ověřit možnosti spolupůsobení mezi nosnými konstrukcemi a membránami, se záměrem praktického ověření na reálném příkladě. Za vhodnou konstrukci pro další vývoj byla zvolena mřížová skořepina (gridshell), kterou tvoří atypický samonosný systém a membrána zde ve své podstatě tvoří pouze výplň, zároveň se s ní dá také počítat ke ztužení konstrukce. K získání potřebných zkušeností a dovedností autor spolu s kolegy organizoval několik workshopů, které se staly velmi cenným zdrojem pro zodpovězení mnoha otázek, především spojených s vlastní realizací konstrukce mřížové skořepiny – gridshellu a možností aplikování membrány. V průběhu autorovy práce došlo k ověření funkčnosti tří variant aplikace membrány – pokrytí konstrukce jednovrstvou membránou a fólií a zavěšení podhledové membrány.

Výchozí ortogonální dřevěný rošt, ze kterého konstrukce vzniká, je při reálném formování velmi nepředvídatelný a citlivý na každou, byť malou změnu. Postup montáže musí být dobře organizovaný a každý účastník stavby musí všechny plánované kroky provést pečlivě, aby se zabránilo nechtěnému formování nebo v nejhorším případě kolapsu konstrukce. Samotný návrh konstrukce je dobrý, pokud konstrukce využije dvojitě zakřiveného tvaru.

Membrána nebo fólie nemůže být reálná samostatně bez přídavných podpůrných či napínacích konstrukcí, naopak tomu lehká konstrukce gridshell může fungovat samostatně, přičemž membrána je ideálním doplňkovým materiálem pro funkční spolupůsobení.

Konstrukce gridshell jsou použitelné zejména jako lehké konstrukce s osobitým výrazem atypického tvaru dvojí křivosti pro menší až střední měřítka, kde nejvíce vynikne subtilnost a elegantnost konstrukce.

CONCLUSION

Lightweight single layer membranes and multilayer ETFE foil structures are the part of a structural system that allows the supporting structure material amount correction, which is necessary to provide sufficient stiffness. With this, the financial savings, the efficiency of the construction and, last but not least, the individual architectural expression are at hand.

The aim of this dissertation was to verify the possibilities of interaction between supporting structures and membranes, with the aim of practical verification on a real examples. A gridshell, which is an atypical self-supporting system and the tensioned membrane forms only a filler, is chosen as a suitable construction for further development, while it is also possible to count on the construction. In order to acquire the necessary experience and skills, the author and his colleagues organized several workshops, which became a valuable resource for answering many questions, mainly related to the actual realization of the grid shell structure and membrane application possibilities. In the course of the author's work, the functionality of three membrane application variants - covering the single-layer membrane and foil structure and suspension of the ceiling membrane, was verified.

The original orthogonal wooden grid, from which the structure is formed, is very unpredictable and sensitive to any even minor change in real formation. The installation procedure must be well organized and every participanton the building site must perform all planned steps carefully to prevent unwanted formation or, in the worst case scenario, collapse of the structure. The design itself is good if the structure uses a double curved shape.

The membrane or foil cannot be real independent without additional supporting or tensioning structures; on the contrary, the lightweight gridshell structure can work independently, the membrane being an ideal complementary material for functional interaction.

The gridshell designs are particularly useful as light constructions with a distinctive atypical shape of double curvature for smaller to medium scales, where the subtlety and elegance of the construction is most evident.

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LIST OF FIGURES

Fig. 9.5 Membrane corner damage, which happened during a strong whirlwind. The membrane was designed for seasonal use, in case of unpredictable events one must expect this could happened [by author 10/2017]

Fig. 9.6 Extreme tension forces perpendicular to the glued joint in the surface of ETFE foil tensioned on the top of a gridhell sample, damage caused during the tests [by author 5/2018]

STUDENT WORKSHOPS ORGANISED DURING AUTHOR´S RESEARCH

[Posters of workshops organized by the author of the dissertation]

Poster from organized membrane workshop [by author]

STUDIO MEMBRÁNOVÉ ARCHITEKTURY

EXPERIMENTÁLNÍ PROJEKT LEHKÉ KONSTRUKCE GRIDSHELL

Projekt řeší plánované zastřešení bazénku před hlavním vsupem FSv ČVUT v Praze. V sučasnosti je prostor využíván pro odpočinek a relaxaci studentů ve volném čase mezi výukou. Po revitalizaci objektu v roce 2014 (nová fasáda budov A a C) došlo také k úpravě parteru – nová trávníková plocha v těsné blízkosti bazénku, který jako takový zůstal nezměněn. Dalším drobným vylepšením jsou lokálně rozmístěné dřevěné prvky pro sezení.

Plánované zastřešení lehkou konstrukcí vzešlo z potřeby ochrany před deštěm a slunečním zářením, prostor je jižně orientovaný.

Ve dnech 22.-23.5. proběhl studentský workshop, kde byli studenti a zájemci o lehké zastřešovací systémy seznámeni s problematikou konstrukce „Gridshell“, tedy laťové mřížkové konstrukce, která byla pro dané zastřešení vybrána jako nejvhodnější zejména díky své estetické kvalitě, příznivé ceně a možnosti realizace svépomocí. Workshop probíhal pod dohledem Dipl.-Ing. Jürgena Hennickeho, Univ.Lektor (Institut für Leichtbau Entwerfen und Konstruieren – ILEK, Univerzita Stuttgart), který se od počátku podílel na projektování Olympijského stadionu v Mnichově pro OH 1972. Dále za pomoci Stephana Töngiho – konstrukční a membránový specialista, Prototyp metallbau, Basel, Švýcarsko.

Realizace projektu je spojena se studiem lehkých konstrukcí a membránové problematiky Ing.arch. Aleše Vaňka (Ph.D. studium A+S FSv ČVUT Praha, magisterské studium Membrane Lightweight Structures TU Vídeň) za podpory Katedry architektury Fakulty stavební ČVUT.

Pro zastřešení bazénku je zvolena laťová mřížková konstrukce, která se dokáže tvarovat pomocí pružnosti latí a díky volným spojům. Konstrukční princip je založen na použití průběžných latí ve dvou směrech spojených v jejich průsečících. finálního tvaru je docíleno vztyčením celé konstrukce, při ohýbání se čtverce z půdorysné mřížky mění v kosočtverce v prostoru. Poté dojde k zafixování obvodu půdorysu a dotažení spojů, čímž vznikne tuhá skořepina. Na závěr je po konzutaci s francouzskou firmou Serge Ferrari plánováno pokrytí celé konstrukce jednovrstvou textilní membránou (PE vlákna s krytím PVC).

více informací naleznete na: ***www.smembrany.cz***

Poster from organized gridshell workshop   [by author]

Poster from organized gridshell workshop [by author]